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Casco Bay Maine: Circulation Modeling

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Casco Bay, Maine: Circulation Modeling

By

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CHAPTER 1

INTRODUCTION

This report is intended as a shortened and largely non-technical version of the report "Casco Bay, Maine - Circulation Modeling" by Bin Gong, Bryan Pearce, and Neal Pettigrew (CBM) (1995). The purpose of the study was to provide a numerical model for the water flows in the Casco Bay region and to provide a few test cases. Neither document is intended as a treatise on the flows in Casco Bay. By its nature this process is technical and the original report presents the information that a knowledgeable user would require to repeat or expand on the numerical experiments already performed for Casco Bay. Material that is important for the conceptual understanding of the modeling process has been left in this version of the report. Also, since this report is about a computer simulation some essential references to model details have been included.

1.1 Study Area

Casco Bay was designated an estuary of national significance and included in EPA's National Estuary Program in the April of 1990. A five-year plan, the Casco Bay Estuary Project was created with the long-term goals of providing a comprehensive evaluation of pollution problems and development of an area-wide plan for environmental protection. The topography of the Gulf of Maine and the location of the Casco Bay region are shown in Figure 1.1. The contours are water depths, in meters, referenced to mean sea level. Tide-producing forces are the most important factors driving the circulation in Casco Bay. The M_2 component (semi-diurnal) has the largest magnitude. "The tides of Casco Bay dominate the circulation and continuously affect the distribution of properties found within it." (Parker, 1982)

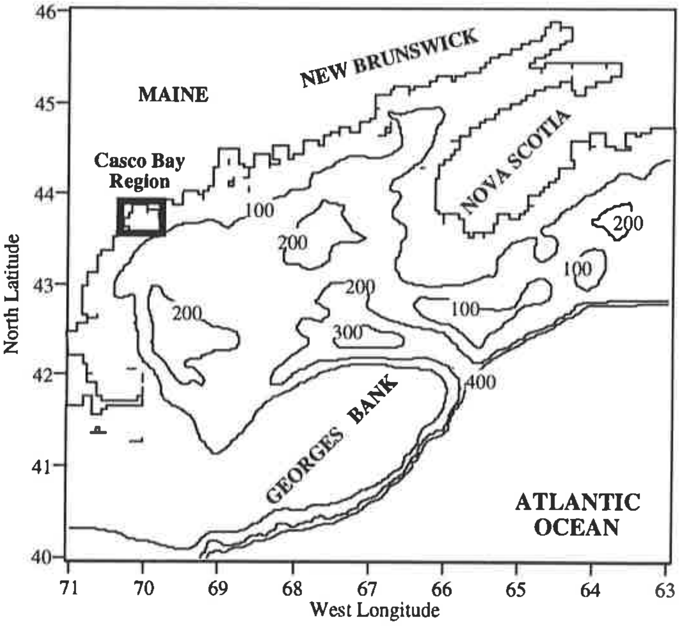


Figure 1.1 - Gulf Of Maine

Casco Bay includes the water body formed by Cape Small to the northeast and Cape Elizabeth to the southwest, with dimensions of approximately 20 by 40 kilometers (see Figure 1.2). Casco Bay receives freshwater from rivers, such as the Kennebec, the Royal, and the Presumpscot. Their discharges vary seasonally with the Kennebec River the largest. Although the Kennebec River is located to the east of Cape Small, outside of Casco Bay, the freshwater discharge may affect and partially flow into Casco Bay. In particular, data by Pettigrew (in press) indicate, at times, the occurrence of a freshwater pool west of Cape Small. The average freshwater discharge in 1992 was about 400 m^3/s. However, during the spring seasons of 1992 and 1993, peak discharges of 3000 m^3/s and 4000 m^3/s were observed, respectively (Figure 1.3). In order to consider the influence, the eastern boundary of the study area includes the mouth of the Kennebec River. The southern and southeastern boundaries were set to match the hydrographic cruises of 1992 and 1993 (Pettigrew, 1992 and 1993). Thus, the study area is enclosed by the coastline of Casco Bay and the thick gray line in Figure 1.2, which indicates the ocean boundary of the study area.

The topography of the Casco Bay region is complex as shown in Figure 1.2. The depths increase from the northwest to the southeast. The average depth at the inner bay area, Maquoit and Middle Bays, is only about 6 meters and over the entire Casco Bay region about 27 meters. From Portland Harbor to Maquoit and Middle Bays, the many islands make the topography even more complex. The orientation of these islands is from southwest to northeast, the same as that of Maquoit and Middle Bays. In this area, the water depths change abruptly. In the wide open Casco Bay basin, near the letters "Casco Bay" in Figure 1.2, the sea bottom is relatively flat and the water depth is around 40 meters. Another important feature is the deep narrow channel, Broad Sound, which connects the inner bays with the Casco Bay basin. The average depth there is over 20 meters.

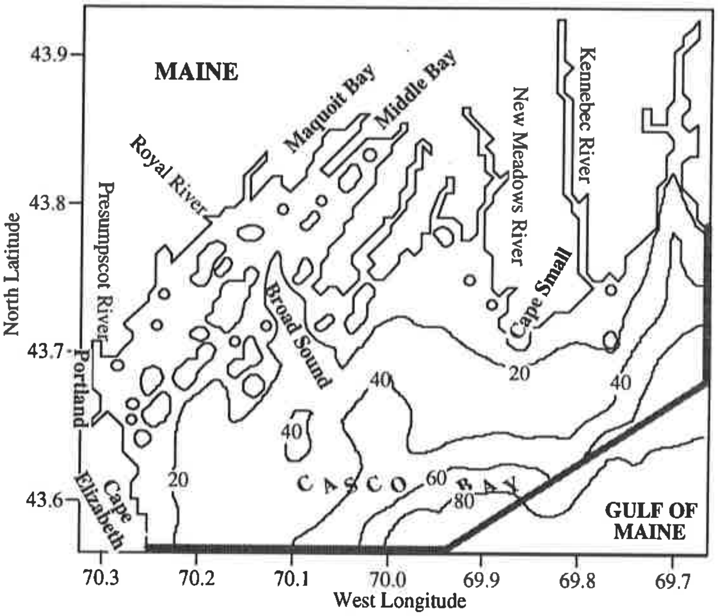


Figure 1.2 - Casco Bay Region

1.2 Project Requirements

Due, in part, to a lack of field data in the region, a hydrodynamic numerical model was proposed. This model could be used to describe water movement in the Casco Bay. This model would have a variety of applications, such as, the fate and transport of floating, dissolved, and suspended pollutants.

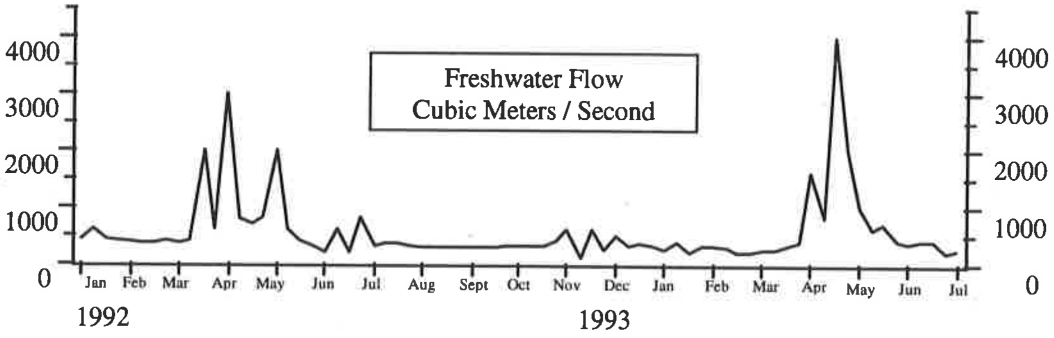


Figure 1.3 - Freshwater Transport for the Kennebec River

The development of a new hydrodynamic model was neither feasible nor necessary because of the availability of documented hydrodynamic numerical models. The hydrodynamic numerical model for Casco Bay had several requirements. First, due to the abrupt bathymetry in the inner bays and Portland Harbor, a model that includes the convective or non-linear terms was needed. In fact, considerable effort was needed to make the model run effectively in Casco Bay using these terms. This will be discussed in more detail in Chapter 3.

Secondly, to incorporate the freshwater influence and resultant density distribution at the mouth of the Kennebec River, a three-dimensional model was needed. That means the model includes the calculations of the horizontal velocities for all the grids at all the layers. An easy way to simulate the continuously changing density and horizontal components of water velocity along the vertical direction is to uniformly divide the distance from the sea surface to the bottom into several layers.

The third requirement was that the model should also be prognostic because of the need to calculate the density distribution caused largely by the freshwater inflows. The term "prognostic" means that the model calculates the density field through time. A related term is diagnostic, which is to calculate the density-driven velocities due to an unchanging density field. Because of the large freshwater inputs, the Kennebec River was selected as a test for the prognostic capability of the Casco Bay model.

Maquoit and Middle Bays are embayments inside Casco Bay with large areas of tidal flats. At the northern ends of these bays, the tidal flats will be dry at low tide, and flooded at high tide. To properly simulate these phenomena it is necessary to have a model which includes flooding and drying. Without flooding and drying shallow depths can cause unrealistically large currents and consequent stability problem. These bays were selected for more detailed study because of the practical interest in determining the role of flushing relative to the low oxygen conditions and massive Menhaden and shell fish mortality that sometimes occurs during the summer months.

Having established the model requirements it was then necessary to select a numerical model. This selection is discussed in Section 1.4. Once selected, the model needed to be "set up" for the Casco Bay region. In this step, various model parameters, such as the viscosities and drag coefficients, are determined by comparing, as well as possible, the model results with known data.

1.3 Field Data

Hydrodynamic numerical models are developed to simulate the movement of fluid using partial differential equations. Because of the complexities of the hydrodynamic processes, it is best to think of a model as interpolating and extrapolating from known data. Accurate calculations always involve the stipulation of one or more "parameters" that must be specified. The availability of prototype or field data allows these "parameters" to be specified so that the model output agrees with the data. Initial and boundary conditions, which provide the unique information needed for an individual simulation.

