



US Army Corps
of Engineers

USER'S GUIDE FOR A THREE-DIMENSIONAL NUMERICAL HYDRODYNAMIC, SALINITY, AND TEMPERATURE MODEL OF CHESAPEAKE BAY

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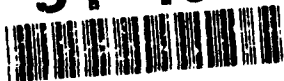


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13. ABSTRACT (Maximum 200 words) A time-varying three-dimensional (3D) numerical hydrodynamic model of Chesapeake Bay has been developed to provide flow fields to a 3D water quality model of the bay. The water surface, 3D velocity field, salinity, and temperature are computed. Major physical processes affecting bay circulation and vertical mixing are modeled. A particular feature of the model is the solution of transformed equations on a boundary-fitted grid in the horizontal plane. This user's guide presents a detailed discussion of theoretical aspects of the 3D model (e.g., basic equations, boundary conditions, turbulence closure, etc.), followed by a discussion of the organization of the computer code and input data requirements. Listings of portions of the various input data files for an application that simulates the hydrodynamics of the Chesapeake Bay during September 1983 are also provided.				
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PREFACE

The study described herein and the preparation of this report were conducted during 1988-90 for the US Army Engineer District, Baltimore, by the US Army Engineer Waterways Experiment (WES) under the general supervision of Mr. Frank Herrmann, Chief of the Hydraulics Laboratory, Dr. James Houston, Chief of the Coastal Engineering Research Center, and Messrs. M. B. Boyd, Chief of the Waterways Division (WD), W. H. McAnally, Chief of the Estuaries Division (ED), and H. Lee Butler, Chief of the Research Division (CR). Dr. Robert W. Whalin, Technical Director of WES, was the director of the study; Mr. D. L. Robey, Chief of the Ecosystem Research and Simulation Division (ES), Environmental Laboratory, was the Study Manager. Mr. Butler was the coordinator for the Hydrodynamics Modeling Team.

Drs. Billy H. Johnson, WD, and Keu W. Kim, CR, prepared this report with assistance from Mr. Ronald H. Heath, Math Modeling Branch, WD, Dr. Bernard B. Hsieh, ED, and Mr. Butler.

Dr. Alan F. Blumberg of HydroQual, Inc., provided the September 1983 data set. These data were collected by the National Oceanic and Atmospheric Association (NOAA). Dr. Y. P. Sheng of University of Florida was a consultant during a portion of the study, and his contributions are gratefully acknowledged.

Commander and Director of WES during preparation of this report was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

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CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI
(metric) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
cubic feet	0.02831685	cubic metres
feet	0.3048	metres

USER'S GUIDE FOR A THREE-DIMENSIONAL NUMERICAL
HYDRODYNAMIC, SALINITY, AND TEMPERATURE MODEL
OF CHESAPEAKE BAY

PART I: INTRODUCTION

1. Chesapeake Bay is one of the largest estuaries in the world. As shown in Figure 1, the main bay extends approximately 300 km north from the ocean entrance to the Susquehanna River. The average depth of the bay is about 8 m, although a natural channel with depths greater than 15 m traverses the bay for more than 60 percent of its length. The bay is irregular in shape, varying in width from 6.4 km to 48.3 km in the middle bay off the Potomac River. The bay is sufficiently long to accommodate one complete tidal wave at all times.

2. Chesapeake Bay is one of the Nation's most valuable natural resources. It supports important commercial and recreational fisheries, transportation, industry, recreation, and tourism, and provides irreplaceable habitat for living marine resources and wildlife. However, the estuary has been subjected to increasing environmental stress in recent decades, and the productivity and beauty of Chesapeake Bay have significantly declined.

3. In 1983, the US Environmental Protection Agency (USEPA) identified major contributing factors to the bay's decline as inputs of nutrients and toxicants from point and nonpoint sources, changes in land use within the basin with resulting modification of the watershed and resource habitat, and concurrent impacts of natural events such as floods and droughts (USEPA 1983a, 1983b). Because population within the bay drainage basin is still increasing, and development pressures will continue into the foreseeable future, it is necessary that strategies are developed to reverse the present bay decline and to accommodate future growth in an environmentally sound manner.

4. The Chesapeake Bay Program (CBP), established in 1983, provides a management structure through which the activities of state and Federal agencies, as well as those of private citizens, can be coordinated toward the goal of bay restoration. A number of tools have been developed by the CBP which will assist in the planning, implementation, and evaluation of these strategies. Among these are a three-dimensional (3D), time-varying water quality

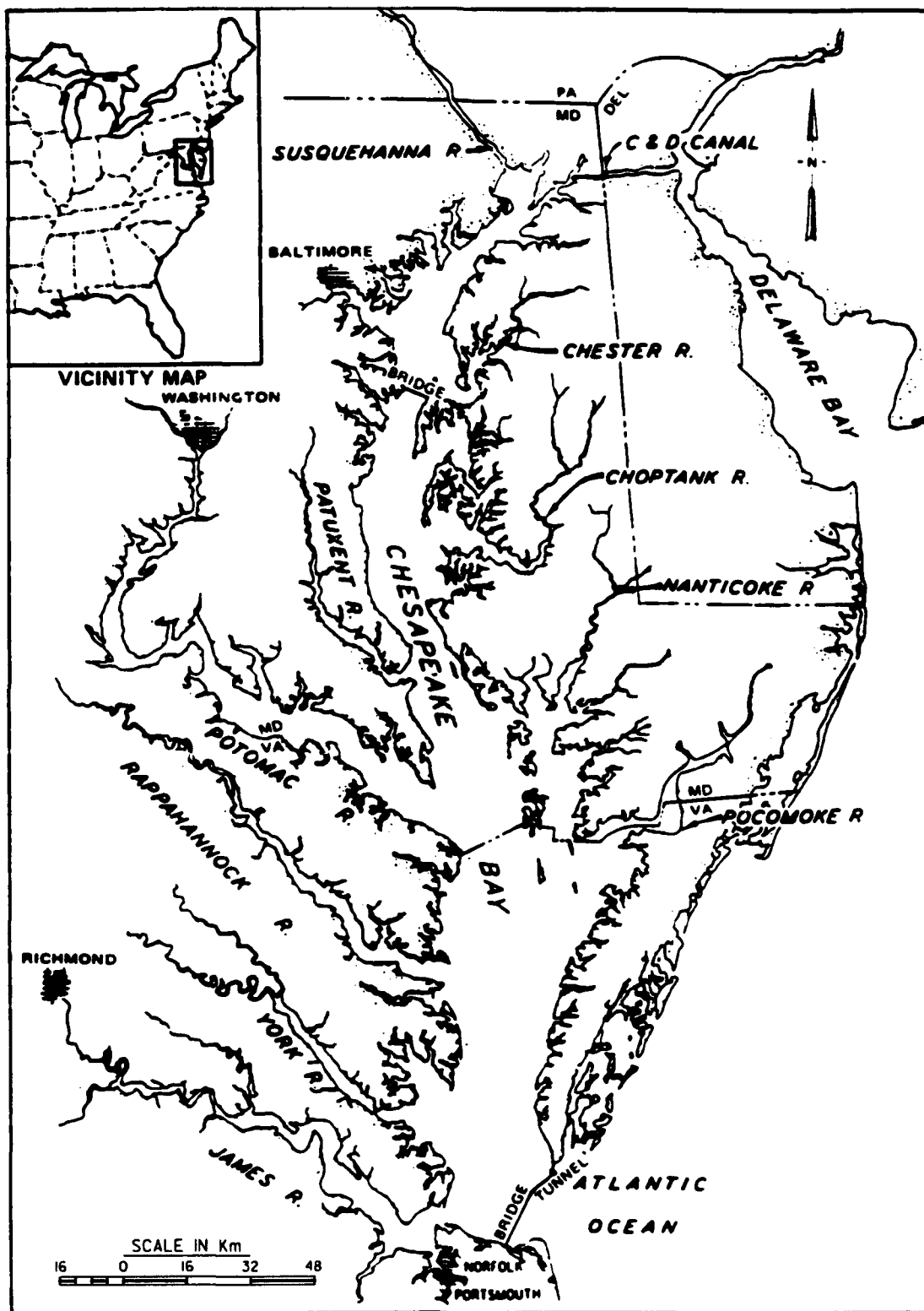


Figure 1. Chesapeake Bay

model for the bay and its tributaries to provide a detailed assessment of the system's response to nutrient inputs and other parameters varied realistically over time and space. The 3D water quality model represents the means through which proposed management actions can be tested before implementation, thereby allowing more cost-effective selection of appropriate strategies. However, it has been acknowledged that water quality impacts in Chesapeake Bay cannot be successfully assessed without an accurate description of the hydrodynamic processes. Thus, a 3D time-varying hydrodynamic model of Chesapeake Bay has been developed at the US Army Engineer Waterways Experiment Station (WES). The model is called CH3D-WES (Curvilinear Hydrodynamics in Three Dimensions).

5. The numerical grid employed in the Chesapeake Bay 3D hydrodynamic model is shown in Figure 2. There are 734 active horizontal cells and a maximum of 15 vertical layers, resulting in 3992 computational cells. To capture the important features of the hydrodynamic processes and bathymetry in the bay, grid resolution is 1.52 m vertical and approximately 10 km longitudinal and 3 km lateral. Major tributaries are modeled fully 3D in the lower reach and as constant-width two-dimensional (2D) in the upper reach.

6. This user's guide presents a detailed discussion of theoretical aspects of the 3D model. The governing equations solved in the 3D model are presented in both Cartesian and curvilinear or boundary-fitted form for both the external and internal modes. The external mode consists of vertically averaged equations, whereas the internal mode contains the full 3D equations. Required boundary conditions, along with a discussion of the algorithm employed to numerically solve the equations, are given. In addition, the structure of the computer model is discussed. Detailed descriptions of the function of each subroutine are provided along with a discussion of the flow of computations in the model. The type of input data required to operate the model and the setup of those data are also presented.

7. Basic input required are time-varying water-surface elevations at the ocean entrance and freshwater inflows at the head of all tributaries. In addition, time-varying salinity and temperature data must be prescribed at all inflow boundaries. Also, time-varying wind and surface heat exchange data must be prescribed at one or more locations. These are then distributed in some manner over the entire grid. All input data, including initial conditions, bathymetry, boundary, and computational control data are input from fixed files. An application using data from September 1983 serves to

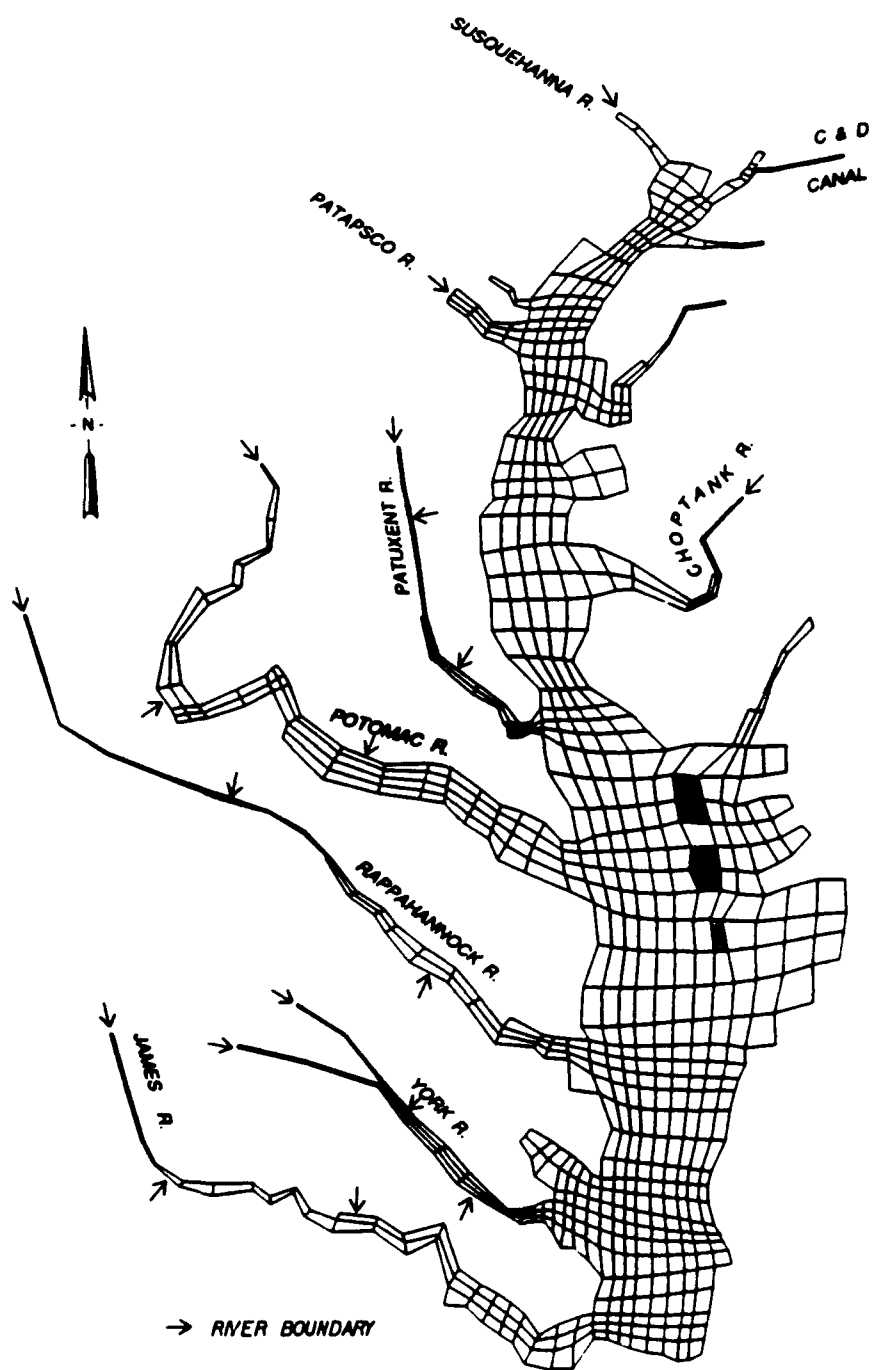


Figure 2. Planform boundary-fitted grid of Chesapeake Bay

demonstrate the setting up of input files. A detailed list of the input data requirements and the proper format are also given. Standard output are water-surface elevations, velocity, salinity, and temperature in each cell of the grid at some specified time interval.

PART II: THEORETICAL BASIS OF CHESAPEAKE BAY 3D HYDRODYNAMIC MODEL

8. As noted, the particular hydrodynamic computer model employed is called CH3D-WES. The basic model (CH3D) was developed by Sheng (1986) for WES but has been extensively modified in its application to Chesapeake Bay. These modifications have consisted of different basic formulations as well as substantial recoding for more efficient computing. As its name implies, CH3D-WES makes hydrodynamic computations on a curvilinear or boundary-fitted planform grid. Physical processes impacting bay-wide circulation and vertical mixing that are modeled include tides, wind, density effects (salinity and temperature), freshwater inflows, turbulence, and the effect of the earth's rotation. Adequately representing the vertical turbulence is crucial to a successful simulation of stratification/destratification. A second-order turbulence model based upon the assumption of local equilibrium of turbulence is employed. The boundary-fitted coordinates feature of the model provides enhancement to fit the deep navigation channel and irregular shoreline configuration of the bay and permits adoption of an accurate and economical grid schematization. The solution algorithm employs an external mode consisting of vertically averaged equations to provide the solution for the free surface to the internal mode consisting of the full 3D equations.

Basic Equations

9. The basic equations for an incompressible fluid in a right-handed Cartesian coordinate system (x,y,z) are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (1)$$

$$\begin{aligned} \frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial z} = f_v - \frac{1}{\rho_o} \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left[A_H \frac{\partial u}{\partial x} \right] \\ + \frac{\partial}{\partial y} \left[A_H \frac{\partial u}{\partial y} \right] + \frac{\partial}{\partial z} \left[A_V \frac{\partial u}{\partial z} \right] \end{aligned} \quad (2)$$

$$\frac{\partial v}{\partial t} + \frac{\partial uv}{\partial x} + \frac{\partial v^2}{\partial y} + \frac{\partial vw}{\partial z} = -fu - \frac{1}{\rho_0} \frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left(A_H \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left(A_H \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left(A_V \frac{\partial u}{\partial z} \right) \quad (3)$$

$$\frac{\partial p}{\partial z} = -\rho g \quad (4)$$

$$\frac{\partial T}{\partial t} + \frac{\partial uT}{\partial x} + \frac{\partial vT}{\partial y} + \frac{\partial wT}{\partial z} = \frac{\partial}{\partial x} \left(K_H \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_H \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_V \frac{\partial T}{\partial z} \right) \quad (5)$$

$$\frac{\partial S}{\partial t} + \frac{\partial uS}{\partial x} + \frac{\partial vS}{\partial y} + \frac{\partial wS}{\partial z} = \frac{\partial}{\partial x} \left(K_H \frac{\partial S}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_H \frac{\partial S}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_V \frac{\partial S}{\partial z} \right) \quad (6)$$

$$\rho = \rho(T, S) \quad (7)$$

where

(u,v,w) = velocities in (x,y,z) directions

t = time

f = Coriolis parameter defined as $2\Omega \sin \phi$

where

Ω = rotational speed of the earth

ϕ = latitude

ρ = density

p = pressure

A_H, K_H = horizontal turbulent eddy coefficients

A_V, K_V = vertical turbulent eddy coefficients

g = gravitational acceleration

T = temperature

S = salinity

Equation 4 implies that vertical accelerations are negligible and thus the pressure is hydrostatic.