The only tidal current data available in Casco Bay can be found in Parker (1982). This report "provides pertinent data on the marine system for the prediction of oil spill movements and contains information on the tidal and non-tidal currents." Most of the data was taken to the west of 70°00'W in Casco Bay and there is no data in Maquoit and Middle Bays. This data set also includes data taken by NOAA current meters in the same region near the sea bottom in 1979. While covering only a subset of the area covered by the Casco Bay model, this data set represents our only resource for comparisons with prototype data and a comparison to the current data at several sites and at different layers is presented in Chapter 4. Further analysis of the Parker study can be found in the data report (Pettigrew, et al, in press).

As part of the Casco Bay Estuary Project, Pettigrew collected water densities during the hydrographic cruises of 1992 and 1993 (Pettigrew et al. In press). These density data were necessary to provide density conditions at the ocean boundary of the model as well as initial conditions to start the Casco Bay Model. In particular, any attempt to calculate the densities inside the modeled areas must include a description of the heat and salt fluxes into and out of the domain as a function of time. Based on these measurements, an estimate of the conditions for an average tidal cycle during the high spring runoff period was created and used in developing the simulation. This is discussed further in Chapter 4. No additional current data were collected during these cruises.

1.4 Choice of Numerical Models

Several hydrodynamic numerical models were currently available. One is the "Mellor-Blumberg model" described in "A Description of A Three-dimensional Coastal Ocean Circulation Model" by Blumberg and Mellor (1987). One version of this model has been placed in the public domain by Prof. George Mellor at Princeton University. The model is: three-dimensional; uses the primitive equations; is time-dependent; uses a σ-coordinate system; has a free surface; and is used primarily for ocean circulation. The model uses a standard finite-difference numerical scheme.

MECCA (Model for Estuarine and Coastal Circulation Assessment) was developed by Kurt W. Hess (1989) at the National Oceanic and Atmospheric Administration to study environmental impacts on sensitive marine areas and to assess the use of satellite data for estuarine research. MECCA differs from Blumberg and Mellor's model in that: 1) its turbulence parameterization is simpler; 2) it contains switches for eliminating certain terms in the equations; 3) its density equation is simpler; 4) the horizontal diffusivities are constant over depth; and 5) it contains a side friction term for subgrid channels.

MECCA has been applied to Chesapeake Bay for studying salinity and temperature distribution (Hess, 1986). This model has also been applied to Cobscook Bay, Maine by Brooks (1992). The application by Brooks did not include the convective terms as the model did not operate correctly with these terms "turned on". At that time the reasons were not apparent. During the course of our investigation these problems have been corrected and are discussed in Chapter 3. These modifications to MECCA required a substantial investment of time and effort and in the end dictated that a larger portion of the project effort be directed to solve this and other numerical problems.

A third model was considered by the project team, 3DENS (3-D Density driven, Sucsy et al, 1993). 3DENS differs largely in that it uses continuous functions in the vertical direction instead of layers as in MECCA and the Mellor Model. Also, 3DENS has been implemented to calculate densities only on a diagnostic basis.

The final decision by the Casco Bay Estuary Project was to implement MECCA.

CHAPTER 2
MODEL APPLICATION TO CASCO BAY

2.1 About the Models

Because MECCA is implemented for the Casco Bay simulation, a brief explanation is included about what MECCA is and how MECCA works. Another model, 3DENS, will also be briefly discussed. In addition to the information presented here, the reader should also refer to the reports referenced in the bibliography, for both MECCA and 3DENS.

2.1.1 MECCA

MECCA is a three-dimensional, time-dependent, prognostic, hydrodynamic numerical model with a semi-implicit numerical scheme (ADI). Implicit methods typically use more computer storage and are computationally more expensive per time step. The allowable time step is larger, however, allowing a solution with fewer time steps.

The driving forces for MECCA are tide, wind, water density, and air pressure. The basic equations used in MECCA are established in a right-hand (x,y,z) Cartesian coordinate system. A description of the equations is included in the CBM report. By defining a new vertical coordinate σ (Phillips, 1957), or q, as Hess used, as:

$$q = \frac{z - h}{H}, \qquad \text{in which} \qquad H = d + h,$$

where h is the water elevation referenced to mean sea level and d is the distance from the mean sea level to sea bottom (Figure 2.1), all the equations in the (x,y,z) system are transformed into the (x,y,q) or σ-system. In this σ-system, the dimensionless coordinate q, varies from 0 at the ocean surface ($z = h$) to -1 at the ocean bottom ($z = -d$). This transformation greatly simplifies three-dimensional models and saves computational effort. It essentially means that all parts of the model have the same number of layers and that the layers in shallow water are thinner than in deep water. However, the use of this mapping may lead to errors in areas which contains abrupt bathymetry and strong stratification. Mellor (Mellor et. al, 1994) indicates that these errors, especially in coastal areas are small.

A mode-splitting technique is used in MECCA. In practice this means that the calculations for the water surface are carried out with the vertically averaged equations at each external time step (which is usually much smaller than the internal time step). The internal mode then calculates the vertical variation of water velocity and density. With this separation, it is not necessary for the internal mode to be updated as frequently as the external mode. This separation results in savings in computational effort and makes it possible to carry out a three dimensional simulation with reasonable computer effort.

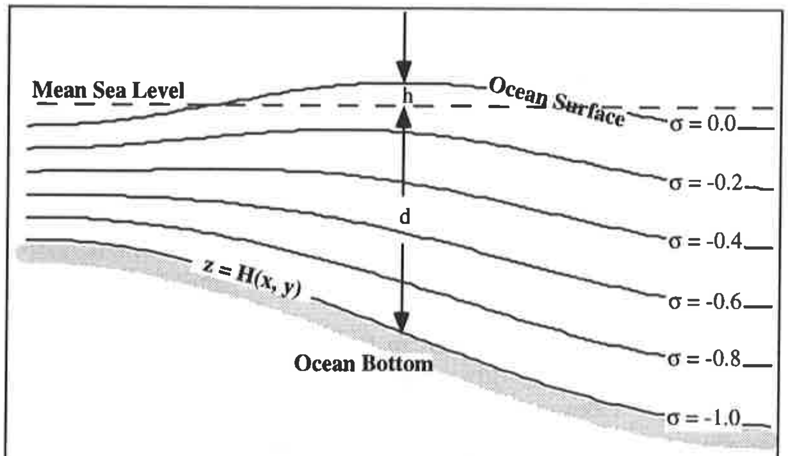


Figure 2.1 - Sigma Coordinate System

The MECCA computational procedure is outlined in Figure 2.2. The INITIAL PHASE gets the model started by establishing the grids and water depths as well as starting values for concentration, velocity, and tidal height. Once the model is started then the ITERATIVE PHASE of MECCA continues until a simulation of the desired duration has been carried out. The OUTPUT PHASE of MECCA will create the files containing the information calculated by MECCA.

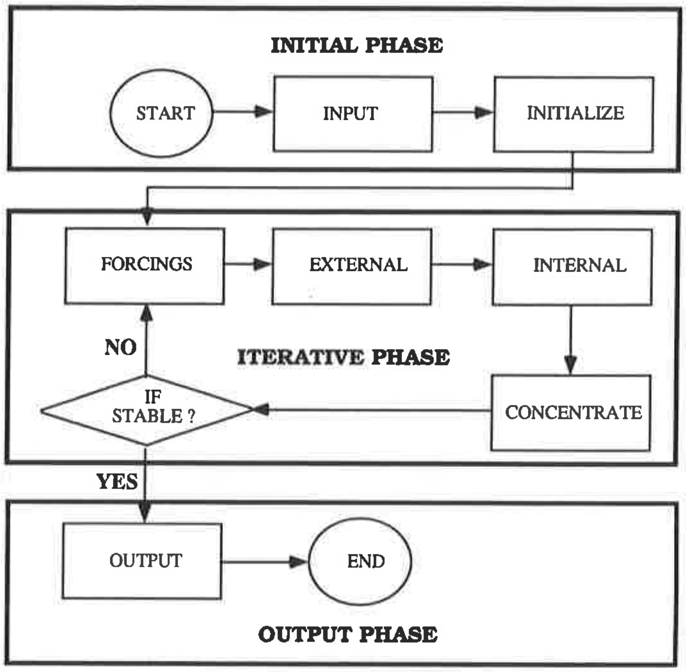


Figure 2.2 - MECCA Flow Chart

2.1.2 Model **3DENS**

To apply MECCA, as a tidal model, to Casco Bay, the tidal information is required at the open ocean boundary, the thick gray line in Figure 1.2. This was provided by the model 3DENS. 3DENS solves the three-dimensional shallow water equations of motion forced by tide, wind, river flow, and gradients of density. 3DENS calculates vertical profiles of horizontal velocity using the Galerkin method.

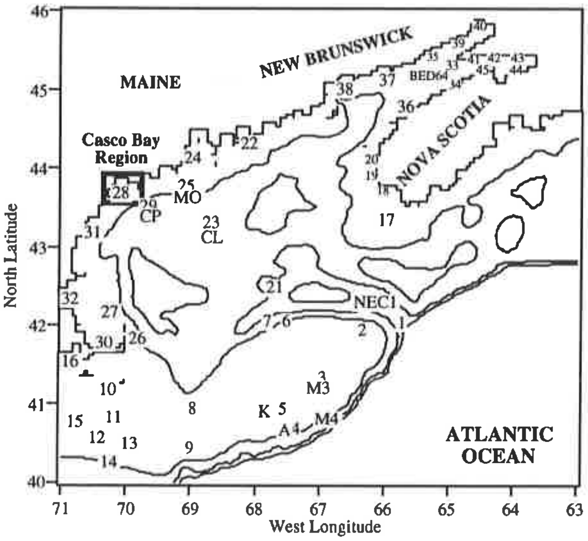


Figure 2.3 - Location of Sites for Tidal Data Comparisons in the Gulf of Maine

3DENS has been tuned for the entire Gulf of Maine by comparing data at approximately 50 stations inside the Gulf of Maine (Figure 2.3). The numbered stations are locations of M_2 elevation data and the lettered stations are locations of velocity data. Figure 2.4 shows the correlation of observed and calculated amplitudes of the M_2 component in the Gulf of Maine. A perfect match with data would lie along the line $y = x$. The RMS error of amplitudes and phases for all these locations in the Gulf of Maine and Bay of Fundy was 7.9 cm and 6° for 3DENS running in a two dimensional mode. 3DENS run as a three-dimensional model provided rms. errors of similar magnitude.