10. Various forms of the equation of state can be used for Equation 7. In the present model, the equation given below is used:

$$\rho = P/(\alpha + 0.698P) \quad (8)$$

where

$$P = 5890 + 38T - 0.375T^2 + 3S$$

$$\alpha = 1779.5 + 11.25T - 0.0745T^2 - (3.8 + 0.01T)S$$

and T is in degrees Celsius, S is in parts per thousand, and ρ is in grams per cubic centimeter.

Non-Dimensionalization of Equations

11. Working with the dimensionless form of the governing equations makes it easier to compare the relative magnitude of various terms in the equations. Therefore, the following dimensionless variables are used:

$$(u^*, v^*, w^*) = (u, v, wX_t/Z_t)/U_t$$

$$(x^*, y^*, z^*) = (x, y, zX_t/Z_t)/X_t$$

$$(\tau_x^*, \tau_y^*) = (\tau_x^v, \tau_y^v)/\rho_o f Z_t U_t$$

$$t^* = tf$$

$$\zeta^* = g\zeta/fU_tX_t = \zeta/S_t$$

$$\rho^* = (\rho - \rho_o)/(\rho_t - \rho_o) \quad (9)$$

$$T^* = (T - T_o)/(T_t - T_o)$$

$$A_H^* = A_H/A_{Hr}$$

$$A_v^* = A_v/A_{vr}$$

$$K_H^* = K_H/K_{Hr}$$

$$K_v^* = K_v/K_{vr}$$

where

(τ_x^w, τ_y^w) = wind stress in (x,y) directions

ζ = water surface elevation

which then yields the following dimensionless parameters in the governing equations:

Vertical Ekman Number: $E_v = A_{vr}/fZ_r^2$

Lateral Ekman Number: $E_H = A_{Hr}/fX_r^2$

Vertical Prandtl (Schmidt) Number: $Pr_v = A_{vr}/K_{vr}$

Lateral Prandtl (Schmidt) Number: $Pr_H = A_{Hr}/K_{Hr}$

Froude Number: $F_r = U_r/(gZ_r)^{1/2}$ (10)

Rossby Number: $R_o = U_r/fX_r$

Densimetric Froude Number: $Fr_D = F_r / \sqrt{\epsilon}$

where $\epsilon = (\rho_r - \rho_o)/\rho_o$

S_r , T_r , U_r , ρ_r , X_r , Z_r , A_{Hr} , A_{vr} , K_{Hr} , and K_{vr} are arbitrary reference values of the salinity, temperature, velocity, density, etc.

External-Internal Modes

12. The basic equations (Equations 1-4) can be integrated over the depth to yield a set of vertically integrated equations for the water surface, ζ , and unit flow rates U and V in the x and y directions. Using the dimensionless variables (asterisks have been dropped) and the parameters previously defined, the vertically integrated equations constituting the external mode are:

$$\frac{\partial \zeta}{\partial t} + \beta \left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} \right) = 0 \quad (11)$$

$$\begin{aligned} \frac{\partial U}{\partial t} = & -H \frac{\partial \zeta}{\partial x} + \tau_{sx} - \tau_{bx} + V \\ & - R_0 \left[\frac{\partial}{\partial x} \left(\frac{UU}{H} \right) + \frac{\partial}{\partial y} \left(\frac{UV}{H} \right) \right] \\ & + E_H \left[\frac{\partial}{\partial x} \left(A_H \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial y} \left(A_H \frac{\partial U}{\partial y} \right) \right] \\ & - \frac{R_0}{Fr_D^2} \frac{H^2}{2} \frac{\partial \rho}{\partial x} \end{aligned} \quad (12)$$

$$\begin{aligned} \frac{\partial V}{\partial t} = & -H \frac{\partial \zeta}{\partial y} + \tau_{sy} - \tau_{by} - U \\ & - R_0 \left[\frac{\partial}{\partial x} \left(\frac{UV}{H} \right) + \frac{\partial}{\partial y} \left(\frac{VV}{H} \right) \right] \\ & + E_H \left[\frac{\partial}{\partial x} \left(A_H \frac{\partial V}{\partial x} \right) + \frac{\partial}{\partial y} \left(A_H \frac{\partial V}{\partial y} \right) \right] \\ & - \frac{R_0}{Fr_D^2} \frac{H^2}{2} \frac{\partial \rho}{\partial y} \end{aligned} \quad (13)$$

where

$$\beta = gZr/f^2X_r^2 = (R_0/F_r)^2$$

As will be discussed later, the major purpose of the external mode is to provide the updated water-surface field.

13. The internal mode equations from which the 3D velocity, salinity, and temperature fields are computed are:

$$\begin{aligned}
 \frac{\partial hu}{\partial t} = & -h \frac{\partial \zeta}{\partial x} + E_v \frac{\partial}{\partial z} \left(A_v \frac{\partial hu}{\partial z} \right) + hv \\
 & - R_o \left(\frac{\partial hu u}{\partial x} + \frac{\partial hu v}{\partial y} + \frac{\partial hu w}{\partial z} \right) \\
 & + E_{II} \left[\frac{\partial}{\partial x} \left(A_{II} \frac{\partial hu}{\partial x} \right) + \frac{\partial}{\partial y} \left(A_{II} \frac{\partial hu}{\partial y} \right) \right] \\
 & - \frac{R_o}{Fr_D^2} \left(\int_z^\zeta \frac{\partial \rho}{\partial x} dz \right)
 \end{aligned} \tag{14}$$

$$\begin{aligned}
 \frac{\partial hv}{\partial t} = & -h \frac{\partial \zeta}{\partial y} + E_v \frac{\partial}{\partial z} \left(A_v \frac{\partial hv}{\partial z} \right) - hu \\
 & - R_o \left(\frac{\partial hv u}{\partial x} + \frac{\partial hv v}{\partial y} + \frac{\partial hv w}{\partial z} \right) \\
 & + E_{II} \left[\frac{\partial}{\partial x} \left(A_{II} \frac{\partial hv}{\partial x} \right) + \frac{\partial}{\partial y} \left(A_{II} \frac{\partial hv}{\partial y} \right) \right] \\
 & - \frac{R_o}{Fr_D^2} \left(\int_z^\zeta \frac{\partial \rho}{\partial y} dz \right)
 \end{aligned} \tag{15}$$

$$W_{k+1/2} = W_{k-1/2} - \left(\frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} \right) \tag{16}$$

$$\begin{aligned}
 \frac{\partial hT}{\partial t} = & \frac{E_v}{Pr_v} \frac{\partial}{\partial z} \left(K_v \frac{\partial T}{\partial z} \right) - R_o \left(\frac{\partial hu T}{\partial x} + \frac{\partial hv T}{\partial y} + \frac{\partial hw T}{\partial z} \right) \\
 & + \frac{E_{II}}{Pr_{II}} \left[\frac{\partial}{\partial x} \left(K_{II} \frac{\partial hT}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{II} \frac{\partial hT}{\partial y} \right) \right]
 \end{aligned} \tag{17}$$

$$\begin{aligned} \frac{\partial hS}{\partial t} = & \frac{E_v}{Pr_v} \frac{\partial}{\partial z} \left[K_v \frac{\partial S}{\partial z} \right] - R_o \left[\frac{\partial h_u S}{\partial x} + \frac{\partial h_v S}{\partial y} + \frac{\partial h_w S}{\partial z} \right] \\ & + \frac{E_H}{Pr_H} \left[\frac{\partial}{\partial x} \left[K_H \frac{\partial hS}{\partial x} \right] + \frac{\partial}{\partial y} \left[K_H \frac{\partial hS}{\partial y} \right] \right] \end{aligned} \quad (18)$$

In these equations h is the thickness of an internal layer and $k+1/2$ and $k-1/2$ represent the top and bottom, respectively, of the k^{th} vertical layer.

Boundary-Fitted Equations

14. To better resolve complex geometries in the horizontal directions, the Chesapeake Bay 3D model makes computations on the boundary-fitted or generalized curvilinear planform grid shown in Figure 2. This necessitates the transformation of the governing equations into boundary-fitted coordinates (ξ, η) . If only the (x, y) coordinates are transformed, a system of equations similar to those solved by Johnson (1980) for vertically averaged flow fields is obtained. However, in the Chesapeake Bay 3D model not only are the (x, y) coordinates transformed into the (ξ, η) curvilinear system but also the velocity is transformed such that its components are perpendicular to the (ξ, η) coordinate lines. This is accomplished by employing the definitions below for the components of the Cartesian velocity (u, v) in terms of contravariant components $\bar{u}$ and $\bar{v}$.

$$\begin{aligned} u &= x_\xi \bar{u} + x_\eta \bar{v} \\ v &= y_\xi \bar{u} + y_\eta \bar{v} \end{aligned} \quad (19)$$

along with the following expressions for replacing Cartesian derivatives

$$\begin{aligned} f_x &= \frac{1}{J} \left[(fy_\eta)_\xi - (fy_\xi)_\eta \right] \\ f_y &= \frac{1}{J} \left[- (fx_\eta)_\xi + (fx_\xi)_\eta \right] \end{aligned} \quad (20)$$

where J is the Jacobian of the transformation defined as

$$J = x_{\xi}y_{\eta} - x_{\eta}y_{\xi}$$

With the governing equations written in terms of the contravariant components of the velocity, boundary conditions can be prescribed on a boundary-fitted grid in the same manner as on a Cartesian grid since $\bar{u}$ and $\bar{v}$ are perpendicular to the curvilinear cell faces (e.g., at a land boundary, either $\bar{u}$ or $\bar{v}$ is set to zero).

15. Initially the vertical dimension was handled through the use of what is commonly called a sigma-stretched grid. Such a grid is illustrated in Figure 3. However, with the grid resolution shown in Figure 2 it was observed that stratification in the deep channels could not be maintained during long term simulations on Chesapeake Bay. With a sigma-stretched grid, the bottom layer in one column communicates with the bottom layer in an adjacent column. Thus, if depth changes are rather coarsely resolved, channel stratification cannot be maintained. As a result, the governing equations presented below for solution on the Cartesian or z -plane in the vertical direction are the ones constituting the internal mode in the Chesapeake Bay model.

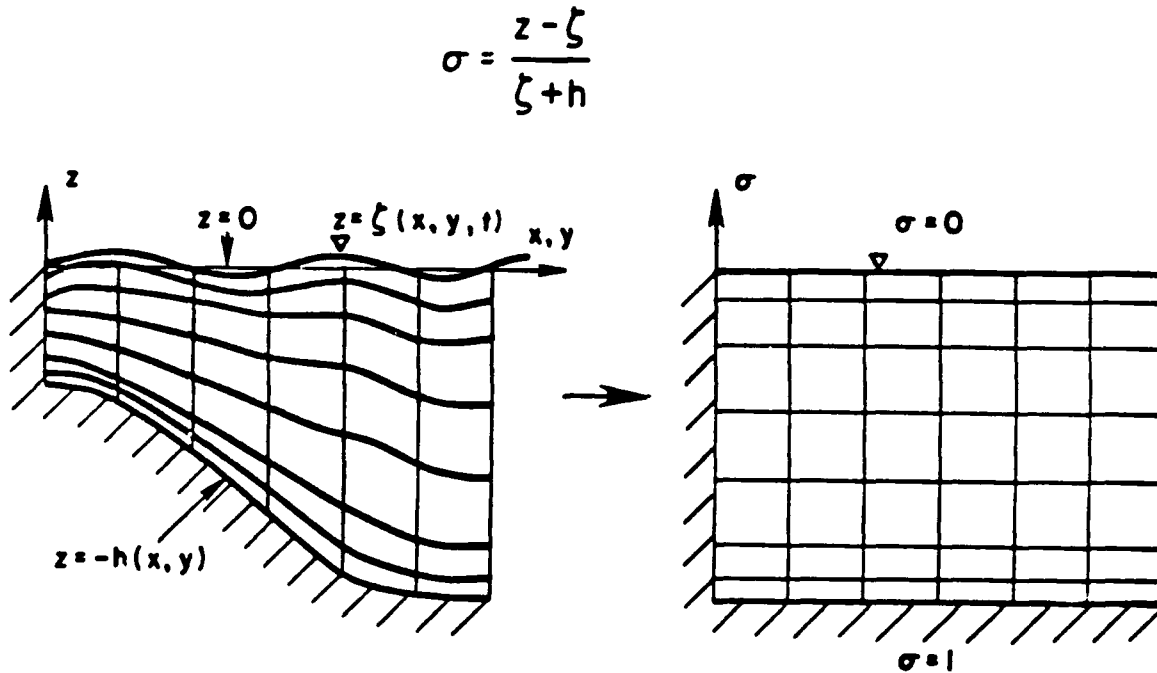


Figure 3. Sigma-stretched grid

16. With both the Cartesian coordinates and the Cartesian velocity transformed, the following boundary-fitted equations for $\bar{u}$, $\bar{v}$, w , S , and T to be solved in each vertical layer are obtained.

$$\begin{aligned}
\frac{\partial \bar{u}}{\partial \tau} = & -h \left[\frac{G_{22}}{J^2} \frac{\partial \zeta}{\partial \xi} - \frac{G_{12}}{J^2} \frac{\partial \zeta}{\partial \eta} \right] + \frac{h}{J} (G_{12} \bar{u} + G_{22} \bar{v}) + \frac{R_o x_\eta}{J^2} \left[\frac{\partial}{\partial \xi} (J y_\xi h \bar{u} \bar{u} \right. \\
& + J y_\eta h \bar{u} \bar{v}) + \frac{\partial}{\partial \eta} (J y_\xi h \bar{u} \bar{v} + J y_\eta h \bar{v} \bar{v}) \left. \right] - \frac{R_o y_\eta}{J^2} \left[\frac{\partial}{\partial \xi} (J x_\xi h \bar{u} \bar{u} + J x_\eta h \bar{u} \bar{v}) \right. \\
& + \frac{\partial}{\partial \eta} (J x_\xi h \bar{u} \bar{v} + J x_\eta h \bar{v} \bar{v}) \left. \right] - R_o [(\bar{w} \bar{u})_{\text{top}} - (\bar{w} \bar{u})_{\text{bot}}] \\
& + E_v \left[\left(A_v \frac{\partial \bar{u}}{\partial z} \right)_{\text{top}} - \left(A_v \frac{\partial \bar{u}}{\partial z} \right)_{\text{bot}} \right] - \frac{R_o h}{Fr_D^2} \left[\int_z^\zeta \left(\frac{G_{22}}{J^2} \frac{\partial \rho}{\partial \xi} \right. \right. \\
& \left. \left. - \frac{G_{12}}{J^2} \frac{\partial \rho}{\partial \eta} \right) dz \right] + \text{Horizontal Diffusion}
\end{aligned} \tag{21}$$

$$\begin{aligned}
\frac{\partial \bar{v}}{\partial \tau} = & -h \left[-\frac{G_{21}}{J^2} \frac{\partial \zeta}{\partial \xi} + \frac{G_{11}}{J^2} \frac{\partial \zeta}{\partial \eta} \right] - \frac{h}{J} (G_{11} \bar{u} + G_{21} \bar{v}) - \frac{R_o x_\xi}{J^2} \left[\frac{\partial}{\partial \xi} (J y_\xi h \bar{u} \bar{u} \right. \\
& + J y_\eta h \bar{u} \bar{v}) + \frac{\partial}{\partial \eta} (J y_\xi h \bar{u} \bar{v} + J y_\eta h \bar{v} \bar{v}) \left. \right] + \frac{R_o y_\xi}{J^2} \left[\frac{\partial}{\partial \xi} (J x_\xi h \bar{u} \bar{u} + J x_\eta h \bar{u} \bar{v}) \right. \\
& + \frac{\partial}{\partial \eta} (J x_\xi h \bar{u} \bar{v} + J x_\eta h \bar{v} \bar{v}) \left. \right] - R_o [(\bar{w} \bar{v})_{\text{top}} - (\bar{w} \bar{v})_{\text{bot}}] \\
& + E_v \left[\left(A_v \frac{\partial \bar{v}}{\partial z} \right)_{\text{top}} - \left(A_v \frac{\partial \bar{v}}{\partial z} \right)_{\text{bot}} \right] - \frac{R_o h}{Fr_D^2} \left[\int_z^\zeta \left(-\frac{G_{21}}{J^2} \frac{\partial \rho}{\partial \xi} + \frac{G_{11}}{J^2} \frac{\partial \rho}{\partial \eta} \right) dz \right] \\
& + \text{Horizontal Diffusion}
\end{aligned} \tag{22}$$

$$w_{\text{top}} = w_{\text{bot}} - \frac{1}{J} \left[\frac{\partial J \bar{u} h}{\partial \xi} + \frac{\partial J \bar{v} h}{\partial \eta} \right] \tag{23}$$

$$\begin{aligned} \frac{\partial hS}{\partial t} = & \frac{E_v}{Pr_v} \left[\left(K_v \frac{\partial S}{\partial z} \right)_{top} - \left(K_v \frac{\partial S}{\partial z} \right)_{bot} \right] - \frac{R_o}{J} \left(\frac{\partial hJ\bar{u}S}{\partial \xi} + \frac{\partial hJ\bar{v}S}{\partial \eta} \right) \\ & - R_o \left[(wS)_{top} - (wS)_{bot} \right] + \text{Horizontal Diffusion} \end{aligned} \quad (24)$$

$$\begin{aligned} \frac{\partial hT}{\partial t} = & \frac{E_v}{Pr_v} \left[\left(K_v \frac{\partial T}{\partial z} \right)_{top} - \left(K_v \frac{\partial T}{\partial z} \right)_{bot} \right] - \frac{R_o}{J} \left(\frac{\partial hJ\bar{u}T}{\partial \xi} + \frac{\partial hJ\bar{v}T}{\partial \eta} \right) \\ & - R_o \left[(wT)_{top} - (wT)_{bot} \right] + \text{Horizontal Diffusion} \end{aligned} \quad (25)$$

where

$$\begin{aligned} G_{11} &= x_\xi^2 + y_\xi^2 \\ G_{22} &= x_\eta^2 + y_\eta^2 \\ G_{12} &= G_{21} = x_\xi x_\eta + y_\xi y_\eta \end{aligned} \quad (26)$$

17. Similarly, the transformed external mode equations become:

$$\frac{\partial \zeta}{\partial t} + \beta \left(\frac{\partial \bar{U}}{\partial \xi} + \frac{\partial \bar{V}}{\partial \eta} \right) = 0 \quad (27)$$

$$\begin{aligned} \frac{\partial \bar{U}}{\partial t} = & - \frac{H}{J^2} \left[G_{22} \frac{\partial \zeta}{\partial \xi} - G_{12} \frac{\partial \zeta}{\partial \eta} \right] \\ & + \frac{1}{J} \left(G_{12} \bar{U} + G_{22} \bar{V} \right) + \frac{R_o x_\eta}{J^2 H} \left[\frac{\partial}{\partial \xi} \left(J y_\xi \bar{U} \bar{U} + J y_\eta \bar{U} \bar{V} \right) + \frac{\partial}{\partial \eta} \left(J y_\xi \bar{U} \bar{V} + J y_\eta \bar{V} \bar{V} \right) \right] \\ & - \frac{R_o y_\eta}{J^2} \left[\frac{\partial}{\partial \xi} \left(J x_\xi \bar{U} \bar{U} + J x_\eta \bar{U} \bar{V} \right) + \frac{\partial}{\partial \eta} \left(J x_\xi \bar{U} \bar{V} + J x_\eta \bar{V} \bar{V} \right) \right] \\ & + \tau_{a\xi} - \tau_{b\xi} - \frac{R_o}{Fr_D^2} \frac{H^2}{2} \left[G_{22} \frac{\partial \rho}{\partial \xi} - G_{12} \frac{\partial \rho}{\partial \eta} \right] \end{aligned}$$

+ Horizontal Diffusion

(28)

$$\begin{aligned} \frac{\partial \bar{v}}{\partial t} = & - \frac{H}{J^2} \left[G_{21} \frac{\partial \xi}{\partial \xi} + G_{11} \frac{\partial \xi}{\partial \eta} \right] - \frac{1}{J} (G_{11} \bar{u} + G_{21} \bar{v}) \\ & - \frac{R_o x_\xi}{J^2 H} \left[\frac{\partial}{\partial \xi} (J y_\xi \bar{u} \bar{u} + J y_\eta \bar{u} \bar{v}) + \frac{\partial}{\partial \eta} (J y_\xi \bar{u} \bar{v} + J y_\eta \bar{v} \bar{v}) \right] \\ & + \frac{R_o y_\xi}{J^2 H} \left[\frac{\partial}{\partial \xi} (J x_\xi \bar{u} \bar{u} + J x_\eta \bar{u} \bar{v}) + \frac{\partial}{\partial \eta} (J x_\xi \bar{u} \bar{v} + J x_\eta \bar{v} \bar{v}) \right] \\ & + \tau_{s\eta} - \tau_{b\eta} - \frac{R_o}{Fr_D^2} \frac{H^2}{2} \left[- G_{21} \frac{\partial \rho}{\partial \xi} + G_{11} \frac{\partial \rho}{\partial \eta} \right] \end{aligned}$$

+ Horizontal Diffusion

(29)

18. Equations 27-29 are solved first to yield the water-surface elevations which are then used to evaluate the water-surface slope terms in the internal mode equations. The horizontal diffusion terms are quite lengthy and thus are presented separately in Appendix A for the internal mode equations. Similar expressions for the vertically averaged equations can be inferred from those for the internal mode.

Boundary Conditions

19. The boundary conditions at the free surface are

$$A_v \left(\frac{\partial \bar{u}}{\partial z}, \frac{\partial \bar{v}}{\partial z} \right) = (\tau_{s\xi}, \tau_{s\eta}) / \rho = (C W_\xi^2, C W_\eta^2)$$

$$\frac{\partial T}{\partial z} = \frac{Pr}{E_v} K (T - T_s) \quad (30)$$

$$\frac{\partial S}{\partial z} = 0$$

whereas the boundary conditions at the bottom are

$$\begin{aligned}
 A_v \left(\frac{\partial \bar{u}}{\partial z}, \frac{\partial \bar{v}}{\partial z} \right) &= (\tau_{b\xi}, \tau_{b\eta}) / \rho \\
 &= \frac{U_r}{A_{vr}} z_1 C_d (\bar{u}_1^2 + \bar{v}_1^2)^{1/2} (\bar{u}_1, \bar{v}_1) \\
 \frac{\partial T}{\partial z}, \frac{\partial S}{\partial z} &= 0
 \end{aligned} \tag{31}$$

where

- C - surface drag coefficient
- W - wind speed
- K - surface heat exchange coefficient
- T_e - equilibrium temperature
- C_d - bottom friction coefficient
- $\bar{u}_1, \bar{v}_1$ - values of the horizontal velocity components next to the bottom.

With z_1 equal to one-half the bottom layer thickness, C_d is given by

$$C_d = k^2 \left[\ln (z_1/z_o) \right]^{-2} \tag{32}$$

where

- k - von Karman constant
- z_o - bottom roughness height

Manning's formulation is employed for the bottom friction in the external mode equations if the model is used purely to compute vertically averaged flow fields. As presented by Garratt (1977), the surface drag coefficient is computed from

$$C = (0.75 + 0.067 W) \times 10^{-3} \tag{33}$$

with the maximum allowable value being 0.003. The surface heat exchange coefficient, K , and the equilibrium temperature, T_e , are computed from meteorological data (wind speed, cloud cover, wet and dry bulb air temperatures, and relative humidity) as discussed by Edinger, Brady, and Geyer (1974).

20. Along the shoreline where river inflow occurs, the freshwater inflow and its temperature are prescribed and the salinity is assumed to be zero. At an ocean boundary, the water-surface elevation is prescribed along with time-varying vertical distributions of salinity and temperature. During flood, the specified values of salinity and temperature are employed, whereas during ebb, interior values are advected out of the grid. Along a solid boundary, the normal component of the velocity and the viscosity and diffusivity are set to zero.

Initial Conditions

21. When initiating a run of the Chesapeake Bay model, the values of ζ , $\bar{u}$, $\bar{v}$, w , $\bar{U}$ and $\bar{V}$ are all set to zero. Values of the salinity and temperature are read from input files. These initial fields are generated from known data at a limited number of locations. Once the values in individual cells are determined by interpolating from the field data, the resulting 3D field is smoothed several times. Generally, the salinity and temperature fields are frozen for the first few days of a simulation.

Numerical Grid

22. A staggered grid is used in both the horizontal and vertical directions of the computational domain (Figure 4). In the horizontal directions, a unit cell consists of a ζ -point in the center ($\zeta_{i,j}$), a U -point to its left ($U_{i,j}$), and a V -point to its bottom ($V_{i,j}$). In the vertical direction, the vertical velocities are computed at the "full" grid points. Horizontal velocities, temperature, salinity, and density are computed at the "half" grid points (half grid spacing below the full points).

23. Two arrays, each of dimension (IMAX, JMAX), are used to index the grid cells. The array NS indicates the condition of the left and right cell

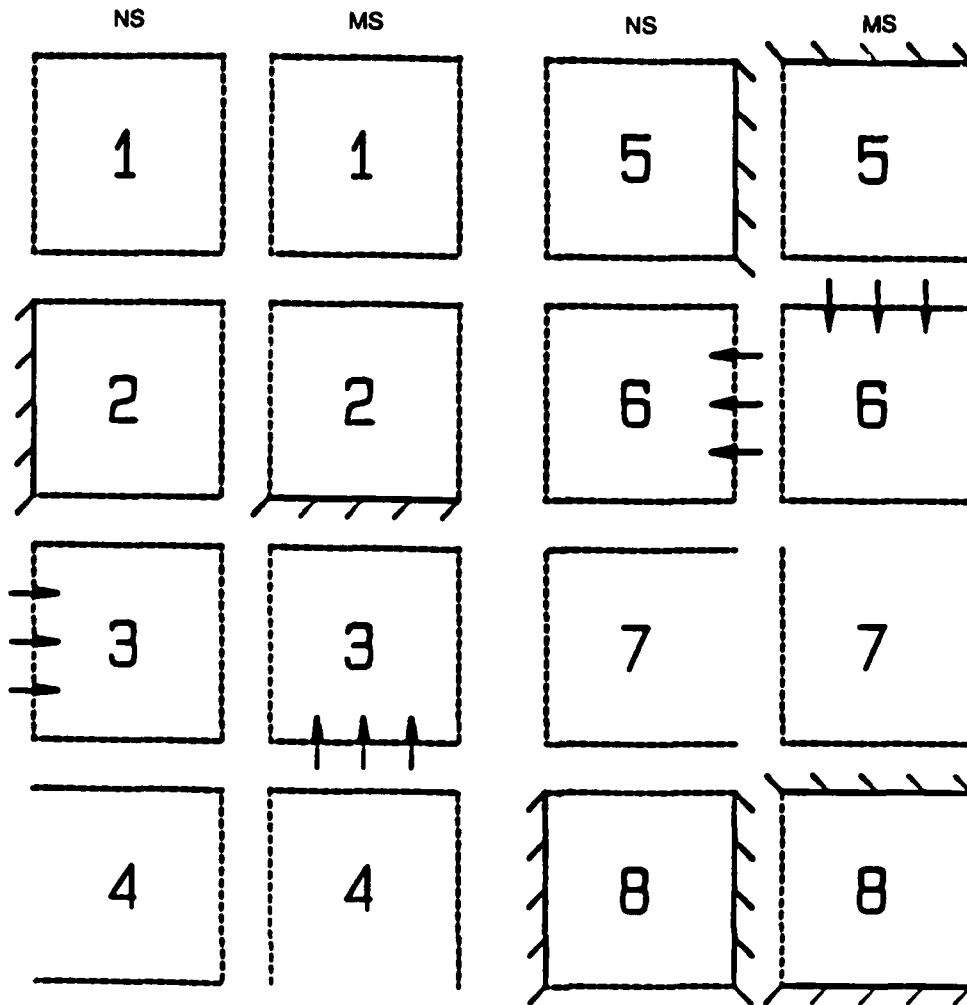


Figure 4. Computational arrays

boundaries, while the array MS denotes the condition of the top and bottom cell boundaries (Figure 4).

Numerical Solution Algorithm

24. Finite differences are used to replace derivatives in the governing equations, resulting in a system of linear algebraic equations to be solved in both the external and internal modes.

25. The external mode solution consists of the surface displacement and vertically integrated contravariant unit flows $\bar{U}$ and $\bar{V}$. All of the terms in the transformed vertically averaged continuity equation are treated implicitly whereas only the water-surface slope terms in the transformed vertically averaged momentum equations are treated implicitly. If the external mode is used as purely a vertically averaged model, the bottom

friction is also treated implicitly. Those terms treated implicitly are weighted between the new and old time-steps. The resulting finite difference equations are then factored such that a ξ -sweep followed by an η -sweep of the horizontal grid yields the solution at the new time-step.

26. Writing Equations 11-13 as

$$\frac{\partial \bar{\zeta}}{\partial \tau} + \beta \left(\frac{\partial \bar{U}}{\partial \xi} + \frac{\partial \bar{V}}{\partial \eta} \right) = 0 \quad (34)$$

$$\frac{\partial \bar{U}}{\partial \tau} + \frac{H}{J^2} G_{22} \frac{\partial \bar{\zeta}}{\partial \eta} = M \quad (35)$$

$$\frac{\partial \bar{V}}{\partial \tau} + \frac{H}{J^2} G_{11} \frac{\partial \bar{\zeta}}{\partial \xi} = N \quad (36)$$

the ξ -sweep is

$$\begin{aligned} \xi\text{-sweep} = & \bar{\zeta}_{ij}^* + \frac{\beta \theta \Delta t}{\Delta \xi} \left(\bar{U}_{i+1,j}^* - \bar{U}_{ij}^* \right) = \bar{\zeta}_{ij}^n \\ & - (1-\theta) \frac{\Delta t}{\Delta \xi} \left(\bar{U}_{i+1,j}^n - \bar{U}_{ij}^n \right) \\ & - \frac{\Delta t}{\Delta \eta} \left(\bar{V}_{i,j+1}^n - \bar{V}_{ij}^n \right) \end{aligned} \quad (37)$$

and

$$\begin{aligned} & \bar{U}_{ij}^{n+1} + \frac{\theta \Delta t H G_{22}}{\Delta \xi J^2} \left(\bar{\zeta}_{ij}^* - \bar{\zeta}_{i-1,j}^* \right) \\ & = \bar{U}_{ij}^n \\ & - (1-\theta) \frac{\Delta t H G_{22}}{\Delta \xi J^2} \left(\bar{\zeta}_{ij}^n - \bar{\zeta}_{i-1,j}^n \right) + \Delta t M^n \end{aligned} \quad (38)$$

The η -sweep then provides the updated ζ and $\bar{v}$ at the $n+1$ time level.

$$\begin{aligned} \eta\text{-sweep} \Rightarrow \zeta_{i,j}^{n+1} + \frac{\beta\theta\Delta t}{\Delta\eta} (\bar{v}_{i,j+1}^{n+1} - \bar{v}_{i,j}^{n+1}) &= \zeta_{i,j}^* \\ &- (1-\theta) \frac{\Delta t}{\Delta\eta} (\bar{v}_{i,j+1}^n - \bar{v}_{i,j}^n) \\ &+ \frac{\Delta t}{\Delta\eta} (\bar{v}_{i,j+1}^n - \bar{v}_{i,j}^n) \end{aligned} \quad (39)$$

and

$$\begin{aligned} \bar{v}_{i,j}^{n+1} + \frac{\theta\Delta t H G_{11}}{\Delta\eta J^2} (\zeta_{i,j+1}^{n+1} - \zeta_{i,j}^{n+1}) \\ = \bar{v}_{i,j}^n \\ - (1-\theta) \frac{\Delta t H G_{11}}{\Delta\eta J^2} (\zeta_{i,j+1}^n - \zeta_{i,j}^n) + \Delta t N^n \end{aligned} \quad (40)$$

A typical value of θ of 0.55 yields stable and accurate solutions.