This is discussed in more detail in Section 2.5. For detailed information about model 3DENS, see "3DENS -- A Three-dimensional Tide and Wind Model for Coastal Applications" (Sucsy et al., 1993) and "Comparison of Two- and Three-Dimensional Model Simulation of the Effect of a Tidal Barrier on the Gulf of Maine Tides" (Sucsy, 1993).

2.2 Casco Bay Model Grid

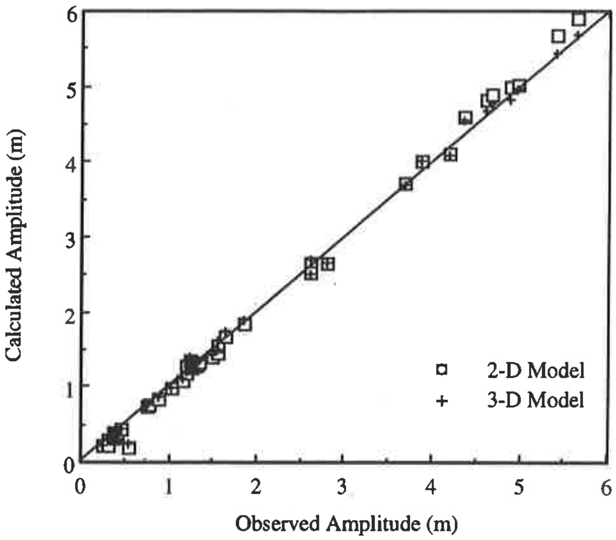


Figure 2.4 - Comparison of Observed and Calculated Tidal Amplitudes For the Gulf of Maine

The modeled region includes Casco Bay with the eastern boundary extended to include the mouth of the Kennebec River (Figure 1.2). In this region, a grid with fixed sizes in x-, y-, and q-directions (vertical) is required. The sizes are denoted as ΔX, ΔY, and Δq, respectively. The origin of the (x, y, q) system is set at the upper-left corner and at mean sea level with positive x southward, positive y eastward, and positive q upward (Here we follow Hess's orientation). The grid size should be able to reflect the detailed variation of topography at the desired resolution. However, the grid size shouldn't be so small that the computational cost is prohibitive. In consideration of the islands in the western part of the bay, 600 meter was set as the grid size in the horizontal plane, i.e., $\Delta X = \Delta Y = 600$ meters (both are denoted as ΔL). This grid was overlaid on the NOAA charts for the Casco Bay region, which include NOAA Charts 13290 (Casco Bay), 13293 (Damariscotta, Sheepscot, and Kennebec Rivers), and 13288 (Monhegan Island to Cape Elizabeth). A total of 80×69 cells were needed to cover the modeled region. The average water depth at each cell was recorded by hand. The NOAA charts are referenced to Mean Lower Low Water. MECCA requires the water depth referenced to mean sea level, and the water depths were adjusted to Mean Sea Level . The elevations of Mean Higher High Water minus Mean Lower Low Water as indicated on the charts are as follows:

Small Point Harbor	(43°44'N, 69°51'W)	9.5 ft
Cundy Harbor	(43°47'N, 69°54'W)	9.6 ft
Harpswell Harbor	(43°47'N, 70°00'W)	9.7 ft
South Freeport	(43°49'N, 70°06'W)	9.7 ft
Portland	(43°40'N, 70°15'W)	9.9 ft.

The average Mean Higher High Water for these five stations is 9.68 ft. The water depths were adjusted from Mean Lower Low Water to Mean Sea Level by adding 4.84 ft (half of 9.68 ft).

The number of layers must be specified before running the model. On one hand, too few layers will not provide a sufficiently detailed vertical velocity profile , especially in the inner bays where the water depths change abruptly between adjacent model cells. On the other hand, too many layers will require prohibitive computational facilities. As a compromise between computational effort and a detailed vertical profile of velocity, 10 layers were chosen. Thus, the vertical resolution, Δq, is 0.1. If the water depth is 10 meters, then the thickness of each layer is $0.1 \times 10 = 1$ m; if the water depth is 100 meters, then the thickness of each layer is $0.1 \times 100 = 10$ m. The thickness of a layer can vary considerably from inner bays to the Casco Bay basin.

2.3 Flag Information

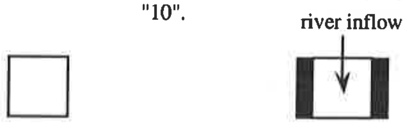
Each cell in the grid can be categorized by its type. These types include water cells, land cells, ocean boundary cells, and river boundary cells. To distinguish the types, each cell is provided with indices and a type identifier. Three integers, M, N, and L, are used as the spatial coordinates in the x-, y-, and q-directions, respectively. For example, M refers to the number of cells from the origin in the x-direction and N in the y-direction. L is the number of layers from the sea surface. In the Casco Bay Model, M ranges from 1 to 69, N from 1 to 80, and L from 1 to 10.

Each cell needs an identifier to indicate whether it is a land cell, a water cell, a river cell, or an open ocean boundary cell. This is called status or flag information. The identifiers follow the rule (Figure 2.5):

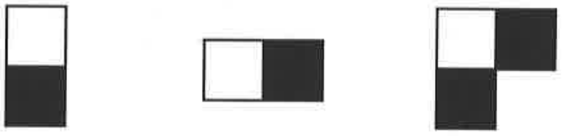
"0"	for a land cell;
"10"	for a half land cell;
"20"	for a water cell (not include boundary);
"50"	for an open ocean boundary cell; and
"60"	for a river boundary cell.

In addition, for a non-land cell: if the next cell in the positive x-direction is a land cell, the identifier for this non-land cell will be increased by 1 (Figure 2.5f); for the positive y-direction, 2 will be added (Figure 2.5g); if for both the positive x- and y-directions, there are land cells adjacent to the non-land cell, 3 will be added (Figure 2.5h). The purpose of the second digit in the flag type is to alert the model to the presence of the land boundary. Generally these 1, 2, and 3's can be automatically dealt with in MECCA. When dealing with half land cells, breakwaters, or flow constraints, however, the user must specify the identifiers.

a) A land cell with an identifier "0". b) A half land cell with an identifier "10". c) A water cell with an identifier "20".



d) An ocean boundary cell with an identifier"50". e) A river cell with an identifier "60".



f) A water cell with an identifier "21". g) A water cell with an identifier "22" h) A water cell with an identifier "23".

Figure 2.5 - Grid Cell Identifiers

2.4 Initial Conditions

MECCA requires initial conditions to begin the time-stepping process. Velocities and water elevations at interior cells are set to zero. Initial concentrations for the model interior are interpolated from the ocean boundary values. Clearly, specification of actual concentrations would lead to a superior short term result on the one hand and would be irrelevant for a long term simulation (if the real world remains static long enough) on the other. In lieu of actual data and recognizing the need to continue with the project, the default extrapolation in MECCA was used to specify the initial interior densities.

2.5 Boundary Conditions

2.5.1 Ocean Boundary Conditions

At an ocean boundary either the water elevation or a radiation condition must be specified. The typical water elevation can be set as a function of time or t:

$$h(t) = h_0 \times \cos(2\pi t/T - g),$$

where h_0 and g are the amplitude and phase, and T is the period of the tide. For the simulation of tidal-driven circulation in the Casco Bay region, only the M_2 component has been considered. Examination of tide data in the region shows that by far this is the dominant component (Sucsy et al., 1993). The reader should note that the Gulf of Maine and Bay of Fundy system is resonant with the M_2 component accounting for the dominance in the area. Thus, T in the above equation is set to 12.42 hours.

The open ocean boundary conditions of the tide (phase and amplitude) for Casco Bay were obtained from the model 3DENS. To establish the boundary conditions for the Casco Bay model, 3DENS was run for 20 simulated days. The data from the first five days were ignored to avoid the transient solution. A harmonic analysis of the rest of the computational data provided the amplitude and phase of the M_2 component for the entire Gulf of Maine (Figure 2.6). The grid size for the Gulf of Maine simulation was 5 by 5.5 kilometers, more than eight times of that of the Casco Bay model. From these data, the values at the ocean boundary cells for the Casco Bay region were interpolated.

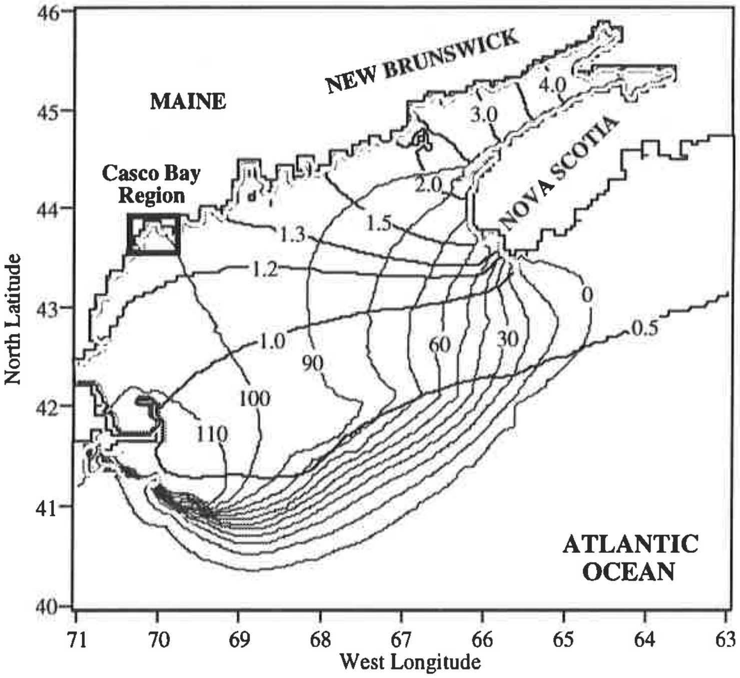


Figure 2.6 - Cotidal Lines M2 Component

Another condition is available at the ocean boundary. For cases when the surface elevation can not be specified, a radiation condition can be applied. A "radiation condition" allows the wave energy inside the model to radiate through the boundary. This is important as it prevents the energy from being trapped inside the model and causing unrealistic solutions or problems with stability.