27. The internal mode consists of computations from Equations 21-25 for the three velocity components $\bar{u}$, $\bar{v}$, and w , salinity, and temperature. The only terms treated implicitly are the vertical diffusion terms in all equations and the bottom friction and surface slope terms in the momentum equations. Values of the water-surface elevations from the external mode are used to evaluate the surface slope terms in Equations 21 and 22. As a result, the extremely restrictive speed of a free-surface gravity wave is removed from the stability criteria. Roache's second upwind differencing is used to represent the convective terms in the momentum equations, whereas a spatially third-order scheme developed by Leonard (1979) called QUICKEST is used to represent the advective terms in Equations 24 and 25 for salinity and

temperature, respectively. For example, if the velocity on the right face of a computational cell is positive then with QUICKEST the value of the salinity used to compute the flux through the face is

$$\begin{aligned}
 S_R = & \frac{1}{2} (S_{i,j,k} + S_{i+1,j,k}) \\
 & - \frac{1}{6} \left[1 - \left(\frac{\bar{U}_{i+1,j,k} \Delta t}{\Delta \xi} \right)^2 \right] (S_{i+1,j,k} - 2 S_{i,j,k} + S_{i-1,j,k}) \\
 & - \frac{1}{2} \frac{U_{i+1,j,k} \Delta t}{\Delta \xi} (S_{i+1,j,k} - S_{i,j,k})
 \end{aligned} \tag{41}$$

The more interested reader is referred to the paper by Leonard (1979).

28. It should be noted that once the $\bar{u}$ and $\bar{v}$ velocity components are computed they are slightly adjusted to ensure the conservation of mass. This is accomplished by forcing the sum of $\bar{u}$ over the vertical to be the vertically averaged velocity $\bar{U}/H$ and the sum of $\bar{v}$ over the vertical to equal $\bar{V}/H$, where H is the total water depth.

Turbulence Parameterization

29. Vertical turbulence is handled by using the concept of eddy viscosity and diffusivity to represent the velocity and density correlation terms that arise from a time averaging of the governing equations. These eddy coefficients are computed from mean flow characteristics using a simplified second-order closure model originally developed by Donaldson (1973). The closure model has been further developed and applied to various types of flows by Lewellen (1977) and Sheng (1982, 1986). A discussion of the implementation of the turbulence model taken from Sheng* follows. For more details the

* Sheng, Y. P. 1990. "A Simplified Second Order Closure Model of Turbulent Transport," unpublished paper prepared for US Army Engineer Waterways Experiment Station, Vicksburg, MS.

interested reader should refer to these references and to Johnson et al. (1991).

30. Assuming local equilibrium of turbulence, i.e., there is no time evolution or spatial diffusion of the second-order correlations, an equation relating the turbulent kinetic energy and the macroscale of turbulence to the mean flow shear and stratification (given by the Richardson number Ri) can be derived as

$$\begin{aligned} 3A^2b^2sQ^4 + A[(bs + 3b + 7b^2s)Ri - Abs(1 - 2b)]Q^2 \\ + b(s + 3 + 4bs)Ri^2 + (bs - A)(1 - 2b)Ri \\ = 0 \end{aligned} \quad (42)$$

where

$$b = 0.125$$

$$s = 1.8$$

$$A = 0.75$$

and

$$Q = \frac{q}{\Lambda \sqrt{(\partial \bar{u} / \partial z)^2 + (\partial \bar{v} / \partial z)^2}} \quad (43)$$

In the above expression, q is defined as

$$q = (\overline{u'u'} + \overline{v'v'} + \overline{w'w'})^{1/2}$$

and Λ is the macroscale of turbulence. u' , v' and w' are the turbulent velocity fluctuations and the overbar indicates time averaging.

31. It can also be shown that the following relations hold

$$\overline{u'w'} = - \frac{\frac{\partial \bar{u}}{\partial z} \Lambda}{q} \frac{1 + \frac{\bar{\omega}}{A}}{1 - \bar{\omega}} \overline{w'w'} \quad (44)$$

$$\overline{v'w'} = - \frac{\frac{\partial \bar{v}}{\partial z} \Lambda}{q} \frac{1 + \frac{\bar{\omega}}{A}}{1 - \omega} \overline{w'w'} \quad (45)$$

$$q^2 b = \left[\frac{(1 + \frac{\bar{\omega}}{A})}{Q^2(1 - \omega)} + \bar{\omega} \right] \overline{w'w'} \quad (46)$$

where

$$\omega = \frac{Ri}{AQ^2} \quad (47)$$

and

$$\bar{\omega} = \frac{\omega}{1 - \frac{\omega}{bs}} \quad (48)$$

Thus, after the velocity shear and flow stratification are determined, q can be computed from Equations 42 and 43. $\overline{w'w'}$ is then determined from

$$\overline{w'w'} = \frac{\frac{q^2}{2} - q^2 b}{\frac{3}{2}(1 - 2\omega)} \quad (49)$$

Finally, after Λ is prescribed, $\overline{u'w'}$ and $\overline{v'w'}$ can be computed from Equations 44 and 45 and the vertical eddy coefficients can be determined from

$$A_v = \frac{\overline{-u'w'}}{\frac{\partial \bar{u}}{\partial z}} = \frac{\Lambda}{q} \frac{A + \bar{\omega}}{A(1 - \omega)} \overline{w'w'} \quad (50)$$

$$K_v = \frac{\overline{-\rho'w'}}{\overline{\frac{\partial \rho}{\partial z}}} = \frac{\Lambda}{q} \frac{bs}{(bs - \omega)\Lambda} \overline{w'w'} \quad (51)$$

In addition to setting $\Lambda = 0.65z$ near boundaries, three basic constraints are used to compute Λ at a vertical position z

$$\left| \frac{d\Lambda}{dz} \right| \leq 0.65 \quad (52)$$

$$\Lambda \leq \frac{q}{N} = q / \left(-\frac{g}{\rho} \frac{\partial \rho}{\partial z} \right)^{0.5} \quad (53)$$

$$\Lambda \leq Q_{cut} (z_{q=q_{max}} - z_{q=q_{max}/2}) \quad (54)$$

where N is the Brunt-Vaisala frequency. Equation 54 states that Λ is less than a fraction of the spread of turbulence as measured by the distance between the location of a maximum q^2 to where q^2 is equal to 25 percent of the maximum. The coefficient Q_{cut} is on the order of 0.15 to 0.25.

PART III: STRUCTURE OF THE CHESAPEAKE BAY 3D
HYDRODYNAMIC COMPUTER MODEL

32. There are several subroutines in the Chesapeake Bay Model plus a main program. Subroutines governing model setup are called from the main program while subroutines governing the computations are called from subroutine CH3DM2. Each subroutine is listed below with a description of its function. Entry points in particular subroutines are also noted.

VCH3D	The main program.
CH3DIR	Reads data from FILE 4 (see Appendix B). Water depths at the center of each computational cell are read from FILE 12 (see Appendix C). Various constants are computed, the layer thicknesses are set, and the array KM(I,J) indicating the bottom layer of each column is set.
CH3DTR	Reads (x,y) coordinates of the boundary-fitted grid from FILE 15. The coordinates are then multiplied by the scale factor, XMAP, and divided by XREF to make them nondimensional. Subroutine BJINTR is called to provide the coordinate derivatives needed to compute the metrics of the transformation.
BJINTR	Computes various coordinate derivatives and sets the water depth HU(I,J) and HV(I,J) on the faces of each computational cell.
CH3DIH	Prints water depth arrays if requested by input data. Also, the water depths are made nondimensional by dividing by ZREF.
CH3DND	Computes many constants as nondimensional quantities. These include the Eckman number, Rosby number, time-step, etc.
CH3DII	Sets up the arrays that indicate the types of boundaries comprising a computational cell. In addition, arrays controlling the computation of the convective terms in the momentum equations and the averaging of water-surface elevations at points other than the cell center are set up.
CH3DIF	Initializes various variables for a cold run and creates time files for tide, salinity, etc. The hot start capability is not operational.
CH3DIV	The arrays created in CH3DII concerning the averaging of water-surface elevations contain logical values. Those arrays are used in this subroutine to create arrays containing a numerical value. These arrays, i.e. AFVI(I,J), etc., are used to control the averaging of not only water-surface elevations but other variables as well.

CH3DWS Controls the reading of either wind speed or wind stress. If the wind speed is read, the stress is computed from Garrett's equation. ENTRY CH3DWT controls the time-varying reads and computations.

CH3DTD Computes a sinusoidal tide from amplitude, phase, and offset values input in CH3DIR. ENTRY CH3DTI controls the reading of time-varying tabular tide data.

33. The subroutines above are called from VCH3D in the sequence given. Before calling CH3DM2, which controls the computations, the initial salinity field is read from FILE 74. The initial temperature field is read from FILE 17.

CH3DM2 Final subroutine called from VCH3D. All subroutines controlling the actual 3D computations are called from this subroutine in the order as they appear below.

CH3DDP Computes total water depths and the thickness of the top layer from the latest water-surface elevation field. ENTRY CH3DDM sets total water depths at the intermediate time level, and ENTRY CH3DDN sets total water depths and the top layer thickness at the previous time level.

CH3DTK Reads equilibrium temperatures and surface-heat exchange coefficients from FILE 19 and then casts them into nondimensional form. ENTRY CH3DTB controls the time-varying read and interpolation.

CH3DRI Reads river inflows from FILE 13. ENTRY CH3DRV controls the time-varying read and interpolation.

CH3DSAI Reads salinity and temperatures at tidal boundaries from FILE 76. ENTRY CH3DSAV controls the time-varying reads, interpolation, and conversion to nondimensional form.

CH3DTEI Reads temperatures at river inflow boundaries from FILE 78. ENTRY CH3DTEV controls the reading of time-varying temperatures and interpolation.

34. At this point the loop over time is entered in CH3DM2 and each of the subroutines below is called each time-step.

CH3DDE Computes the water density using Eckert's equation. The baroclinic terms in the momentum equations are then evaluated.

CH3DED Sets up arrays that are then used in SUBROUTINE CH3DEZ for the computation of the eddy viscosity and eddy diffusivity coefficients.

CH3DWT ENTRY in CH3DWS for reading time-varying wind data.

CH3DTB ENTRY in CH3DTK for reading time-varying equilibrium temperature and heat-exchange coefficients.

CH3DRV ENTRY in CH3DRI for reading time-varying river flows.

CH3DTEV Entry in CH3DTEI for reading time-varying temperatures at river inflow boundaries.

CH3DTI ENTRY in CH3DTD for reading time-varying tabular tide data.

CH3DTD If a sinusoidal tide is imposed this subroutine is called instead of ENTRY CH3DTI.

CH3DSAV Entry in CH3DSAI for reading time-varying salinity and temperatures at tidal boundaries.

CH3DDN ENTRY in CH3DDP for assigning total water depths at the previous time level.

CH2DXY Computes the vertically averaged flow field from the vertically averaged equations of motion.

CH3DDP Using the water-surface field computed in CH2DXY, computes the total water depths.

CH3DXYZ Computes the 3D velocity field. Mass conservation is ensured by forcing the vertical sum of the horizontal components of the 3D velocity to match the vertically averaged values computed in CH2DXY.

CH3DDI Computes the convective and diffusion terms in the momentum equations using the most recent computations from CH3DDP and CH3DXYZ. These terms are then employed at the next time step in CH2DXY and CH3DXYZ.

CH3DSA Computes the salinity field.

CH3DTE Computes the temperature field.

CH3DOT Controls the output printed and/or written to files for plotting. Output can be requested in terms of the transformed nondimensional variables or the physical dimensional variables. Generally, values for the physical variables in dimensional form are more meaningful. If physical velocities and dimensional output are requested by setting IDIM = 1, SUBROUTINE CH3DC1 is called with ENTRIES CH3DC2, CH3DC3, CH3DC4, CH3DC5, CH3DC6, CH3DC7, CH3DC8, CH3DC9, CH3DCA, CH3DCB, CH3DCC, CH3DCD, CH3DCE. Each is described below.

CH3DC1 Provides dimensional water-surface elevations.

CH3DC2 Provides dimensional physical vertically averaged unit flow rate in x-direction.

CH3DC3 Provides dimensional physical vertically averaged unit flow rate in y-direction.

CH3DC4 Provides dimensional physical components of wind shear stress.

CH3DC5	Provides dimensional physical horizontal components of 3D velocity.
CH3DC6	Provides dimensional physical vertical component of 3D velocity.
CH3DC7	Provides dimensional physical components of the vertically averaged velocity.
CH3DC8	Provides dimensional water density.
CH3DC9	Provides dimensional physical horizontal components of 3D velocity averaged over some period of time.
CH3DCA	Provides dimensional physical horizontal components of 3D velocity at the center of a cell.
CH3DCB	Provides dimensional water temperature.
CH3DCC	Provides dimensional physical horizontal components of 3D velocity at the center of a cell averaged over some period of time.
CH3DCD	Provides dimensional vertical eddy viscosity.
CH3DCE	Provides dimensional vertical eddy diffusivity.

35. In SUBROUTINE CH3DOT, the following files are created for use in generating either time series plots, vector plots, or contour plots.

FILE 22	For generating time series plots of dimensional, Cartesian vertically integrated velocities (x & y direction) at cell faces at specified horizontal locations.
FILE 23	For generating time series plots of dimensional, Cartesian vertically averaged velocities (x & y direction) at cell faces at specified horizontal locations.
FILE 24	For generating time series plots of nondimensional contravariant vertically integrated velocities at cell faces at specified horizontal locations.
FILE 25	For generating time series plots of dimensional x & y-direction components of velocity at cell faces at specified horizontal locations in all layers.
FILE 26	For generating time series plots of dimensional x & y-direction components of velocity at cell centers at specified horizontal locations in all layers.
FILE 31	For generating time series plots of salinity at specified horizontal locations in all layers.
FILE 32	For generating average salinity plots over some specified time interval at specified horizontal locations in all layers.

- FILE 33 For generating time series plots of temperatures at specified horizontal locations in all layers.
- FILE 34 For generating time series plots of vertical eddy viscosity at specified horizontal locations in all layers.
- FILE 35 For generating time series plots of vertical eddy diffusivity at specified horizontal locations in all layers.
- FILE 36 For generating time series plots of density at specified horizontal locations in all layers.
- FILE 40 Geometry of basin needed to generate snapshot plots.
- FILE 41 For generating snapshot velocity vector plots (nondimensional, contravariant) at particular points in time in all layers.
- FILE 42 For generating snapshot velocity vector plots (dimensional, Cartesian) at particular points in time in all layers.
- FILE 43 For generating snapshot salinity plots at particular points in time in all layers.
- FILE 44 For generating a vector plot of time-averaged velocities in all layers.
- FILE 45 For generating a time-averaged salinity plot in all layers.

PART IV: DEMONSTRATION OF SETUP OF INPUT FILES

36. To illustrate the setup of input data files (see Appendix C), portions of the input files for an application in which the hydrodynamics of the Chesapeake Bay during September 1983 were simulated are presented. During this period the bay destratified during a strong wind event with a subsequent restratification as the wind abated. Rapid cooling of the surface waters near the middle of the month contributed to the destratification process. Results from this application are presented by Johnson, et al. (1991).

Basic Control Data

37. Input data controlling the computations are provided in FILE 4 and are listed in Appendix D. These data are the response to the read statements presented in Appendix B. As can be seen, the computational time-step is 600 sec with a total of 3850 time-steps simulated. Both temperature and salinity computations are made with the initial fields frozen for 720 time-steps. As can be seen from Figure 2, there are 19 river boundaries. The base flow for each is set to zero; however, the time-varying river inflow at the fall line is multiplied by a factor which varies from river to river. This factor is the ratio of the below fall line drainage area to that upstream of the fall line. There are two tidal boundaries. Time-varying tabular data are prescribed for the tides since ITIDE = -1.

Water Depths

38. The water depth field read from FILE 12 is shown in Appendix E. These depths are adjusted in the code to reflect the fact that the thickness of the top layer is initially 213.4 cm, whereas all other layers are 152.4 cm thick. These water depths are applied at the center of each of the computational cells shown in Figure 2. They were obtained from a bathymetric map of Chesapeake Bay generated by the Virginia Institute of Marine Sciences.

Freshwater Inflows

39. Daily averaged freshwater inflows at the fall lines of the James,

Pamunkey, Mattaponi, Rappahannock, Potomac, Patuxent, Susquehanna, Patapsco, and Choptank Rivers are given in Appendix F for the first four days of the simulation period. It can be seen that after the day and hour are specified, the location of the eleven fall line boundaries and a discharge for each are given. These data continue in this fashion for the remainder of the simulation period. The inflows at the lateral locations shown in Figure 2 are set internally in the computer code as a percentage of the fall line flows.

Wind Speed

40. Wind data are read from FILE 14. Since IWIND = 5, time-varying wind speed is read and the wind stress is computed from Equation 30. For the September 1983 application three wind fields are read (NWIND = 3). However, since the factors WINDFX and WINDFY that multiply the input winds to account for overland effects are 0.0 for the second wind field, only the first and third wind fields are used. These correspond to data collected at the Norfolk International Airport and the Patuxent River Naval Station. Internal coding results in the wind speed assigned to each computational cell being a linear interpolation between these two locations. Cells north of the Patuxent station are assigned wind speeds from the Patuxent station. As can be seen in Appendix G, each line of input in FILE 14 contains the day, hour of the day, and the x and y components of the wind speed from each of the three wind stations. The wind stresses computed in the x and y components are then transformed to the contravariant components $\bar{\tau}_\xi$ and $\bar{\tau}_\eta$ by

$$\bar{\tau}_\xi = \frac{1}{J} (\tau_x y_\eta - \tau_y x_\eta)$$

$$\bar{\tau}_\eta = \frac{1}{J} (-\tau_x y_\xi + \tau_y x_\xi)$$

Hourly wind data at the three stations are presented in Appendix G for only the first couple of days in September 1983.

Grid Coordinates

41. The (x,y) coordinates of the computational grid shown in Figure 2

are read from FILE 15. File 15 was created from running the grid generation code WESCORA. The form of these data for a few points is illustrated in Appendix H. The first line is the number of points in the ξ and η directions, respectively. The (x,y) coordinates of each point, starting with row 1 and moving from left to right, are then input as one point per line. These values correspond to the arbitrary Cartesian system used to generate the grid. They are multiplied by the variable XREF to convert them into real world distances. Points outside the grid are assigned a value of 9.0×10^{18} .

Tabular Tides

42. The tabular tide data are read from FILE 16. Each line of input contains the hour, minutes, and seconds since the initiation of the simulation along with the value of the water-surface elevation relative to the top of the top layer. Appendix I illustrates the form of these data in FILE 16 for the first 59 hours of September 1983.

Initial Temperature (Salinity)

43. FILES 17 and 74 are identical in form. FILE 17 contains the initial temperature field, whereas FILE 74 contains the initial salinity field. These files were generated by a computer program which uses a few observed values to assign values to the individual cells in each of the vertical layers. The resulting field is then smoothed in each horizontal direction in each layer before writing the final field to either FILE 17 or FILE 74. Appendix J presents the initial temperature field for layer 1 and a portion of layer 2. Note that most of the values are zero since the only active cells in layer 1 (bottom layer) are in the deep channel in the middle of the bay.

Drag Coefficient

44. Since the Chesapeake Bay model is a 3D model, the bottom drag coefficient is computed from Equation 32. Thus, FILE 18 containing a spatially varying Manning's n field is not needed. In addition, since the bottom roughness is constant FILE 20 containing a spatially varying roughness height field is not needed.

Surface Heat Exchange Information

45. Daily averaged equilibrium temperatures and surface heat exchange coefficients computed from meteorological data at the Patuxent Naval Station are read from FILE 19. As indicated in Appendix K, each input data line consists of the day and hour since the initiation of the simulation and the equilibrium temperature in degrees Celsius, and the surface heat exchange coefficient in $\text{watts/m}^2/^{\circ}\text{C}$.

Tidal Boundary Salinity and Temperature

46. At tidal boundaries, the time-varying vertical distributions of temperature and salinity are read from FILE 76. As illustrated in Appendix L, these data are grouped in the following manner. The day and hour since the initiation of the simulation is input on a line and followed by separate lines of coding giving the (I,J) location of the tidal boundary cell followed by the vertical distribution of salinity. A separate line gives the same (I,J) location followed by the vertical distribution of temperature. These distributions consist of values in each active layer starting with the surface layer. Only the first two days of data from September 1983 are presented in Appendix L for illustrative purposes.

47. Since ITEMP = 1 in FILE 4 (see Appendix D), equilibrium temperatures are assigned to the river inflows and FILE 78 does not exist for the September 1983 simulation.

PART V: SUMMARY

48. This report serves two purposes. First, a discussion of the equations solved, turbulence closure, numerical techniques employed, boundary conditions applied, etc., provides the interested reader with theoretical details concerning the 3D model. Secondly, because sufficient information is presented concerning the structure of the computer code and input data requirements the report serves as a user's guide for those readers who may be interested in applying the model. Examples of the setup of input data files for the September 1983 simulation serve to strengthen the use of the report as a user's guide.

49. The basic equations solved are first presented in their dimensional form for a Cartesian coordinate system. The numerical solution of the governing equations involves an external mode consisting of vertically averaged equations along with the full 3D internal mode equations. The Cartesian equations for the two modes are then nondimensionalized before casting them into a form for solution on a boundary-fitted coordinate system. In this transformation, only terms in the horizontal directions are transformed since the Cartesian form is retained in the vertical direction. It was found in the Chesapeake Bay long-term simulations that this form was required to maintain the observed stratification in the deep channels.

50. A discussion of boundary conditions reveals that both the wind stress at the free surface and the bottom friction stress are cast in a quadratic form. The exchange of heat at the free surface is represented using the concept of an equilibrium temperature. At a tidal boundary the time-varying water surface and vertical distributions of salinity and temperature are required, whereas at river boundaries the freshwater discharge and the temperature of the inflow are required.

51. The method of finite differences is used to solve the governing equations. In the external mode the vertically averaged continuity equation is treated completely implicit, whereas only the water-surface slope terms are treated implicitly in the momentum equations. The resulting difference equations are factored into (ξ, η) sweeps to yield an extremely efficient solution scheme. In the internal mode equations, the only terms treated implicitly are the vertical diffusion terms, the bottom friction and the water-surface slope

terms. The surface slope terms are "fed" into the internal mode computations from the external mode.

52. The vertical turbulence closure model is based upon the assumption of local equilibrium of turbulence. Thus, all time derivatives plus the advection and diffusion terms in the Reynold's stress equations are neglected. This results in algebraic equations relating the eddy coefficients to the water column stratification, a turbulence length scale and the kinetic energy of the turbulence.

53. A discussion of the functions of all subroutines and the order in which they are called provides a basic understanding of the flow of computations in the computer program. Appendices B and C provide detailed information on the input and the form of the input required in various files for operation of the numerical model. A partial listing of all the input files created for the simulation of the hydrodynamics of Chesapeake Bay during September 1983 illustrates the setup of these input data.

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APPENDIX A: TRANSFORMED HORIZONTAL DIFFUSION TERMS

1. When transforming second derivative terms many additional terms arise. For example, the horizontal diffusion of momentum terms in Equation 14 of the main text become:

$$\begin{aligned}
 & \left[\frac{\partial}{\partial x} \left[A_H \frac{\partial hu}{\partial x} \right] + \frac{\partial}{\partial y} \left[A_H \frac{\partial hu}{\partial y} \right] \right] = \\
 & \frac{Y_\eta}{J^2} \left[\frac{A_H Y_\eta}{J} (X_\xi Y_\eta h\bar{u})_\xi + \frac{A_H X_\eta}{J} (X_\xi X_\eta h\bar{u})_\xi \right]_\xi \\
 & - \frac{X_\eta}{J^2} \left[\frac{A_H Y_\eta}{J} (Y_\xi Y_\eta h\bar{u})_\xi + \frac{A_H X_\eta}{J} (X_\eta Y_\xi h\bar{u})_\xi \right]_\xi \\
 & + \frac{Y_\eta}{J^2} \left[\frac{A_H Y_\xi}{J} (X_\xi Y_\xi h\bar{u})_\eta + \frac{A_H X_\xi}{J} (X_\xi X_\xi h\bar{u})_\eta \right]_\eta \\
 & - \frac{X_\eta}{J^2} \left[\frac{A_H Y_\xi}{J} (Y_\xi Y_\xi h\bar{u})_\eta + \frac{A_H X_\xi}{J} (X_\xi Y_\xi h\bar{u})_\eta \right]_\eta \\
 & + \frac{Y_\eta}{J^2} \left[\frac{A_H Y_\eta}{J} (Y_\eta X_\eta h\bar{v})_\xi + \frac{A_H X_\eta}{J} (X_\eta X_\eta h\bar{v})_\xi \right]_\xi \\
 & - \frac{X_\eta}{J^2} \left[\frac{A_H Y_\eta}{J} (Y_\eta Y_\eta h\bar{v})_\xi + \frac{A_H X_\eta}{J} (X_\eta Y_\eta h\bar{v})_\xi \right]_\xi \\
 & + \frac{Y_\eta}{J^2} \left[\frac{A_H Y_\xi}{J} (X_\eta Y_\xi h\bar{v})_\eta + \frac{A_H X_\xi}{J} (X_\xi X_\eta h\bar{v})_\eta \right]_\eta \\
 & - \frac{X_\eta}{J^2} \left[\frac{A_H Y_\xi}{J} (Y_\xi Y_\eta h\bar{v})_\eta + \frac{A_H X_\xi}{J} (X_\xi Y_\eta h\bar{v})_\eta \right]_\eta \\
 & + \frac{Y_\eta}{J^2} \left[- \left\{ \frac{A_H Y_\eta}{J} (X_\xi Y_\xi h\bar{u})_\eta \right\}_\xi - \left\{ \frac{A_H Y_\xi}{J} (X_\xi Y_\eta h\bar{u})_\xi \right\}_\eta \right. \\
 & \left. - \left\{ \frac{A_H X_\eta}{J} (X_\xi X_\xi h\bar{u})_\eta \right\}_\xi - \left\{ \frac{A_H X_\xi}{J} (X_\xi X_\eta h\bar{u})_\xi \right\}_\eta \right]
 \end{aligned}$$

$$\begin{aligned}
& - \frac{X_\eta}{J^2} \left[- \left\{ \frac{A_H Y_\eta}{J} (Y_\xi Y_\xi h \bar{u})_\eta \right\}_\xi - \left\{ \frac{A_H Y_\xi}{J} (Y_\xi Y_\eta h \bar{u})_\xi \right\}_\eta \right. \\
& \quad \left. - \left\{ \frac{A_H X_\eta}{J} (X_\xi Y_\xi h \bar{u})_\eta \right\}_\xi - \left\{ \frac{A_H X_\xi}{J} (X_\eta Y_\xi h \bar{u})_\xi \right\}_\eta \right] \\
& + \frac{Y_\eta}{J^2} \left[- \left\{ \frac{A_H Y_\eta}{J} (Y_\xi X_\eta h \bar{v})_\eta \right\}_\xi - \left\{ \frac{A_H Y_\xi}{J} (X_\eta Y_\eta h \bar{v})_\xi \right\}_\eta \right. \\
& \quad \left. - \left\{ \frac{A_H X_\eta}{J} (X_\xi X_\eta h \bar{v})_\eta \right\}_\xi - \left\{ \frac{A_H X_\xi}{J} (X_\eta X_\eta h \bar{v})_\xi \right\}_\eta \right] \\
& - \frac{X_\eta}{J^2} \left[- \left\{ \frac{A_H Y_\eta}{J} (Y_\xi Y_\eta h \bar{v})_\eta \right\}_\xi - \left\{ \frac{A_H Y_\xi}{J} (Y_\eta Y_\eta h \bar{v})_\xi \right\}_\eta \right. \\
& \quad \left. - \left\{ \frac{A_H X_\eta}{J} (X_\xi Y_\eta h \bar{v})_\eta \right\}_\xi - \left\{ \frac{A_H X_\xi}{J} (X_\eta Y_\eta h \bar{v})_\xi \right\}_\eta \right]
\end{aligned}$$

Likewise, these terms in Equation 15 of the main text become:

$$\begin{aligned}
& \left[\frac{\partial}{\partial x} \left[A_H \frac{\partial h v}{\partial x} \right] + \frac{\partial}{\partial y} \left[A_H \frac{\partial h v}{\partial y} \right] \right] = \\
& + \frac{X_\xi}{J^2} \left[\frac{A_H Y_\xi}{J} (Y_\xi Y_\eta h \bar{v})_\eta + \frac{A_H X_\xi}{J} (X_\xi Y_\eta h \bar{v})_\eta \right] \\
& - \frac{Y_\xi}{J^2} \left[\frac{A_H Y_\xi}{J} (X_\eta Y_\xi h \bar{v})_\eta + \frac{A_H X_\xi}{J} (X_\xi X_\eta h \bar{v})_\eta \right] \\
& + \frac{X_\xi}{J^2} \left[\frac{A_H Y_\eta}{J} (Y_\eta Y_\eta h \bar{v})_\xi + \frac{A_H X_\eta}{J} (X_\eta Y_\eta h \bar{v})_\xi \right] \\
& - \frac{Y_\xi}{J^2} \left[\frac{A_H Y_\eta}{J} (Y_\eta X_\eta h \bar{v})_\xi + \frac{A_H X_\eta}{J} (X_\eta X_\eta h \bar{v})_\xi \right]
\end{aligned}$$

$$\begin{aligned}
& + \frac{X_\xi}{J^2} \left[- \left\{ \frac{A_H Y_\eta}{J} (Y_\xi Y_\eta h \bar{v})_\eta \right\}_\xi - \left\{ \frac{A_H Y_\xi}{J} (Y_\eta Y_\eta h \bar{v})_\xi \right\}_\eta \right. \\
& \quad \left. - \left\{ \frac{A_H X_\eta}{J} (X_\xi Y_\eta h \bar{v})_\eta \right\}_\xi - \left\{ \frac{A_H X_\xi}{J} (X_\eta Y_\eta h \bar{v})_\xi \right\}_\eta \right] \\
& - \frac{Y_\xi}{J^2} \left[- \left\{ \frac{A_H Y_\eta}{J} (Y_\xi X_\eta h \bar{v})_\eta \right\}_\xi - \left\{ \frac{A_H Y_\xi}{J} (X_\eta Y_\eta h \bar{v})_\xi \right\}_\eta \right. \\
& \quad \left. - \left\{ \frac{A_H X_\eta}{J} (X_\xi X_\eta h \bar{v})_\eta \right\}_\xi - \left\{ \frac{A_H X_\xi}{J} (X_\eta X_\eta h \bar{v})_\xi \right\}_\eta \right] \\
& + \frac{X_\xi}{J^2} \left[\frac{A_H Y_\eta}{J} (Y_\xi Y_\eta h \bar{u})_\xi + \frac{A_H X_\eta}{J} (X_\eta Y_\xi h \bar{u})_\xi \right]_\xi \\
& - \frac{Y_\xi}{J^2} \left[\frac{A_H Y_\eta}{J} (X_\xi Y_\eta h \bar{u})_\xi + \frac{A_H X_\eta}{J} (X_\xi X_\eta h \bar{u})_\xi \right]_\xi \\
& + \frac{X_\xi}{J^2} \left[\frac{A_H Y_\xi}{J} (Y_\xi Y_\xi h \bar{u})_\eta + \frac{A_H X_\xi}{J} (X_\xi Y_\xi h \bar{u})_\eta \right]_\eta \\
& - \frac{Y_\xi}{J^2} \left[\frac{A_H Y_\xi}{J} (X_\xi Y_\xi h \bar{u})_\eta + \frac{A_H X_\xi}{J} (X_\xi X_\xi h \bar{u})_\eta \right]_\eta \\
& + \frac{X_\xi}{J^2} \left[- \left\{ \frac{A_H Y_\eta}{J} (Y_\xi Y_\xi h \bar{u})_\eta \right\}_\xi - \left\{ \frac{A_H Y_\xi}{J} (Y_\xi Y_\eta h \bar{u})_\xi \right\}_\eta \right. \\
& \quad \left. - \left\{ \frac{A_H X_\eta}{J} (X_\xi Y_\xi h \bar{u})_\eta \right\}_\xi - \left\{ \frac{A_H X_\xi}{J} (X_\eta Y_\xi h \bar{u})_\xi \right\}_\eta \right] \\
& - \frac{Y_\xi}{J^2} \left[- \left\{ \frac{A_H Y_\eta}{J} (X_\xi Y_\xi h \bar{u})_\eta \right\}_\xi - \left\{ \frac{A_H Y_\xi}{J} (X_\xi Y_\eta h \bar{u})_\xi \right\}_\eta \right.
\end{aligned}$$

$$- \left\{ \frac{A_H Y_\eta}{J} (X_\xi X_\xi h \bar{u})_\eta \right\}_\xi - \left\{ \frac{A_H X_\xi}{J} (X_\xi X_\eta h \bar{u})_\xi \right\}_\eta \right]$$

2. The transformed horizontal diffusion terms in Equations 17 and 18 of the main text are somewhat simpler since contravariant velocity components are not involved. These terms, written for the salinity, are given below. Identical terms exist for the temperature.