The density at the ocean boundary is a function of whether the flow is from inside the model to the outside or vice versa. For flow leaving the model the concentration is specified as a function of the concentration at the cells immediately upstream of the boundary cell. For flow entering the model, the concentration is ramped from the last outflow value over a six hour period to the user specified ocean boundary condition at that location. For a detailed description of this, see page I-16, MECCA Documentation (Hess, 1989). The density field data collected from the hydrographic cruises of 1992 and 1993 were used to specify the ocean boundary condition.

2.5.2 River Boundary Condition

A volumetric discharge, Q, into the model region must be provided. At the Kennebec River, the volumetric discharge can be specified according to Figure 1.3. In our simulation, the peak value of 8000 m^3/s was used. The salinity was set to be 1.0 ppt, which was observed during the hydrographic cruises (Pettigrew, et al, 1994) at the mouth of the river during the time of peak flow.

2.5.3 Surface Boundary Condition

In order to include the effect of wind in the model it is necessary to provide for a wind stress at the surface. This is accomplished by specifying the wind speed and drag coefficients. MECCA defaults to a standard set of coefficients if none are provided as outlined in the CBM report.

2.5.4 Bottom Boundary Condition

Just as it is necessary to specify the surface "boundary condition" the user must also specify what friction coefficients are to be used at the bottom. There are two possible conditions. One is a slip condition in which the stresses are matched at the ocean bottom. The other is a no-slip condition in which the bottom velocities are zero. For the Casco Bay simulation the former condition, matching the stresses was used.

2.5.5 Land Boundary Condition

At land boundaries, the normal horizontal velocities are set to zero. The heat and salinity fluxes are also set to zero.

2.6 Parameters And Switches

The model parameters include time steps for both external and internal modes, horizontal and vertical viscosities, diffusivities, wind drag coefficient, bottom friction coefficient, etc. MECCA uses the alternating-direction-implicit (ADI) method for the external mode calculations. The ADI method can be shown to be unconditionally stable, for the linearized equations. The user must take care, however, that while stable the scheme can become inaccurate with sufficiently large time steps. Recent simulations of Casco Bay have been carried out with $\Delta t_{\text{model}} = 60$ seconds for the external mode. By comparison, a similar explicit method is numerically stable only if

$$\Delta t_e \leq \frac{\Delta X}{\sqrt{2gH_{\max}}}$$

where g is gravity, and $H_{\max}$ is the maximum depth in the model region. This equation provides for $\Delta t_e = 14$ seconds for conditions in Casco Bay: ($H_{\max} \cong 100$ m, and $\Delta X = 600$ m). The ratio of these two time steps, referred to as the Courant number, is $\Delta t_{\text{model}} / \Delta t_e = 60 / 14 \approx 4$. The solution is smooth and shows no sign of incipient instability (see Figure 2.7). Simple conservation of mass indicates that the solution is approximately correct. Comparisons to available current data are shown in Chapter 4.

For the internal mode calculations, the constraints on the time step are relaxed. Stability criteria for equivalent explicit methods with diffusion are given by Hess (1989) as:

$$\Delta T \leq \Delta T_i = \frac{\Delta z^2}{2A_v},$$

where Δz is the minimum distance between layers. Using values for the Casco Bay simulation: $\Delta z = 0.1$ m and $A_v = 0.003$ m^2/s, provides $\Delta T_i = 2$ seconds. This limit need not be adhered to rigidly for the implicit method. The time step actually used for the internal mode in the Casco Bay simulation was $\Delta T_{\text{model}} = 300$ seconds, 150 times of that for an explicit internal mode ΔT_i.

For concentration, the calculation is also implicit over the vertical. Leendertse and Liu (1975) reported a time step limitation for the analogous explicit scheme as:

$$\Delta T \leq \Delta T_c = \frac{\Delta z^2}{4D_v}.$$

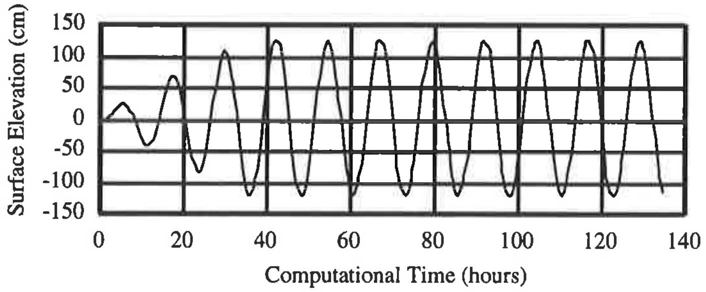
This condition is similar to the above but is much less severe because the coefficient, D_v, is much smaller than A_v. Using values for the Casco Bay simulation: $\Delta z = 0.1$ m and $D_v = 0.001$ m^2/s, we have that $\Delta T_c = 2.5$ seconds. The actual time step for the concentration for the Casco Bay simulation is the same as that for the internal mode, ΔT_{model}.

The horizontal viscosity, A_h, and diffusivity, D_h, are assumed to be equal in MECCA and the default value is 1.0 m^2/s. In fact, the value of these coefficients is usually higher. Numerical experience in Casco Bay showed that 1.0 m^2/s and 10.0 m^2/s both failed causing model instabilities. A value of 100.0 m^2/s was found to work and provide a smooth solution. To provide additional tuning it is necessary to have sufficient prototype velocity data which, currently, does not exist. For the wind-driven circulation calculation without tide at the open ocean boundary, the value of 100 m^2/s caused a difficult numerical instability while the value of 10000.0 m^2/s was found to be a working value. The increased horizontal viscosity is probably due to the fact that with near zero velocities the damping of the system is small and the large value of A_h was needed to provide sufficient damping to keep the system stable. In this case it is more reasonable to think of A_h as a parameter needed for numerical stability rather than a physical parameter. Remember, we are fundamentally using these models to extrapolate and interpolate existing data Also, a sensitivity study using intermediate values has not yet been carried out. This should be done. In addition, an examination of how the radiation boundary condition is functioning would be prudent as well.

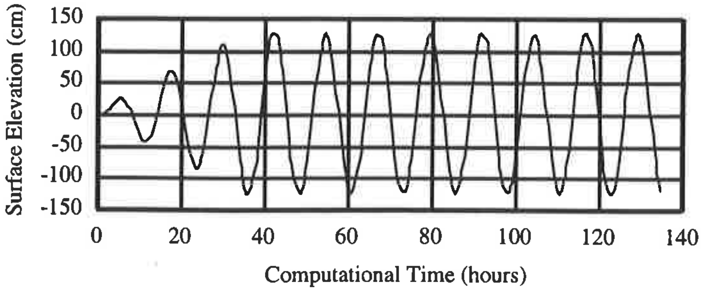
MECCA's default value for the vertical viscosity, A_v, is 0.003 m^2/s. In Casco Bay, that value was used for the tidal circulation. For wind-driven circulation, 0.125 m^2/s was used to increase the shear stresses between layers and provided a reasonable solution. The vertical diffusivity, D_v, was set to be 0.001 m^2/s, the default value in MECCA.

2.7 Test Runs

After the parameters have been set, test runs were undertaken. First, MECCA was run as a two-dimensional model. With reasonable results the switch "INTER" (for inner solution) was set to "TRUE" so that MECCA was to run as a three-dimensional model. As it turned out when the switch "IBETAA"(for the non-linear convective terms) was set to "FALSE", the model worked; if "IBETAA" was set to "TRUE", the model "crashed" after some time (usually around 30 simulated hours of computation). The calculated velocities resulted from an overflow condition (numbers too large for the computer to handle). To track down the problem causing the instability, the model parameters were adjusted in an attempt to find a stable solution. The parameters varied were: time step Δt, the horizontal viscosity A_h, the vertical viscosity A_v. The program still "crashed" for any reasonable set of parameters. At this point it became apparent that the problem must lie in those parts of the model involved with the calculation of the advection terms for the internal mode calculation.



a) Time series of tide at open ocean boundary.



b) Time series of tide at a location inside model area.

Figure 2.7 Computed Surface Elevation

The FORTRAN code was checked several times from beginning to end. The program was rewritten with indents so that the logical sequence could be easily followed. After several passes of line by line checking, a few minor errors were found and corrected. The model was run again as a three-dimensional model with the advection terms turned on. It still didn't work.

The next step was to check the original application of the program. An application for Chesapeake Bay, included with the original documentation was tested. When the switch "INTER" was turned off, the application ran well as a two-dimensional model. However, when the switches "INTER" and "IBETAA" were both turned on, the program, as a three-dimensional model, "crashed" in the same way we found in our application to Casco Bay. If the switch "INTER" was left on, but the switch "IBETAA" off, the program ran well. At this point, it became apparent that something might be wrong in the numerical scheme, not just the FORTRAN code.

The original documentation was checked line by line. By rederiving the finite difference numerical equations from the basic equations, several fatal errors were found. The following chapter will discuss them briefly. A more detailed analysis is provided in the Casco Bay report.

CHAPTER 3

MODIFICATIONS TO MECCA

In Casco Bay, the abrupt bathymetry and the mixing of freshwater from rivers with salt water from the Gulf of Maine require a three-dimensional simulation. Furthermore, the convective acceleration plays an important role in the physical mixing process. To use the convective acceleration terms in a three-dimensional application, it was necessary to modify the approach that MECCA uses with these terms. In addition, a variety of "bugs" have been found and fixed. This chapter briefly outlines changes that were necessary to run MECCA and shows, where appropriate, time-saving considerations. The following discussion is based on the MECCA Documentation (Hess, 1989) and the CBM report. A large portion of the project effort was spent in finding and making these corrections.

The first part of this chapter will be about the changes of the model input, the CONTROL file. Then the mistakes found in the derivation of numerical equations will be discussed. Following that, approximations made as part of the density calculations will be discussed. Finally, the calculation of flooding and drying was added to the MECCA program.

3.1 CONTROL File

To run MECCA, two input files are needed to provide all the necessary parameters, constants, and depth information. One is called the geography file, in which the grid dimension, grid size, boundary conditions, depth, and flag information are provided. The other file is called the control file, in which the time step, the number of layers, and turbulence variables are provided. To simplify the application of MECCA to Casco Bay, the depth data were separated from the geography file and stored in a new file "CASCO.DEP". The flag information was also separated from the geography file and stored in a new file called "CASCO.FLAG". The remains of the information in the geography and control files were combined into a file with the name of "CONTROL". An example of this file and the detailed description can be found in the CBM report.

3.2 Numerical Problems

As mentioned above, early attempts to run MECCA for Casco Bay, as a three-dimensional model with the convective or "non-linear" terms, showed problems with stability, that is, the model "crashed". Other attempts to run MECCA for Chesapeake Bay with exactly the same conditions provided by the MECCA documentation also showed the same stability problems. If the convective terms and the internal-mode were turned on, or used, the program would "hang" after some computational time. If either the convective terms or the internal-mode was turned off, the program would complete its computational routines. Comments by Brooks (1992) indicated similar problems. After considerable investigation of both the MECCA Documentation and the FORTRAN program, the problems were found with the non-linear terms in the internal-mode calculations. The problems were with the finite difference approximations to the governing equations and are discussed in the CBM report In addition to bug fixes, MECCA was modified to use upstream differencing in the concentration calculations.

3.4 Miscellaneous Problems

MECCA has some limitations which are described in APPENDIX D of the documentation (Hess, 1989). For example, the numbers of grid cells in the x- and y-directions are limited to not more than 60 (variable MMAX) and 40 (variable NMAX), respectively; the number of vertical layers ranges from 3 to 9 (variable LAYRS). In the Casco Bay Model, these limitations have been removed. The user can establish a dimensioning parameter according to their application. A grid of 80 by 69 with 10 vertical layers was used in the simulations of Casco Bay.

In the Casco Bay model, about one-third of the ocean boundaries are not on a straight line oriented in either the x- or y-direction. To represent this boundary, the original definition of ocean boundaries used in MECCA was changed. Instead of defining the ocean boundary along a line oriented in either the x- or y-direction, the ocean boundaries in the Casco Bay model are defined cell by cell. Some of the consequences of this change are discussed in the conclusions. There are 100 cells at the ocean boundary in the Casco Bay Model.

In addition to the above, the original version of MECCA lost or gained salt at land boundaries. This was due to the specification of a constant concentration at land boundaries. MECCA was modified to include a no flux boundary condition at the land boundaries to solve this problem.

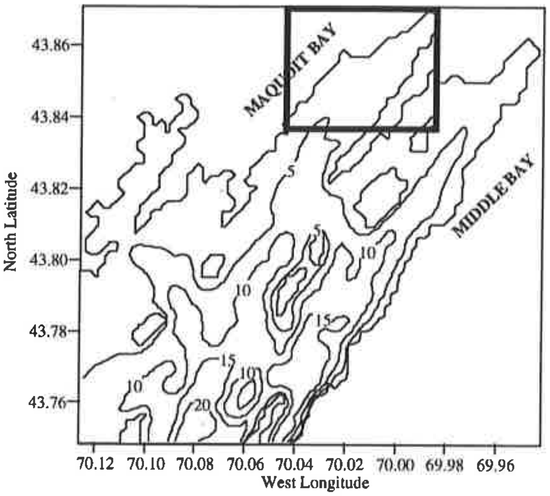


Figure 3.1 Maquoit and Middle Bays

3.5 Flooding and Drying

To adequately model Maquoit and Middle Bays, it is necessary to consider the flooding and drying phenomena. To do this, a new feature has been added to MECCA. In the FORTRAN code, a subroutine called SFLOOD has been supplied to include the flooding and drying calculation. The simulations in the Maquoit and Middle Bay will be discussed here by way of example.

In the Maquoit and Middle Bay model, the horizontal grid size is 250 by 250 meters. Figure 3.1 shows the bathymetry of Maquoit and Middle Bays and the test area for flooding and drying (bold rectangle). The contours are of water depth referenced to mean sea level in meters. At the (north) upper ends of Maquoit Bay and Middle Bay, there are areas of tidal flats. The boundary values for the tide were about 1.25 meters (amplitude), which were interpolated from the output of the Casco Bay Model. The values of horizontal and vertical viscosities are the same as those used in the Casco Bay model. The time step for the external mode was 30 seconds.

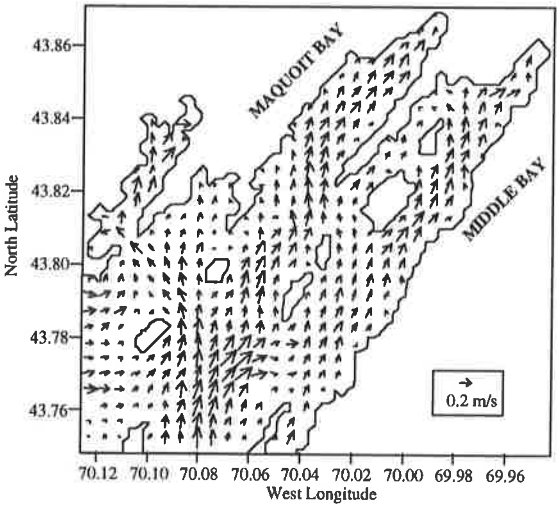


Figure 3.2 Vertically Averaged Currents - Flood Tide

Figures 3.2 and 3.3 show the vertically averaged currents at the flood and ebb tides, respectively. The maximum values for both ebb and flood are about 0.4 m/s. The flow pattern is dominated mainly by the local bathymetry.

In the model grid, land cells are not allowed to be flooded. All the other cells can be flooded or dried during the model run. A criterion for drying is specified (here 0.1 meters has been used). That means if the calculated depth of sea water in the cell is less than or equal to 0.1 meters, that cell will be "dried". This cell will then not be flooded for a specified period of time, such as 10 minutes. This is to simulate the real world process and to prevent instabilities caused by the model hunting between the wet and dry state at each time step.

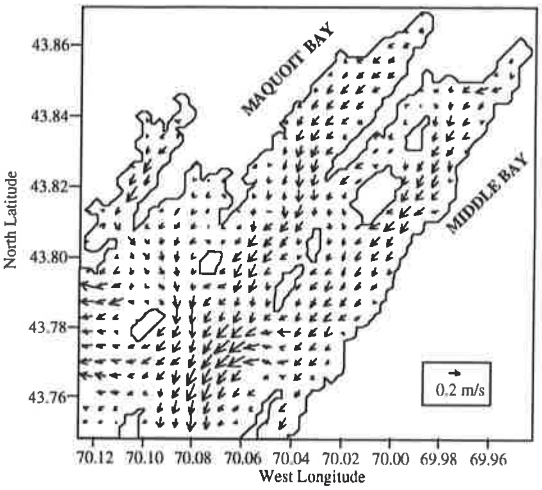
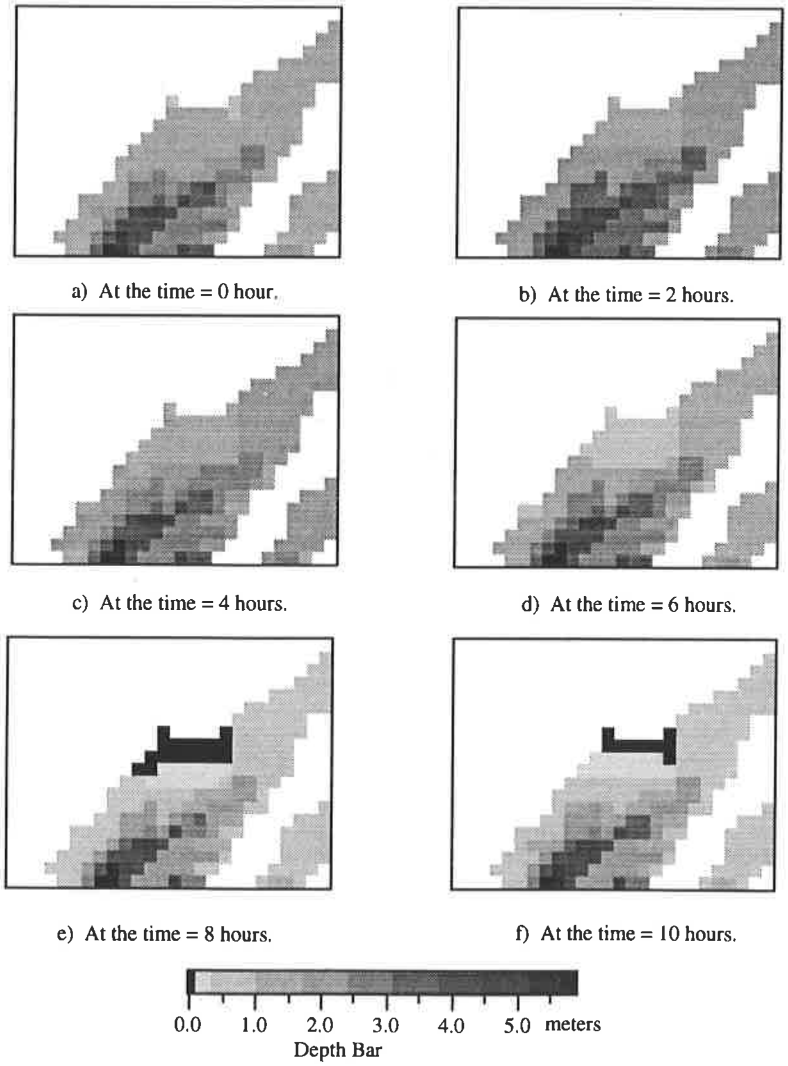


Figure 3.3 - Vertically Averaged Currents - Ebb Tide

The criterion for flooding is more complex. If one of the four adjacent cells is flooded, i.e., its total depth is greater than 0.1 meters, then the water level at that adjacent cell will be used to compare with that of the current cell, which is dry. The sea surface is assumed level. If the sea surface at the adjacent cell is high enough so that the sea surface at the current cell can be greater than 0.1 meters, then the current cell will be flooded. The water depth at the current cell will then be set to be 0.1 meters at that time step regardless of the water depth at the adjacent cell.