$$\begin{aligned} \left[\frac{\partial}{\partial x} \left[K_H \frac{\partial hS}{\partial x} \right] + \frac{\partial}{\partial y} \left[K_H \frac{\partial hS}{\partial y} \right] \right] &= \frac{1}{J} \left\{ \left[\frac{K_H Y_\eta}{J} (hSY_\eta)_\xi \right. \right. \\ &\quad + \left. \frac{K_H X_\eta}{J} (hSX_\eta)_\xi \right]_\xi + \left[\frac{K_H Y_\xi}{J} (hSY_\xi)_\eta \right. \\ &\quad + \left. \frac{K_H X_\xi}{J} (hSX_\xi)_\eta \right]_\eta - \left[\frac{K_H Y_\eta}{J} (hSY_\xi)_\eta \right]_\xi \\ &\quad - \left[\frac{K_H Y_\xi}{J} (hSY_\eta)_\xi \right]_\eta - \left[\frac{K_H X_\eta}{J} (hSX_\xi)_\eta \right]_\xi \\ &\quad \left. - \left[\frac{K_H X_\xi}{J} (hSX_\eta)_\xi \right]_\eta \right\} \end{aligned}$$

APPENDIX B: LIST OF INPUT DATA IN FILE 4

DUMMY		
TITLE	Run descriptor	A80

DUMMY
ICHES. IRUNYR 1018

```

ICHES  - 1   ; For Chesapeake Bay Run
        - 0   ; Other Areas
IRUNYR - 1984   Year simulated if
        - 1985   ICHES = 1. Only used to control the generation
        - 1986   of seasonal averaged salinity plots

```

```
DUMMY
IT1, IT2, DT, ISTART, ITEST, ITSALT                218.F8.0.718
```

```

IT1      ; Starting time step ( - 1 )
IT2      ; Ending time step
DT       ; Computational time step in Sec.
ISTART = 0 ; Cold start
         > 0 ; Hot start (not operational)
ITEST  = 0 ; No diagnostic output
         > 0 ; Diagnostic output
ITSALT =   ; Number of time steps before salinity and temperature
            computations are initiated

```

DUMMY	
IGI, IGH, IGM, IGSA, IGTE, IGW, IGP, IGS, IGC	1018

```

IGI      - 1      ; Printout arrays such as NS, MS, etc.
          - 0      ; No printout
IGH      - 1      ; Printout all depth arrays
          - 0      ; No printout
IGM      - 1      ; Printout Manning's n values
          - 0      ; No printout
IGSA     - 1      ; Printout initial salinity arrays
          - 0      ; No printout
IGTE     - 1      ; Printout initial temperature arrays
          - 0      ; No printout
IGW      - 1      ; Printout the initial wind shear stress
          - 0      ; No printout
IGP      - 1      ; Save cell centered depth along with other information to
                FILE 40 for snapshot plot
          - 0      ; Does not save
IGS      - 1      ; Printout starting S,UI,VI for hot start (not operational)
          - 0      ; No printout
IGC      - 1      ; Printout Grid coordinates
          - 0      ; No printout

```

DUMMY

IDIM, IPA, IPB, ID, JPA, JPB, JD, KPA, KPB, KD

1018

IDIM - 1 ; Printout in dimensional form
 - 0 ; Printout in non-dimensional form
 IPA ; Beginning I index for printout
 IPB ; Ending I index for printout
 ID ; I index printout interval
 JPA ; Beginning J index for printout
 JPB ; Ending J index for printout
 JD ; J index printout interval
 KPA ; Beginning K index (vertical) for printout
 KPB ; Ending K index for printout
 KD ; K index printout interval

DUMMY

IPTD, IPUI, IPVI, IPUA, IPVA, IPU3, IPV3, IPW3

1018

IPTD ; Time step interval at which water surface
 elevations are printed
 IPUI ; Time step interval at which UI is printed
 IPVI ; Time step interval at which VI is printed
 IPUA ; Time step interval at which 2D vertically averaged U
 is printed
 IPVA ; Time step interval at which 2D vertically averaged V
 is printed
 IPU3 ; Time step interval at which 3D u is printed
 IPV3 ; Time step interval at which 3D v is printed
 IPW3 ; Time step interval at which 3D w is printed

IPSA, IPTE, IPRO, IPGA, IPGB, IPSS, IPU3A, IPV3A

1018

IPSA ; Time step interval at which salinity is printed
 IPTE ; Time step interval at which temperature is printed
 IPRO ; Time step interval at which density is printed
 IPGA ; Time step interval at which vertical eddy viscosity (GA)
 is printed
 IPGB ; Time step interval at which vertical eddy diffusivity (GB)
 is printed
 IPSS ; Time step interval at which wind shear stress is printed
 IPU3A ; Time step interval at which averaged u over time step
 interval is printed
 IPV3A ; Time step interval at which averaged v over time step
 interval is printed

DUMMY

XREF, ZREF, UREF, COR, GR, ROO, ROR, TO, TR

10F8.0

XREF ; Reference horizontal grid distance
 (Maximum horizontal dimension divided by
 number of cells in that direction in cm)
 ZREF ; Reference depth
 (Average typical depth in cm)

UREF ; Reference horizontal velocity
 (Average velocity in cm/sec)
 COR ; Coriolis parameter
 GR ; Gravitational acceleration (cm/sec²)
 ROO ; Minimum density expected (gm/cc)
 ROR ; Reference density (Maximum expected) (gm/cc)
 TO ; Minimum temperature (Celcius)
 TR ; Reference temperature (Maximum expected) (Celcius)

DUMMY

ISPAC(1), I-1,10

10I8

ISPAC(1) - 1 ; Use spatially variable Manning's n in vertically averaged
 model
 - 0 ; Use constant Manning's n in vertically averaged model
 ISPAC(2) - 1 ; Bottom drag coefficient computed in 3D model
 - 0 ; Bottom drag coefficient set to CBF in 3D model
 ISPAC(3) - 1 ; Coriolis ON
 - 0 ; Coriolis OFF
 ISPAC(4) - 1 ; Variable bottom roughness height
 - 0 ; Constant bottom roughness height given by BZ1
 ISPAC(5-8) ; Not used currently
 ISPAC(9) - 0 ; Constant vertical eddy coefficient
 - 2 ; Variable vertical eddy coefficients
 - 3 ; Variable vertical eddy coefficients
 computed from Kent-Prichard formulation
 ISPAC(10) ; Not used currently

DUMMY

SSSO, DELTAZ, DELTAZM

10F8.0

SSSO ; Initial water surface elevation relative
 to initial water depth
 DELTAZ ; Layer thickness in cm of all layers except the top layer
 DELTAZM ; Thickness of top layer in cm

DUMMY

ITB, ZREFBN, CTB, BZ1, BFL, BFCB, MANN

18,9F8.0

ITB - 1 ; Linear bottom friction for internal mode
 - 2 ; Quadratic bottom friction for internal mode
 ZREFBN ; Reference height above bottom in cm
 CTB ; Constant bottom drag coefficient (typical value of 0.003)
 BZ1 ; Bottom roughness height in cm
 BFL ; Water depth in cm below which the bottom
 friction is increased
 BFCB ; Bottom friction coefficient below BFL
 MANN ; Manning's n in vertically averaged model if ISPAC(1) - 0

DUMMY
THETA, THETAS

10F8.0

THETA ; Time level weighing factor in external
mode numerical scheme
THETAS ; Time level weighing factor in transport-diffusion equation

DUMMY
ITEMP, ISALT, IFI, IFD, IFDS

10I8

ITEMP - 2 ; Compute temperature (use time-varying temperature as
river boundary temperature)
- 1 ; Compute temperature (use daily equilibrium
temperature as river boundary temperature)
- 0 ; No computation of temperature
ISALT - 1 ; Compute salinity
- 0 ; No computation of salinity
IFI - 1 ; Compute nonlinear inertia terms in the momentum equations
- 0 ; Do not compute inertia terms
IFD - 1 ; Include viscous terms in momentum equations
- 0 ; Does not include
IFDS - 1 ; Include diffusion terms in salinity and temperature
computations
- 0 ; Does not include

DUMMY
S1, S2

10F8.0

S1 ; Constant in computation of variable vertical
eddy viscosity [$GA = GX (1+S1*RI)^{PM1}$] if first-order
turbulence model is used
S2 ; Constant in computation of variable vertical
eddy diffusivity [$GB = GX (1+S2*RI)^{PM2}$] if first-order
turbulence model is used

DUMMY
IEXP, AVR, AVM, AVM1, AHR

1I8,8F8.0

IEXP ; Vertical eddy coefficient flag
IEXP - 0 ; Constant eddy coefficient
-1 ; Munk-Anderson type first order turbulence model
Richardson-number dependent eddy coefficient
with length scale linearly increasing from the
bottom and surface
-2 ; Munk-Anderson type first order turbulence model
Richardson-number dependent eddy coefficient
with length scale linearly increasing from the
bottom to the surface
-3 ; Second order turbulence model
AVR ; Reference vertical eddy coefficient (cm^2/sec)
AVM ; Minimum vertical eddy viscosity (cm^2/sec)

AVM1 ; Minimum vertical eddy diffusivity (cm²/sec)
 AHR ; Reference horizontal eddy diffusivity or viscosity (cm²/sec)

DUMM1

FM1, FM2, ZTOP, SLMIN, QQMIN

10F8.0

FM1 ; Parameter in Richardson-number dependent
 eddy-viscosity (see definition of S1)
 FM2 ; Parameter in Richardson-number dependent
 eddy-diffusivity (see definition of S2)
 ZTOP ; Distance between the top of the computational domain
 and the free surface. Used in computing turbulence
 length scale (cm)
 SLMIN ; Minimum value of turbulence macroscale (cm)
 QQMIN ; Minimum value of turbulent kinetic energy (gm/cm/sec²)

DUMMY

ICUT, KSM, KSL, QCUT, GAMAX, GBMAX, FZS

3I8,7F8.0

ICUT = 0 ; Eddy coefficients constant below halocline
 = 1 ; Eddy coefficients computed below halocline
 KSM ; Number of times eddy viscosity/diffusivity in
 turbulence model are smoothed
 KSL ; Layer number above which smoothing of eddy
 viscosity/diffusivity will be performed
 QCUT ; Coefficient in second-order turbulence model (0.15 - 0.25)
 GAMAX ; Maximum value of eddy viscosity (cm²/sec)
 GBMAX ; Maximum value of eddy diffusivity (cm²/sec)
 FZS ; Turbulence scale is not allowed to exceed the
 product of FZS and depth

DUMMY

NWIND, IWIND, TAUX, TAUY

2I8,8F8.0

NWIND ; Number of stations where wind data are input
 IWIND = 0 ; Steady and uniform wind stress
 = 1 ; Steady and uniform wind speed
 = 2 ; Steady and space variable wind stress
 = 3 ; Steady and space variable wind speed
 = 4 ; Time variable and uniform wind stress
 = 5 ; Time variable and uniform wind speed
 = 6 ; Time and space variable wind stress
 = 7 ; Time and space variable wind speed
 TAUX ; Uniform wind stress in x-direction if IWIND = 0
 Uniform wind speed in x-direction if IWIND = 1
 TAUY ; Uniform wind stress in y-direction if IWIND = 0
 Uniform wind speed in y-direction if IWIND = 1

If NWIND = 0, use the following card

DUMMY

If NWIND > 0, use the following cards

DUMMY

WINDFX(K), WINDFY(K)

10F8.0

WINDFX(K) ; Adjustment factor of wind speed in x direction

WINDFY(K) ; Adjustment factor of wind speed in y direction

* Repeat NWIND times

DUMMY

XMAP

10F8.0

XMAP ; Factor that scales the (x,y) coordinates
created by GRID Generation Code to the
real world

DUMMY

NRIVER ; Number of river boundaries

10I8

NRIVER = 0 ; No river boundaries

< 0 ; River inflows are steady

> 0 ; Time variable inflows

If NRIVER = 0, use the following cards

DUMMY

DUMMY

If NRIVER > 0, use the following cards

DUMMY

IJRDIR(K), IJRROW(K), IJRSTR(K), IJREND(K)

10I8

IJRDIR(K) = 1 ; River boundary is on left(west)

= 2 ; River boundary is on bottom (south)

= 3 ; River boundary is on right (east)

= 4 ; River boundary in on top (north)

IJRROW(K) ; Index of the row (J) or column (I)
of the river boundary

IJRSTR(K) ; Starting I or J index of the river boundary

IJREND(K) ; Ending I or J index of the river boundary

* Repeat NRIVER times

DUMMY

FACTOR(K), BASEF(K)

10F8.0

FACTOR(K) ; Factor by which time-varying inflow is multiplied
BASEF(K) ; Additional inflow added to time-varying inflow (ft³/sec)

* Repeat NRIVER times

If NRIVER < 0, use the following cards

DUMMY

IJRDIR(K), IJRROW(K), IJRSTR(K), IJREND(K)

10I8

IJRDIR(K) - 1 ; River boundary is on left (west)
 - 2 ; River boundary is on bottom (south)
 - 3 ; River boundary is on right (east)
 - 4 ; River boundary is on top (north)
IJRROW(K) ; Index of the row (J) or column (I)
 of the river boundary
IJRSTR(K) ; Starting I or J index of the river boundary
IJREND(K) ; Ending I or J index of the river boundary

DUMMY

ICELL, JCELL, QRIVER(K,IJ)

2I8,8F8.0

ICELL, JCELL ; Coordinate of a cell(I,J) where QRIVER is
 prescribed
QRIVER(K,IJ) ; Steady river inflow

* Repeat NRIVER times

DUMMY

NBAR

10I8

NBAR ; Number of interior barriers

If NBAR = 0, Use the following card

DUMMY

If NBAR > 0, Use the following cards

DUMMY

IJBDIR(K), IJBROW(K), IJBSTR(K), IJBEND(K)

10I8

IJBDIR(K) - 1 ; barrier is horizontal (ξ -direction)
 - 2 ; barrier is vertical (η -direction)
IJBROW(K) ; Index of row (J) or column (I) of
 interior barrier

IJBSTR(K) ; Starting I or J index of interior
barrier
IJBEND(K) ; Ending I or J index of interior barrier

* Repeat NBAR times

DUMMY
ITIDE ; Flags for tidal boundaries 1018

ITIDE = 0 ; No tidal boundaries
> 0 ; Sinusoidal boundaries
< 0 ; Tabular tidal boundaries

For ITIDE = 0, use the following cards

DUMMY
DUMMY
DUMMY

For sinusoidal tidal boundaries, use the following cards

DUMMY
IJLINE, NCG 1018

IJLINE ; Number of tidal boundaries
NCG ; Number of tidal constituents

DUMMY
IJDIR(I), IJROW(I), IJSTR(I), IJEND(I) 1018

IJDIR(I) - 1 ; Tidal boundary is on left (west)
- 2 ; Tidal boundary is on bottom (south)
- 3 ; Tidal boundary is on right (east)
- 4 ; Tidal boundary is on top (north)
IJROW(I) ; The index of the row (J) or column (I)
of the tidal boundary
IJSTR(I) ; Starting I or J of the tidal boundary
IJEND(I) ; Ending I or J of the tidal boundary

* Repeat IJLINE times

DUMMY
AMP(I), PHA(I), CA(I), TP(I) 10F8.0

AMP(I) ; Tidal amplitude of the constituent I (cm)
PHA(I) ; Tidal phase of the constituent I (degrees)
CA (I) ; Constant tidal amplitude added to AMP(I) (cm)
TP (I) ; Tidal period of the constituent I (sec)

* Repeat NCG times for each IJLINE.