The total water depth in a portion of Maquoit Bay has been plotted to display the flooding and drying phenomena in one tidal cycle (Figure 3.4). Figure 3.4a shows that, at time 0 (referenced to 150 simulated hours), all "water" cells are flooded. Figures 3.4b to d show the flooding phase. In Figure 3.4e, some of the "water" cells have dried (black color). However, in Figure 3.4f, some of the "dried" cells have flooded. As it turns out, the areas that flood and dry compared to the total area in the Maquoit and Middle Bay is relatively small. Flooding and drying can be initiated by setting the parameter FLOOD to "TRUE" in the CONTROL file.


a) At the time = 0 hour.

b) At the time = 2 hours.

c) At the time = 4 hours.

d) At the time = 6 hours.

e) At the time = 8 hours.

f) At the time = 10 hours.

Figure 3.4 - Illustration of Flooding and Drying

CHAPTER 4
CIRCULATION AND DENSITY SIMULATIONS

In approaching the final result, the model was calibrated step by step. First, the model was run for the external mode, producing a vertically averaged circulation pattern. At this time, model parameters, such as the time step for the external mode and horizontal viscosity were determined. Next, the model was run using both the external and internal modes. In this step, the ratio of time steps for the external and internal modes were finalized at 1:5. Several values of parameters for the internal mode calculation were tried using 10 layers. Finally, the calculation using variable water density was carried out.

4.1 2-D Tidal-driven Circulation

In this case, the calculations for internal mode and concentration were ignored. Wind stresses and air pressure gradients were set to zero. The value for water density was constant. The only driving force was the tide at the ocean boundary.

MECCA was then run for several tidal cycles to reach "steady state"[1] (usually 10 are sufficient). A harmonic analysis of the output was used to obtain the amplitude and phase of the M_2 component at desired grid cells. Based on the field data availability inside Casco Bay, several locations were chosen for the data comparison. Table 1 shows the data from the NOAA Tide Table (1993) and the MECCA results. In Table 1, the first column contains the numbers of stations used by the NOAA table. In the column headed by "Difference", the values are the times in minutes at High Water referenced to PORTLAND (station 865). The minus sign indicates that the tide, at that station, reaches High Water before the tide at PORTLAND reaches High Water. The column headed by "Range" contains the harmonic range of M_2 provided by MECCA.

Table 1. The data from Tide Tables (1993) and MECCA.

No.	Place	Data (All components)		MECCA Results (M2 only)			
		Mean Range (meter)	Difference* (minute)	Amplitude (meter)	Phase (degree)	Range** (meter)	Difference* (minute)
819	Small Point Harbor	2.68	-12	1.26	101	2.52	-6
821	Cundy Harbor, New Meadows River	2.71	-1	1.25	101	2.50	-6
825	Lowell Cove, Orrs Island	2.68	-7	1.26	101	2.51	-5
831	Wilson Cove, Middle Bay	2.77	2	1.30	103	2.59	0
833	Little Flying Point, Maquoit Bay	2.74	-1	1.30	103	2.59	0
837	Chebeaque Point, Great Chebeaque Isl	2.74	-4	1.28	103	2.56	-1
839	Prince Point	2.80	0	1.29	103	2.57	0
843	Falmouth Foreside	2.77	1	1.28	103	2.56	-1
849	Vaill Island	2.74	5	1.26	101	2.52	-4
865	PORTLAND	2.77	0	1.27	104	2.55	0
869	Portland Head Light	2.71	-2	1.26	102	2.51	-3

Note: * Time difference (in minutes) at High Water referenced to PORTLAND (No. 865).
** Two times of the appropriate amplitude.

From Table 1, the ranges of M_2 provided by MECCA for all eleven stations are about 93% of

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[1] The condition where transient solutions have dissipated and the remaining solution repeats every tidal cycle.

those in the column "Mean Range". Considering that the field data include all the tidal components, while only the M_2 component is included in the MECCA, the results are reasonable. The phases between the data and the model results do not match exactly. The phase from the measured data are actually the phases of the combined tidal components at those locations. This should not necessarily be the same as those provided by MECCA, which are the phases of the M_2 component.

At PORTLAND (station 865), a further comparison has been made. Sucsy et al (1993) provides that the amplitude and phase of M_2 are 1.33 m and 103°. The simulation with MECCA provided 1.27 m and 104°.

It is also possible that these small errors arise from the impositions of the boundary conditions by 3DENS. There are two mechanisms for this. First, the grid scale of the 3DENS simulation was about 5 × 5.5 km which required the output from 3DENS to be interpolated to each MECCA grid cell with some resultant error. Second as the comparison to data in 3DENS, indicates, errors of several centimeters in elevation and several degrees in phase (for this comparison, one degree is equal to about 2 minutes in time) occurred. These errors, in addition to the problems mentioned above, can easily account for these relatively small discrepancies. Since, for practical use, these errors have little meaning, they would be swamped by Spring/Neap differences for example, it was decided to place emphasis on other aspects of the project.

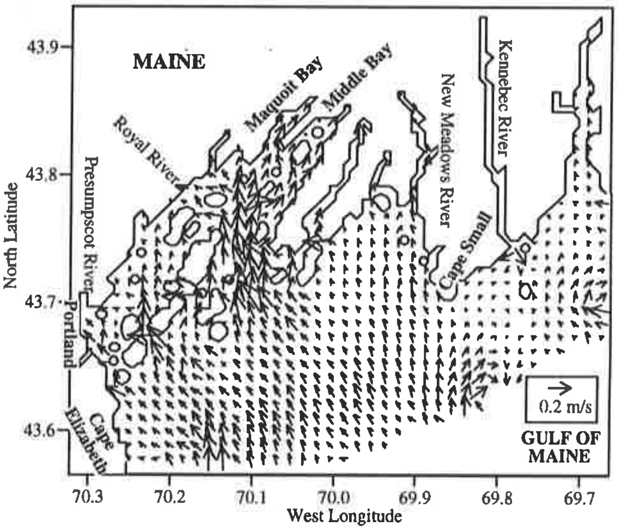


Figure 4.1 - Vertically Averaged Currents - Flood Tide

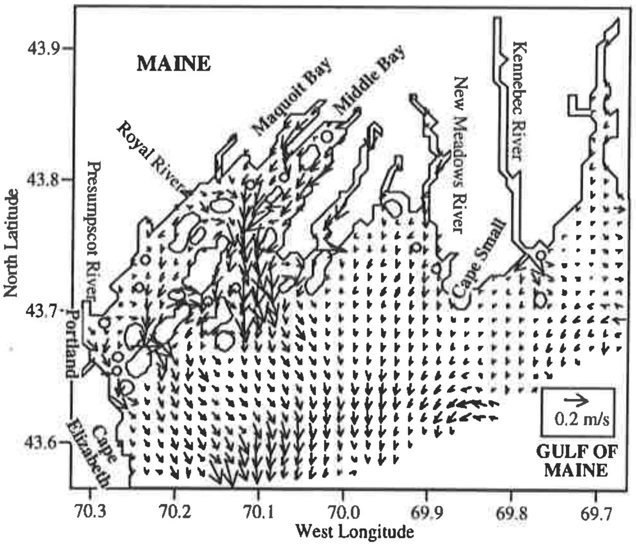


Figure 4.2 - Vertically Averaged Currents - Ebb Tide

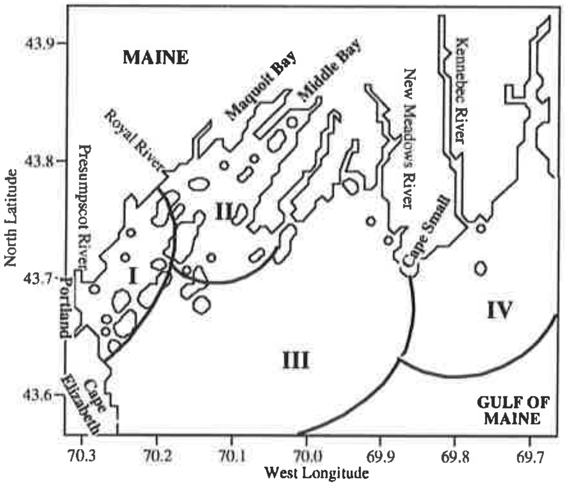


Figure 4.3 Casco Bay Flow Regimes

Figure 4.1 shows the calculated vertically averaged velocity field at flood tide. Figure 4.2 shows the calculated vertically averaged velocity field at ebb tide. The maximum value of velocity is 0.41 m/s for flood tide and 0.43 m/s for ebb tide. Regardless of the tide phase, the currents at Broad Sound are large, around 0.4 m/s. This phenomenon can be explained by the abrupt topography and the sudden narrowing of the land boundary formed by the coastlines and islands. Due to the islands in Casco Bay, most of the water exchange between the Maquoit and Middle Bays and the Gulf of Maine (GOM) is forced through Broad Sound. In general, the circulation pattern is a reversing type. Examining the flow patterns, allows us to divide the modeled region (MR) into four sections as shown in Figure 4.3. They are numerated from left to right as I, II, III, and IV. In section I, the currents are relatively small compared with those in section II. Section II includes the Maquoit and Middle Bays and Broad Sound. In this section, the flow following the coastlines turns almost 90 degrees during both ebb tide and flood tide. Inside Maquoit and Middle Bay, the flows are simply up and down and dominated by the coastline. In Broad Sound, the velocity reaches its maximum value. Section III is the open estuarine region effected mainly by processes in the Gulf of Maine. Flows come in from south to north during the flood tide phase and go out from north to south. In section IV, the currents are small over most of the region. The velocity at the mouth of the Kennebec River is large because of the 4000 m^3/s discharge.