For tabular tidal boundary conditions, use the following cards

DUMMY

TIDFNO, TIDBND

10F8.0

TIDFNO ; Number of tidal elevation tables entered as input
TIDBND ; Number of tidal elevation boundaries

DUMMY

TIDSTR(I), I=1,TIDFNO

10I8

TIDSTR(I) ; The entry number in each tidal elevation
table corresponding to the starting time
of the simulation

DUMMY

IJDIR(I), IJROW(I), IJSTR(I), IJEND(I), TIDTYP(I),
TIDFN1(I), TIDFN2(I)

4I8,A8,5I8

IJDIR(I) - 1 ; Tidal boundary is on left (west)
 - 2 ; Tidal boundary is on bottom (south)
 - 3 ; Tidal boundary is on right (east)
 - 4 ; Tidal boundary is on top (north)
IJROW(I) ; Index of the row (J) or column (I) of the
 tidal boundary
IJSTR(I) ; Starting I or J index of the tidal boundary
IJEND(I) ; Ending I or J index of the tidal boundary
TIDTYP(I) - "CONSTANT" ; Constant tidal elevation between
 IJSTR(I) and IJEND(I)
 - "INTERP " ; Linear interpolation of tidal
 elevation IJSTR(I) and IJEND(I)
TIDFN1(I) ; The number of the tidal elevation table for CONSTANT
 or INTERP type of boundaries
TIDFN2(I) ; The number of the 2nd tidal elevation table used for
 interpolation on "INTERP" type boundary

DUMMY

ITBRK(I), I = 1, 20

10I8

ITBRK(I) ; Time steps at which information is written to
files for snapshot plots

DUMMY

ISBRK(I), I = 1, 10

10I8

ISBRK(1) - 1 ; Save 3D dimensionless, contravariant
 velocities at cell faces
 - 0 ; Does not save

ISBRK(2) - 1 ; Save 3D cell centered velocities
 - 0 ; Does not save
 ISBRK(3) - 1 ; Save salinities
 - 0 ; Does not save
 ISBRK(4) - 1 ; Save average 3D velocities over simulation period
 at cell faces
 - 0 ; Does not save
 ISBRK(5) - 1 ; Save average salinities over simulation period
 - 0 ; Does not save
 ISBRK(6-10) ; Not used currently

DUMMY

NSTA, NFREQ, NSTART

1018

NSTA ; Number of stations where information is saved for
 time series plots of currents
 NFREQ ; Time step interval for saving currents
 NSTART ; Beginning time step for saving current information

DUMMY

IST(K), JST(K), STATID(K)

214,A48

IST(K), JST(K) ; Coordinate (I,J) of a station where currents are saved
 STATID(K) ; Station descriptor

DUMMY

JSPAC(I), I - 1, 10

JSPAC(1) - 1 ; Save dimensional Cartesian unit flows UI and VI on a file
 - 0 ; Does not save
 JSPAC(2) - 1 ; Save depth-averaged dimensional Cartesian U and V
 on a file
 - 0 ; Does not save
 JSPAC(3) - 1 ; Save dimensional Cartesian 3D u and v at cell faces
 on a file
 - 0 ; Does not save
 JSPAC(4) - 1 ; Save dimensional Cartesian 3D u and v at cell center
 - 0 ; Does not save
 JSPAC(5) - 1 ; Save nondimensional Cartesian UI and VI
 - 0 ; Does not save
 JSPAC(6-10) ; Not used currently

DUMMY

NSTATS, NFREQS, NSTRTS

1018

NSTATS ; Number of stations where water surface
 elevations are saved for time series plots
 NFREQS ; Time step interval for saving water surface
 elevations
 NSTRTS ; Beginning time step for saving water surface elevations

ISTS(K), JSTS(K), STATS(K)

```

ISTS(K), JSTS(K) ; Coordinate (I,J) of a station where water surface
                    elevations are saved
STATS(K)         ; Station descriptor

```

MSTA, MFREQ, MSTART

```

MSTA    ; Number of stations where salinity, temperature,
        ; etc., are saved for time series plots
MFREQ    ; Time step interval for saving information
MSTART   ; Beginning time step for saving information

```

ISTSA(K), JSTSA(K), STATSA(K)

ISTSA(K), JSTSA(K) ; Coordinate (I,J) of a station where salinities,
etc., are saved
STATSA(K) ; Station descriptor

JTPAC(I), I = 1, 10

```
JTPAC(1) - 1 ; Save salinities on file at MFREQ
          - 0 ; Does not save
JTPAC(2) - 1 ; Save average salinity over simulation
          period on file
          - 0 ; Does not save
JTPAC(3) - 1 ; Save temperatures on file at MFREQ
          - 0 ; Does not save
JTPAC(4) - 1 ; Save eddy viscosities on file at MFREQ
          - 0 ; Does not save
JTPAC(5) - 1 ; Save eddy diffusivity on file at MFREQ
          - 0 ; Does not save
JTPAC(6) - 1 ; Save density on file at MFREQ
          - 0 ; Does not save
JTPAC(7-10) ; Not used currently
```

I,J,K, NS(I,J,K)

I,J ; Horizontal coordinates of cell
K ; Vertical layer

NS ; Indicates type of left/right boundary of the cell
(See Figure 4, main text). Allows for changing
internally computed values. Peculiar to Chesapeake
Bay.

DUMMY

I,J,K, MS(I,J,K)

1018

I,J ; Horizontal coordinates of cell
K ; Vertical layer
MS ; Indicates type of top/bottom boundary of the cell
(See Figure 4, main text). Allows for changing
internally computed values. Peculiar to Chesapeake
Bay.

DUMMY

I,J,K, NS(I,J,K)

1018

I,J ; Horizontal coordinates of cell
K ; Vertical layer
NS ; Indicates type of left/right boundary of the cell
(See Figure 4, main text). Allows for second
change of internally computed values. Peculiar
to Chesapeake Bay.

DUMMY

I,J,K, MS(I,J,K)

1018

I,J ; Horizontal coordinates of cell
K ; Vertical layer
MS ; Indicates type of top/bottom boundary of the cell
(See Figure 4, main text). Allows for second
change of internally computed values. Peculiar
to Chesapeake Bay.

APPENDIX C: LIST OF DATA INPUT FILES

FILE 12

The water depths at the center of each horizontal grid cell relative to the zero of the datum, e.g., NGVD, are read from FILE 12. These data are formatted by 16F5.0 and are read by rows with the first row being at the bottom of the transformed plane. The depths are input in units of feet* and then converted to centimeters in the model.

FILE 13

River inflows are read from FILE 13. These data are read first as a time line (DAY and HOUR) formatted by 2I8. Next the (I,J) location and discharge in cubic feet per second for each cell of each river boundary are read and formatted by 2I8,F8.0.

FILE 14

Wind data are read from FILE 14. These data are in the form of time (DAY and HOUR) and the ξ (east-west) and η (north-south) components of the wind speed in meters per second of each wind field used. These data are formatted by (2I5,6F10.0).

FILE 15

The (x,y) coordinates of the Chesapeake Bay grid are read from FILE 15. This file was created from a run of the grid generation code called WESCORA. It is an unformatted file containing NX, NY, X(I,J), Y(I,J).

FILE 16

Tabular tide data are read from FILE 16. These data are in the form of time (HOUR, MINUTES, SECONDS) and the water-surface elevations in centimeters relative to NGVD for TIDFNO points on a tidal line. These data are formatted by (3I5,8F8.0).

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

FILE 17

The initial temperature field in degrees Celsius is read from FILE 17 by format (10E12.5). This file is created from a few observed values. The resulting field is then smoothed in each horizontal direction several times before creating FILE 17.

FILE 18

If the model is run in a purely 2D vertically averaged mode, a field of Manning's n values may be input by format (20F4.0). The input values are multiplied by 0.001 to yield the actual values. They are input by rows, with the first row being at the bottom of the transformed plane.

FILE 19

Daily average equilibrium temperatures in degrees Celsius and surface heat exchange coefficients in units of watts/m²/° are read from FILE 19. These data are in the form of time (DAY and HOUR), equilibrium temperature, and heat exchange coefficient. They are formatted by (2I5, F10.0, E12.5).

FILE 20

If the model is run in 3D mode, a field of bottom roughness heights in centimeters may be input by format (20F4.0) if ISPAC(4) = 1. They are input by rows, with the first row being at the bottom of the transformed plane.

FILE 74

The initial salinity field in parts per thousand is read from FILE 74 by format (10E12.5). This file is normally created from a few observed values. The resulting salinity field is then smoothed in each horizontal direction several times before creating FILE 74. These data are read by rows, with the first row being at the bottom of the transformed plane.

FILE 76

Time-varying salinity in parts per thousand and temperatures in degrees Celsius at tidal boundaries are read from FILE 76 if salinity and temperature are to be computed. These data are in the form of time (DAY and HOUR) formatted by (2I5). Next the (I,J) location of each tidal boundary cell and a vertical distribution of salinity, starting from the top layer to the bottom

layer are read. These data are followed by temperature data using the same format as for the salinity. They are formatted by (2I5, 11F6.0).

FILE 78

Time-varying temperature at river flow boundaries are read from FILE 78 if temperatures are to be computed and equilibrium temperatures are not used as river flow boundary temperatures. These data are in the form of a time (DAY and HOUR) formatted by (2I5). Next read (I,J) location of river flow boundary cells and corresponding temperatures starting from top layer to bottom layer. These data are formatted by (2I5,11F6.0).

APPENDIX D: INPUT DATA IN FILE 4 FOR
SEPTEMBER 1983 APPLICATION

CHESAPEAKE BAY : SEP83-RUN(26.7 DAYS), 9 MAJOR RIVERS WITH 10 LATERAL FLOWS,
WIND STRESS, 2 TABULAR TIDES, SALINITY AND TEMPERATURE

ICHES	IRUNYR								
1	1983								
IT1	IT2	DT	ISTART	ITEST	ITSALT				
1	3850	600.0	0	0	720				
IGI	IGH	IGM	IGSA	IGTE	IGW	IGP	IGS	IGC	
1	0	0	0	0	0	0	0	0	
IDIM	IPA	IPB	ID	JPA	JPB	JD	KPA	KPB	KD
1	1	67	1	1	34	1	1	15	2
IPTD	IPUI	IPVI	IPUA	IPVA	IPU3	IPV3	IPW3		
1440	0	0	0	0	1440	1440	1440		
IPSA	IPTE	IPRO	IPGA	IPGB	IPSS	IPU3A	IPV3A		
1440	1440	0	0	0	0	3850	3850		
XREF	ZREF	UREF	COR	GR	R00	ROR	T0	TR	
452628.	1000.	10.0	.0001	981.0	1.0	1.021	1.	30.	
ISPAC(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	1	1	0					2	
SSSO	DELTAZ	DELTAZM							
0.0	152.4	213.4							
ITB	ZREFBN	CTB	BZ1	BFL	BFCB	MANN			
2	5.0	0.0025	0.005	100.	0.008	0.025			
THETA	THETAS								
1.0	1.0								
ITEMP	ISALT	IFI	IFD	IFDS					
1	1	1	0	0					
S1	S2								
10.	3.33								
IEXP	AVR	AVM	AVM1	AHR					
-3	10.	10.0	0.005	100000.					
FM1	FM2	ZTOP	SLMIN	QQMIN					
-.5	-1.5	0.	1.	0.01					
ICUT	KSM	KSL	QCUT	GAMAX	GBMAX	FZS			
0	1	1	0.15	5000.	5000.	0.2			
NWIND	IWIND	TAUX	TAUY						
3	5	0.0	0.0						
WNDFX	WNDFY								
2.03	1.40								
0.00	0.00								
1.53	1.85								
XMAP									
570738.1									
NRIVER									
19									

IJRDIR	IJRROW	IJRSTR	IJREND	(ONE CARD FOR EACH RIVER)
4	34	2	2	JAMES R.
1	2	31	31	Appomattox R. at Matoaca
3	3	24	24	James R. Lat. 2
4	27	6	6	YORK (PAMUNKEY R.)
1	6	22	22	Pamunkey R. Lat. 1
4	27	8	8	YORK (MATTAPONI R.)
3	8	25	25	Mattaponi R. Lat. 1
4	31	17	17	RAPPAHANNOCK R.
1	16	19	19	Rappahannock R. Lat. 1
3	17	26	26	Rappahannock R. Lat. 2
4	34	22	22	POTOMAC R.
1	21	26	26	Potomac R. Lat. 1
3	26	21	21	Potomac R. Lat. 2
3	40	15	15	PATUXENT R.
2	15	34	34	Patuxent R. Lat. 1
4	15	38	38	Patuxent R. Lat. 2
4	14	62	62	SUSQUEHANNA R.
4	16	48	50	BALTIMORE HARBOUR(PATAPSCO R.)
2	1	37	37	CHOPTANK R.

FACTOR	BASEF
1.507	0.
1.507	0.
1.507	0.
1.699	0.
1.699	0.
1.699	0.
1.699	0.
1.699	0.
1.808	0.
1.808	0.
1.808	0.
1.230	0.
1.230	0.
1.230	0.
2.514	0.
2.514	0.
2.514	0.
1.015	0.
1.346	0.
6.602	0.

NBAR
2
IJRDIR IJRROW IJRSTR IJREND (ONE CARD FOR EACH BAR)
1 9 30 33
2 34 8 8
ITIDE
-1
TIDFNO TIDBND
1 2
TIDSTR(1 (2) (3) (4) (5) (6) (7) (8) (9) (10)
1
IJDIR IJROW IJSTRT IJEND TIDTYP TIDFN1 TIDFN2
1 5 4 4CONSTANT 1 1
2 4 1 5CONSTANT 1 1
ITBRK(1) (2) (3) (4) (5) (6) (7) (8) (9) (10)
900000 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0
ISBRK(1) (2) (3) (4) (5) (6) (7) (8) (9) (10)
1 0 0 0 1
NSTA NFREQ NSTART (CURRENT STATIONS)
4 3 1
IST JST STATID(K) (2I4,A48) (ONE CARD FOR EACH STATION)
3 5 BAY ENTRANCE
13 9 WOLF TRAP
31 11 MID BAY
43 10 BAY BRIDGE
JSPAC(I) (2) (3) (4) (5) (6) (7) (8) (9) (10)
0 0 1 0 0
NSTAS NFREQS NSTRTS (TIDE STATIONS)
7 3 1
IST JST STATS(K) (2I4,A48) (ONE CARD FOR EACH STATION)
3 5 CHESAPEAKE BAY TUNNEL, VA (6008863)
1 13 HAMPTON ROADS, VA (6008610)
23 21 COLONIAL BEACH, VA (6005150)
23 13 LEWISSETTA, VA (6005750)
30 14 SOLOMONS, MD (6007330)
45 12 ANNAPOLIS, MD (6005512)
60 11 HAVRE DE GRACE, MD (6004070)
MSTA MFREQ MSTART (SALINITY STATIONS)
4 3 720
IST JST STATSA(K) (2I4,A48) (ONE CARD FOR EACH STATION)
3 5 BAY ENTRANCE
13 9 WOLF TRAP
31 11 MID BAY
43 10 BAY BRIDGE
JTPAC(1) (2) (3) (4) (5) (6) (7) (8) (9) (10)
1 0 1 0 0 0

RESET	NS(I,J,K)	VALUES	
2	31	15	8
2	31	14	8
3	24	15	5
3	24	14	5
6	22	15	2
6	22	14	2
8	25	15	5
8	25	14	5
16	19	15	2
16	19	14	2
17	26	15	8
17	26	14	8
21	26	15	2
21	26	14	2
26	21	15	5
26	21	14	5
RESET	MS(I,J,K)	VALUES	
34	15	15	2
34	15	14	2
34	15	13	2
34	15	12	2
34	15	11	2
38	15	15	8
38	15	14	8
RESET	NS(I,J,K)	VALUES	
2	31	15	3
2	31	14	3
3	24	15	6
3	24	14	6
6	22	15	3
6	22	14	3
8	25	15	6
8	25	14	6
16	19	15	3
16	19	14	3
17	26	15	6
17	26	14	6
21	26	15	3
21	26	14	3
26	21	15	6
26	21	14	6
RESET	MS(I,J,K)	VALUES	
34	15	15	3
34	15	14	3
34	15	13	3
34	15	12	3
34	15	11	3
38	15	15	6
38	15	14	6