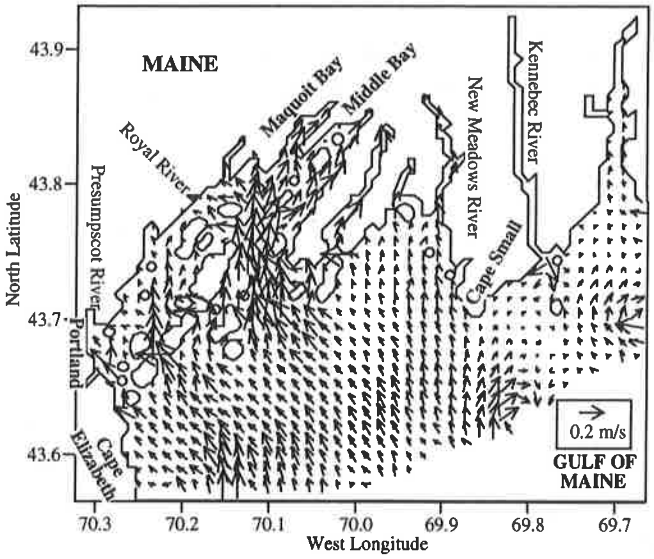


Figure 4.4 - Surface Currents - Flood Tide

4.2 3-D Tidal-driven Circulation

Ten vertical layers were used in the Casco Bay model. The general circulation patterns at layer one, five, and ten during flood tide were shown in Figures 4.4, 4.5 and 4.6, respectively. Bear in mind that the word "layer" here refers not to the horizontal plane, but to a σ-plane on which the coordinate σ is constant.

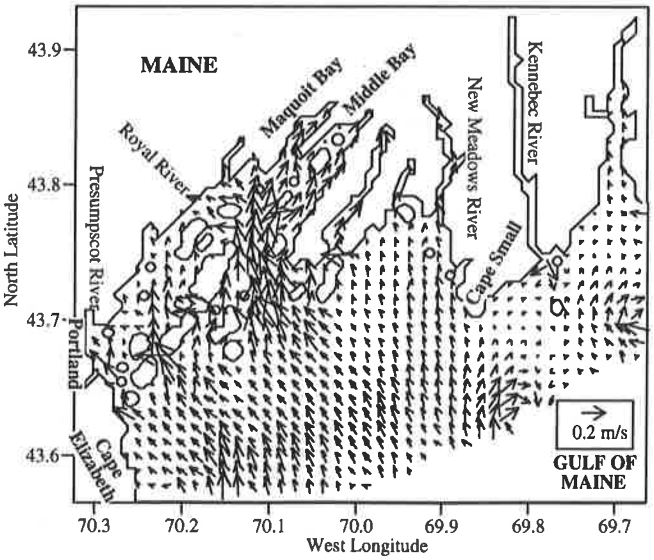


Figure 4.5 - Currents Middle Layer - Flood Tide

The maximum values of the currents decrease from the top layer with a value of 0.47 m/s down to the bottom layer with a value of 0.30 m/s. By comparing with the averaged currents, the flow patterns at different layers are similar to the vertically averaged circulation pattern but with different magnitudes. As might be expected, the velocities in the lower layers are smaller due to the presence of the bottom boundary and the associated bottom friction.

4.3 Tidal Current Comparisons

Comparing calculated results with prototype data is an important step in tuning numerical models. As mentioned in Chapter 1, the only available current data in the Casco Bay region is found in Parker (1982). The data set was collected during cruises of 1980 and 1981 which were part of a program called "Coastal Energy Impact Program Oceanographic Observations" as well as from NOAA current meter observations in 1979. Most of the data were taken in late August and early September.

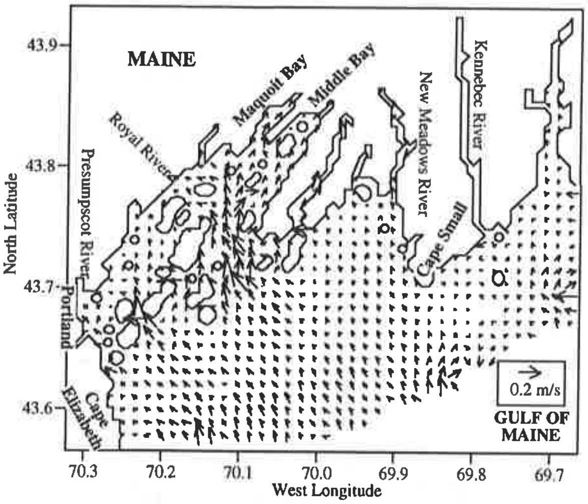


Figure 4.6 - Currents Bottom Layer - Bottom Layer

4.3.1 Parker (1982)

Some locations occupied or reported by Parker (1982) are shown in Figure 4.7. Currents were measured using three basic methods. The first two, surface and subsurface current drogues were tracked by ship and their positions determined periodically with Loran-C and precision radar. The usual procedure was to set two to four surface drogues in an area of about four square miles. These drogues were then visited as often as possible by ship until it was no longer feasible to do so, or about one tidal cycle. The position of each drogue was recorded about every two hours. Positional errors fell within the range of ±100 meters. All drogue measurements were restricted to daylight hours.

The third method of measuring currents was with self-recording current meters anchored to the bottom. Bottom current was measured 3.1 m above the sea bottom with a reported error of 2.6 cm/s in magnitude and 1° in direction.

The Casco Bay model provides current data at each cell of the model grid. That means, time series at every square area with a side of 600 meters, are available at each (Figure 4.7) level from sea surface to sea bottom for the horizontal velocities u and v. However, as can be seen from Parker (1982), current data is only available at certain stations. In general the available data in the Casco Bay region is sparse so that systematic comparisons cannot be made. For the surface measurement, the currents were collected using two or four drogues in a four square mile area. Because both the drogue data at the sea surface and the current meter data at the sea bottom were measured at two hour interval, more detailed variations of tidal currents are not available in the comparisons. Comparisons at particular stations were made and are discussed in the following.

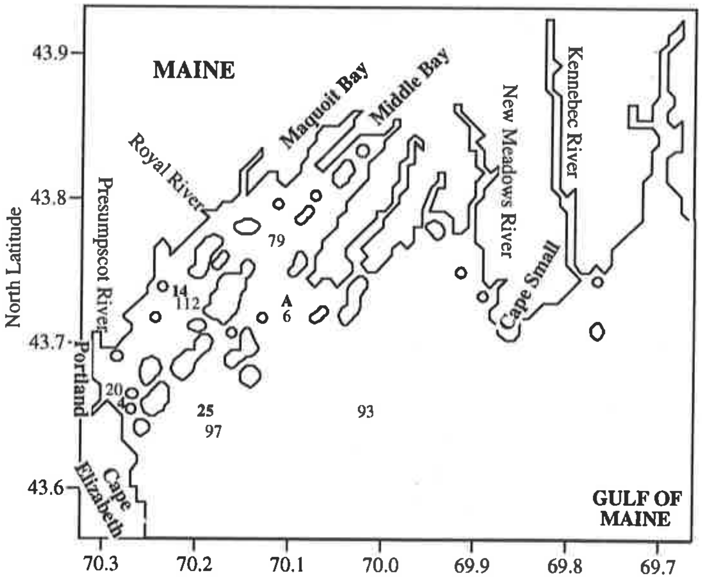
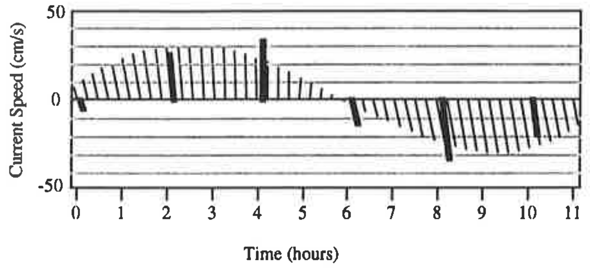
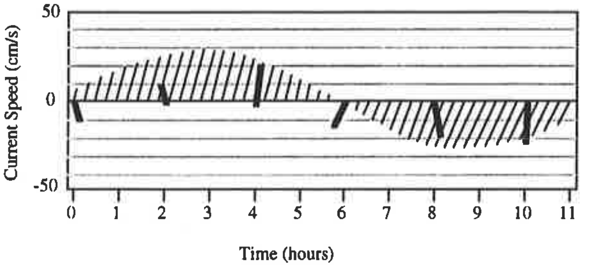


Figure 4.7 Location of Current Meter Data - Plain numbers are surface and bold bottom stations



a) Surface currents at Station 6.



b) Surface currents at Station 79.