END OF DATA
END OF FILE

APPENDIX E: WATER DEPTH FIELD IN FILE 12

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	15	15	15	0	10	0	10	0	0	0	0	0
0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	25	25	15	15	0	10	10	10	0	10	0	0	0
0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	25	25	25	15	15	0	10	10	10	0	10	0	0	0
0	0	0	0	15	15	0	0	0	0	0	0	15	15	15	15
10	10	10	0	0	0	0	0	10	0	0	0	0	0	0	0
35	0	0													
55	55	35	20	20	35	35	35	35	25	25	25	25	25	25	25
25	25	25	25	50	50	50	50	50	50	50	25	10	10	10	10
10	0	0	0	15	15	0	0	0	0	0	0	20	20	20	15
0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0
35	0	0													
55	55	35	20	35	35	35	35	35	25	25	25	25	25	25	25
25	25	50	50	50	0	25	25	25	25	25	25	10	10	0	0
0	0	0	0	15	15	0	0	0	0	0	0	20	20	0	0
0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0
35	0	0													
55	55	35	20	35	35	35	50	60	60	60	60	60	60	60	60
60	60	55	45	35	20	15	0	0	20	0	0	10	0	0	0
0	0	0	0	15	15	0	0	15	15	0	0	20	20	15	0
0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0
35	0	0													
20	50	50	50	50	50	50	50	55	55	55	55	55	55	55	55
55	50	45	40	30	20	15	15	15	20	20	15	0	0	0	0
0	0	0	0	15	15	0	0	15	15	0	0	20	20	15	0
0	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0
35	0	0													
20	50	30	30	40	40	40	40	40	40	40	40	40	40	40	40
40	50	50	40	30	30	30	25	25	25	25	25	15	10	10	10
15	15	15	15	20	20	15	20	20	20	20	20	15	15	15	15
20	20	20	35	35	35	35	35	35	35	35	35	35	35	35	35
35	20	20													
20	50	25	25	25	40	40	40	40	40	40	40	40	40	40	40
40	40	50	50	65	70	70	65	40	40	40	40	40	30	25	25
40	40	35	25	25	25	25	50	50	50	50	50	35	25	20	20
20	20	35	35	20	20	15	15	15	15	10	10	10	0	0	0
0	0	0													
15	50	25	25	25	35	35	35	35	35	35	25	25	25	25	25
30	30	30	45	60	75	75	75	75	75	75	75	75	75	75	75
75	75	75	75	75	75	75	75	75	75	75	50	50	50	50	50
50	35	35	20	15	15	15	15	10	10	10	10	10	10	0	0
0	0	0													
15	60	35	35	30	30	35	35	35	25	25	25	20	20	20	20
30	20	20	20	25	30	40	50	55	55	55	55	55	55	55	55
55	55	55	55	55	55	55	55	50	45	45	40	35	25	20	20
50	15	15	10	10	10	10	10	10	10	10	10	10	15	0	0
0	0	0													
15	60	35	25	20	20	35	35	35	25	15	15	15	15	15	15
30	25	15	15	15	15	25	50	50	25	25	25	25	35	35	25
25	25	25	25	25	25	20	20	20	15	15	15	15	15	15	20
50	20	10	10	10	10	0	0	0	0	0	0	0	20	0	0
0	0	0													

15	50	20	0	0	15	35	35	25	25	15	0	0	0	15	20
30	45	0	0	0	0	20	50	50	20	0	0	0	25	40	20
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20
50	20	0	10	0	0	0	0	0	0	0	0	0	20	0	0
0	0	0													
15	50	15	0	0	10	30	25	20	20	15	0	0	0	0	15
30	45	0	0	0	0	20	50	50	20	0	0	0	25	40	20
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20
50	20	0	10	0	0	0	0	0	0	0	0	0	20	0	0
0	0	0													
10	50	15	0	0	10	30	25	20	20	15	0	0	0	0	10
30	45	0	0	0	0	20	50	50	20	0	0	0	25	40	30
30	25	20	15	10	10	10	10	0	0	0	0	0	0	0	20
50	20	0	10	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0													
10	50	15	0	0	10	30	25	20	15	15	0	0	0	0	10
25	45	0	0	0	0	20	50	50	20	0	0	0	15	15	15
15	15	15	15	0	0	0	0	0	0	0	0	0	0	0	20
50	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0													
10	20	10	0	0	10	30	25	0	15	15	0	0	0	0	10
20	0	0	0	0	0	15	40	40	15	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0													
10	20	10	0	0	10	30	20	0	15	15	0	0	0	0	10
15	0	0	0	0	0	15	40	40	15	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0													
10	20	10	0	0	10	50	15	0	15	15	0	0	0	0	10
10	0	0	0	0	0	15	40	40	15	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0													
10	20	10	0	0	10	50	10	0	0	0	0	0	0	0	10
10	0	0	0	0	0	15	15	30	30	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0													
0	15	10	0	0	10	30	10	0	0	0	0	0	0	0	10
10	0	0	0	0	0	15	15	30	30	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0													
0	15	10	0	0	10	25	10	0	0	0	0	0	0	0	10
10	0	0	0	0	0	15	15	15	55	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0													
0	15	10	0	0	10	20	10	0	0	0	0	0	0	0	10
10	0	0	0	0	0	0	0	15	55	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0													
0	15	10	0	0	10	20	10	0	0	0	0	0	0	0	0
10	0	0	0	15	15	15	15	15	55	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0													

E3

APPENDIX F: RIVER INFLOWS IN FILE 13

0	0	
2	34	-1470.
6	27	-49.
8	27	-49.
17	31	-105.
22	34	-1560.
40	15	-115.
62	14	-7800.
48	16	-14.
49	16	-14.
50	16	-14.
37	1	61.
1	0	
2	34	-1520.
6	27	-51.
8	27	-51.
17	31	-98.
22	34	-1550.
40	15	-110.
62	14	-6170.
48	16	-14.
49	16	-14.
50	16	-14.
37	1	48.
2	0	
2	34	-1370.
6	27	-52.
8	27	-52.
17	31	-95.
22	34	-1860.
40	15	-106.
62	14	-5070.
48	16	-13.
49	16	-13.
50	16	-13.
37	1	42.
3	0	
2	34	-1400.
6	27	-49.
8	27	-49.
17	31	-92.
22	34	-2290.
40	15	-103.
62	14	-5040.
48	16	-12.
49	16	-12.
50	16	-12.
37	1	39.
4	0	
2	34	-1330.
6	27	-49.
8	27	-49.
17	31	-91.
22	34	-1980.
40	15	-100.
62	14	-5140.
48	16	-12.
49	16	-12.
50	16	-12.
37	1	37.

APPENDIX G: WIND SPEED DATA IN FILE 14

		Wind Speed, m/sec					
		Norfolk Int'l Airport		Patuxent River Naval Station		Baltimore-Washington Int'l Airport	
DAY	HOUR	E-W	N-S	E-W	N-S	E-W	N-S
0	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0	1	-0.9927	-1.1831	-3.1208	-1.8018	-2.0592	-3.5666
0	2	-0.4837	-0.1761	-3.1208	-1.8018	-2.0592	-3.5666
0	3	0.0000	0.0000	-3.6035	0.0000	-3.0418	-0.5364
0	4	-0.2682	-1.5209	-3.6035	0.0000	-3.0418	-0.5364
0	5	-1.3375	-0.7722	-3.6035	0.0000	-3.0418	-0.5364
0	6	-2.2291	-1.2870	-2.6472	3.1548	-2.5348	0.4470
0	7	-3.1208	-1.8018	-2.6472	3.1548	-2.5348	0.4470
0	8	-3.5666	-2.0592	-2.6472	3.1548	-2.5348	0.4470
0	9	-3.0418	-0.5364	-2.7605	2.3163	-1.9854	2.3661
0	10	-4.1183	0.0000	-2.7605	2.3163	-1.9854	2.3661
0	11	-4.0558	0.7151	-2.7605	2.3163	-1.9854	2.3661
0	12	-4.1183	0.0000	0.0000	2.0592	-0.6257	3.5488
0	13	-3.3090	3.9435	0.0000	2.0592	-0.6257	3.5488
0	14	-2.4187	0.8803	0.0000	2.0592	-0.6257	3.5488
0	15	-2.0279	0.3576	0.0000	0.0000	-0.3576	2.0279
0	16	-2.5740	0.0000	0.0000	0.0000	-0.3576	2.0279
0	17	-2.4187	0.8803	0.0000	0.0000	-0.3576	2.0279
0	18	-2.3661	1.9854	0.0000	-2.0592	0.9927	1.1831
0	19	0.0000	0.0000	0.0000	-2.0592	0.9927	1.1831
0	20	-0.2682	1.5209	0.0000	-2.0592	0.9927	1.1831
0	21	2.6749	1.5444	-0.3576	-2.0279	0.0000	2.0592
0	22	1.9718	1.6545	-0.3576	-2.0279	0.0000	2.0592
0	23	1.2870	2.2291	-0.3576	-2.0279	0.0000	2.0592
0	24	1.6545	1.9718	0.0000	0.0000	-0.3576	2.0279
1	1	0.6618	0.7887	0.0000	0.0000	-0.3576	2.0279
1	2	0.0000	0.0000	0.0000	0.0000	-0.3576	2.0279
1	3	0.0000	0.0000	0.0000	0.0000	-0.8045	4.5627
1	4	0.0000	0.0000	0.0000	0.0000	-0.8045	4.5627
1	5	0.0000	0.0000	0.0000	0.0000	-0.8045	4.5627
1	6	0.0000	0.0000	0.3364	3.0418	0.0000	6.1775
1	7	0.0000	0.0000	0.3364	3.0418	0.0000	6.1775
1	8	-1.3236	1.5774	0.3364	3.0418	0.0000	6.1775
1	9	-0.4470	2.5348	1.9854	2.3661	-1.5846	4.3537
1	10	0.0000	3.6035	1.9854	2.3661	-1.5846	4.3537
1	11	0.6257	3.5488	1.9854	2.3661	-1.5846	4.3537
1	12	-0.5364	3.0418	2.7605	2.3163	-1.4085	3.8700
1	13	-0.5364	3.0418	2.7605	2.3163	-1.4085	3.8700
1	14	1.4085	3.8700	2.7605	2.3163	-1.4085	3.8700
1	15	0.8803	2.4187	1.2870	2.2291	0.0000	4.1183
1	16	0.0000	2.5740	1.2870	2.2291	0.0000	4.1183
1	17	0.4470	2.5348	1.2870	2.2291	0.0000	4.1183
1	18	0.0000	2.0592	0.0000	0.0000	-1.2325	3.3862
1	19	-0.7043	1.9350	0.0000	0.0000	-1.2325	3.3862
1	20	-0.3576	2.0279	0.0000	0.0000	-1.2325	3.3862
1	21	-0.8803	2.4187	0.0000	0.0000	-2.5740	4.4582
1	22	-0.5282	1.4512	0.0000	0.0000	-2.5740	4.4582
1	23	-0.5282	1.4512	0.0000	0.0000	-2.5740	4.4582
1	24	-0.5282	1.4512	-2.4187	-0.8803	-3.1548	2.6472
2	1	-0.7887	0.6618	-2.4187	-0.8803	-3.1548	2.6472
2	2	0.0000	0.0000	-2.4187	-0.8803	-3.1548	2.6472
2	3	-1.3375	0.7722	0.7043	-1.9350	-4.8374	1.7607
2	4	-1.3375	0.7722	0.7043	-1.9350	-4.8374	1.7607
2	5	-1.9718	1.6545	0.7043	-1.9350	-4.8374	1.7607
2	6	-0.6618	0.7887	-1.0564	2.9025	-3.1548	2.6472
2	7	-1.7833	1.0296	-1.0564	2.9025	-3.1548	2.6472
2	8	-0.9675	0.3521	-1.0564	2.9025	-3.1548	2.6472
2	9	-1.7833	1.0296	-2.9025	-1.0564	-3.1208	1.8018
2	10	-1.7833	1.0296	-2.9025	-1.0564	-3.1208	1.8018
2	11	-1.7833	1.0296	-2.9025	-1.0564	-3.1208	1.8018

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H1

APPENDIX I: TIDE DATA AT THE OCEAN BOUNDARY IN FILE 16

<u>Hr</u>	<u>min</u>	<u>sec</u>	Water Surface <u>El. cm</u>
0	0	0	0.00
1	0	0	20.66
2	0	0	42.37
3	0	0	45.42
4	0	0	43.89
5	0	0	37.49
6	0	0	20.42
7	0	0	1.52
8	0	0	-5.79
9	0	0	-7.01
10	0	0	-6.71
11	0	0	11.58
12	0	0	27.43
13	0	0	45.42
14	0	0	57.91
15	0	0	65.53
16	0	0	66.14
17	0	0	56.69
18	0	0	45.42
19	0	0	29.87
20	0	0	12.80
21	0	0	-2.13
22	0	0	-7.92
23	0	0	-4.27
24	0	0	5.79
25	0	0	19.20
26	0	0	34.44
27	0	0	45.11
28	0	0	47.24
29	0	0	44.50
30	0	0	35.97
31	0	0	21.64
32	0	0	7.01
33	0	0	-4.27
34	0	0	-7.92
35	0	0	-5.49
36	0	0	6.40
37	0	0	23.77
38	0	0	42.98
39	0	0	57.61
40	0	0	67.36
41	0	0	67.67
42	0	0	63.70
43	0	0	53.64
44	0	0	34.14
45	0	0	13.72
46	0	0	-1.52
47	0	0	-4.88
48	0	0	-1.52
49	0	0	8.23
50	0	0	24.38
51	0	0	39.32
52	0	0	49.38
53	0	0	58.52
54	0	0	55.47
55	0	0	44.50
56	0	0	29.57
57	0	0	12.19
58	0	0	-1.83
59	0	0	-10.06

APPENDIX J: INITIAL TEMPERATURE FIELD IN FILE 17

[illegible]

J2

J3

J4

J5

J6

APPENDIX K: EQUILIBRIUM TEMPERATURE AND SURFACE
HEAT EXCHANGE COEFFICIENT IN FILE 19

<u>Day</u>	<u>Hr</u>	<u>Temp</u> <u>°C</u>	Surface Heat Exchange
			<u>Coef. watts/m²/°C</u>
0	0	24.20000	0.99663E-03
1	0	23.60000	0.75046E-03
2	0	27.20000	0.47800E-03
3	0	26.00000	0.10779E-02
4	0	28.70000	0.83172E-03
5	0	28.80000	0.98946E-03
6	0	29.40000	0.66442E-03
7	0	23.40000	0.66681E-03
8	0	26.50000	0.59989E-03
9	0	26.90000	0.70505E-03
10	0	25.80000	0.10086E-02
11	0	25.40000	0.10253E-02
12	0	21.30000	0.10373E-02
13	0	17.10000	0.11042E-02
14	0	18.10000	0.91059E-03
15	0	19.40000	0.71461E-03
16	0	22.30000	0.78392E-03
17	0	22.60000	0.70744E-03
18	0	23.40000	0.11783E-02
19	0	23.40000	0.14483E-02
20	0	20.80000	0.15057E-02
21	0	12.90000	0.11114E-02
22	0	15.40000	0.50190E-03
23	0	15.70000	0.53297E-03
24	0	20.60000	0.32265E-03
25	0	18.20000	0.31787E-03
26	0	21.30000	0.44693E-03
27	0	17.50000	0.96536E-03
28	0	14.50000	0.13121E-02
29	0	16.90000	0.13958E-02
30	0	20.80000	0.53536E-03
31	0	19.90000	0.46127E-03

APPENDIX L: TIME-VARYING VERTICAL DISTRIBUTIONS OF SALINITY
AND TEMPERATURE AT THE OCEAN BOUNDARY IN FILE 76

```

0      0
5      4 28.30 28.30 28.30 28.30
5      4 24.90 24.90 24.90 24.90
1      4 28.30 28.30 28.30 28.30 28.30 29.50 29.50 29.50 29.50 29.50 29.50
1      4 25.00 25.00 25.00 25.00 25.00 23.00 23.00 23.00 23.00 23.00 23.00
2      4 28.30 28.30 28.30 28.30 28.30 29.50 29.50 29.50 29.50 29.50 29.50
2      4 24.90 24.90 24.90 24.90 24.90 23.00 23.00 23.00 23.00 23.00 23.00
3      4 28.30 28.30 28.30 28.30 28.30 29.50 29.50
3      4 24.90 24.90 24.90 24.90 24.90 23.00 23.00
4      4 28.30 28.30 28.30 28.30
4      4 24.90 24.90 24.90 24.90
5      4 28.30 28.30 28.30 28.30
5      4 24.90 24.90 24.90 24.90
0      12
5      4 27.60 27.60 27.60 27.60
5      4 24.90 24.90 24.90 24.90
1      4 27.60 27.60 27.60 27.60 27.60 28.80 28.80 28.80 28.80 28.80 28.80
1      4 24.90 24.90 24.90 24.90 24.90 22.90 22.90 22.90 22.90 22.90 22.90
2      4 27.60 27.60 27.60 27.60 27.60 28.80 28.80 28.80 28.80 28.80 28.80
2      4 24.90 24.90 24.90 24.90 24.90 22.90 22.90 22.90 22.90 22.90 22.90
3      4 27.60 27.60 27.60 27.60 27.60 28.80 28.80
3      4 24.90 24.90 24.90 24.90 24.90 22.90 22.90
4      4 27.60 27.60 27.60 27.60
4      4 24.90 24.90 24.90 24.90
5      4 27.60 27.60 27.60 27.60
5      4 24.90 24.90 24.90 24.90
1      0
5      4 28.20 28.20 28.20 28.20
5      4 25.20 25.20 25.20 25.20
1      4 28.20 28.20 28.20 28.20 28.20 29.70 29.70 29.70 29.70 29.70 29.70
1      4 25.20 25.20 25.20 25.20 25.20 23.80 23.80 23.80 23.80 23.80 23.80
2      4 28.20 28.20 28.20 28.20 28.20 29.70 29.70 29.70 29.70 29.70 29.70
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