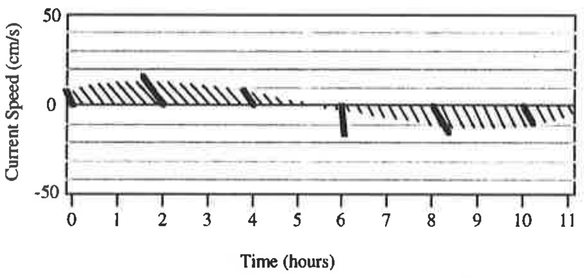
Figure 4.8- Surface Currents - Broad Sound

4.3.2 Surface Current Comparisons

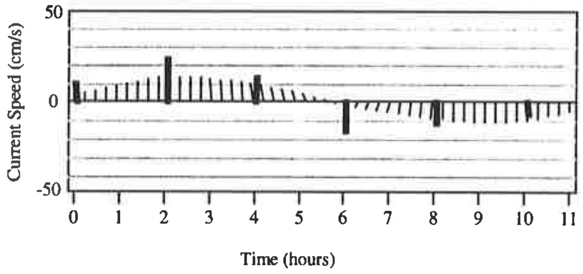
Six stations were selected to undertake our current comparisons at the sea surface. The station numbers are: 6, 20, 79, 93, 97, and 112 in Figure 4.7. Two of them (Stations 6 and 79) are located in the middle and north end of Broad Sound, a narrow channel connecting the inner bays and the outer basin. Large currents are expected to occur in this long narrow area. Station 20 is located near Portland Harbor and Stations 93 and 97 are located in the outer bay.

The comparisons are shown in Figures 4.8, 4.9, and 4.10. Because the period of the M_2 component is 12.42 hours, the current at the thirteenth hour is about the same as that at the zero hour. The horizontal axes are time. The vertical axes are the northern component of the tidal current (cm/s). That is, the positive values are for north, the negative values for south. East and west are to the right and left respectively. The thinner lines represent the tidal currents (vectors) from the model. The bold lines represent for the data set collected from the Parker study, which were averaged over two hours. Only one data point was available for every two hours.

Figures 4.8, a) and b) are the surface current comparisons at Stations 6 and 79, respectively. Both are located in the northern end of Broad Sound. At Station 6, the comparison matches well. The current directions are almost the same through the entire tidal cycle as well as the magnitude. At Station 79, both current directions and magnitudes are not as well matched. Figure 4.9, a) and b) are for the current comparisons at Stations 20 and 112. In both stations, the current directions match well, but the current magnitudes are consistently smaller than the field data. Figure 4.10, a) and b) are the current comparisons for Stations 93 and 97. In these two stations, the current directions from the field data are to the south in most of the tidal cycle. It is easy to imagine tidal currents superimposed on a net baroclinic circulation producing these results, particularly for station 93.



a) Surface currents at Station 20.

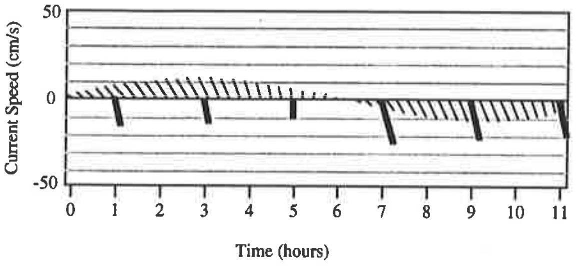


a) Surface currents at Station 112.

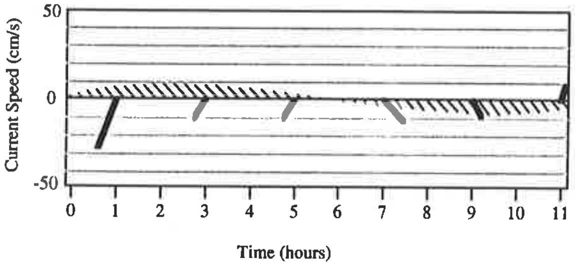
Figure 4.9 - Surface Currents - Portland Harbor

4.3.3 Bottom Currents Comparisons

Four stations were selected for the bottom currents comparisons: A, 4, 14, and 25 as



c) Surface currents at Sattion 93.



a) Surface currents at Station 97.

Figure 4.10 - Surface Currents - Casco Bay

are shown in bold in Figure 4.7. Station A is located in the middle of Broad Sound, 4 and 14 inner Casco Bay, and 25 in outer Casco Bay.

Figure 4.11 a) and b) are the bottom current comparisons for Stations A and 25. At Station A, both directions and magnitudes of currents match well. In Station 25, the current data are not well matched. Figure 4.12, a) and b) are for Stations 4 and 14. At station 4 the phase and direction appear to agree well with the calculated magnitudes being slightly smaller than the data. Station 14, more or less in the center of Casco Bay, seems to agree fairly well.

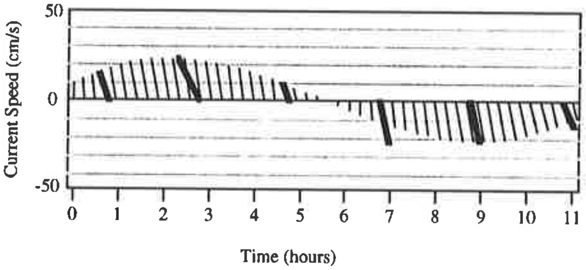
Over all the agreements seem reasonable. Bear in mind that the model results are for an average tidal condition using the M_2 component only. The data contain significant errors, wind effects, all the tidal components, and varying spring and neap conditions. In addition the drogue data is smoothed of two hour time periods. It seems premature to further tune the model until better data is available for comparison.

4.4 Density Distribution

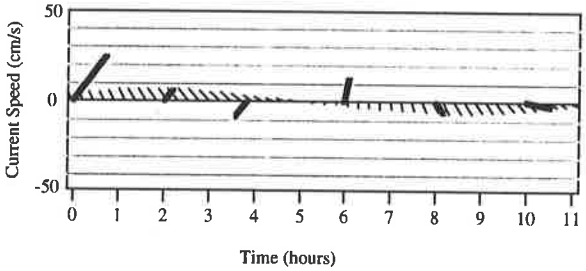
As a test, the Casco Bay model was run to simulate the density distribution during a spring season. From Figure 1.3, the peak value of the freshwater transport from the Kennebec River was around 8000 m^3/s during April of 1993 and this value was used in our simulations.

The density data at the ocean boundaries were obtained from the hydrographic cruises of 1992 and 1993. To start the run, the default numerical scheme in MECCA was used to calculate the interior initial values by interpolation . Figure 4.13 shows the surface salinity distribution as a initial condition.

Figures 4.14, 4.15, and 4.16 show the surface salinity calculated after 2, 4 and 8 days respectively.

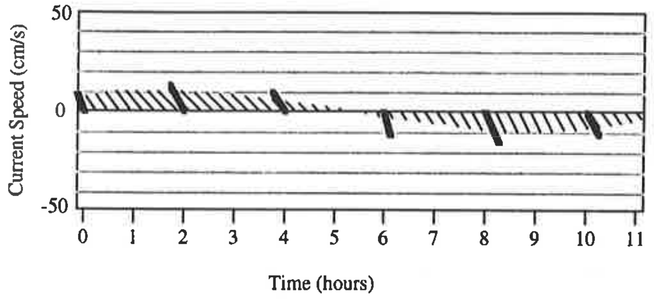


a) Bottom currents at Station A.

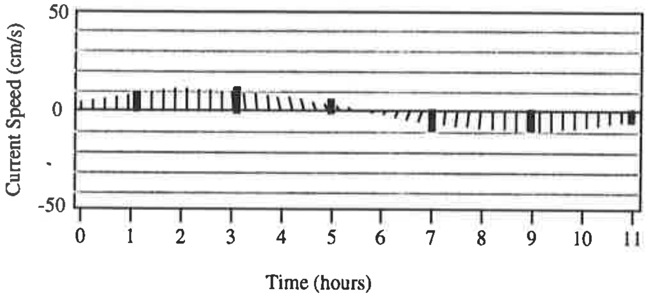


b) Bottom currents at Station 25.

Figure 4.11 - Bottom Currents - A & 25



a) Bottom currents at Station 4.



b) Bottom currents at Station 14.

Figure 4.12 - Bottom Currents - Portland Harbor

driven by some overall circulation in the bay. To help simulate such a process this test case included a 10 m/s wind from the east. An examination of sub-surface salinities indicates that the model currently is incorporating too much vertical mixing into the solution. Further effort should include tuning to obtain a more realistic lower layer. In addition the model by Mellor, discussed earlier should also be examined as it has been reported to exhibit better performance with regard to the surface mixed layer.

4.5 Concentration Comparisons

Hydrographic data in Casco Bay were collected by Pettigrew during the hydrographic cruises in 1992 and 1993. The contours at high and low tide are shown in Figures 4.17 and 4.18, respectively. The shape of both figures is about the same with a shift of several kilometers occurring with the tide. In Figure 4.17, which represents contours of surface salinity (ppt) at high tide, a freshwater pool is formed near the south corner of Cape Small. However, in Figure 4.15, which represents the model results for flood tide, there is a freshwater pool formed at the mouth of the Kennebec River rather than at the south corner of Cape Small. The calculated salinities for the surface show similar behavior including the little "hook" to the south and salinities after about 8 days which are within about one ppt of the measured values. To obtain this solution it became clear that the plume of fresh water was

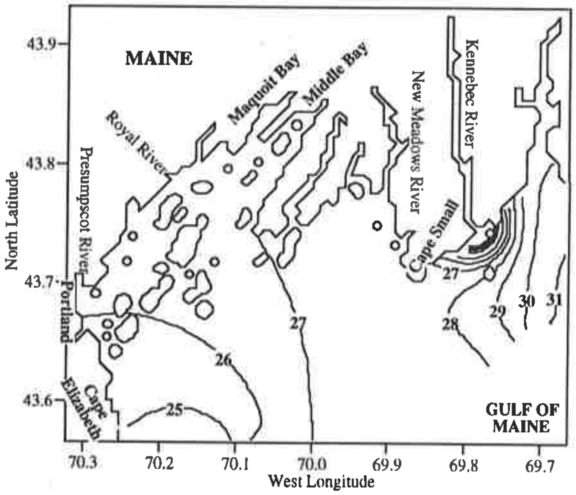


Figure 4.13 - Initial Condition for MECCA - Surface Salinity (ppt)

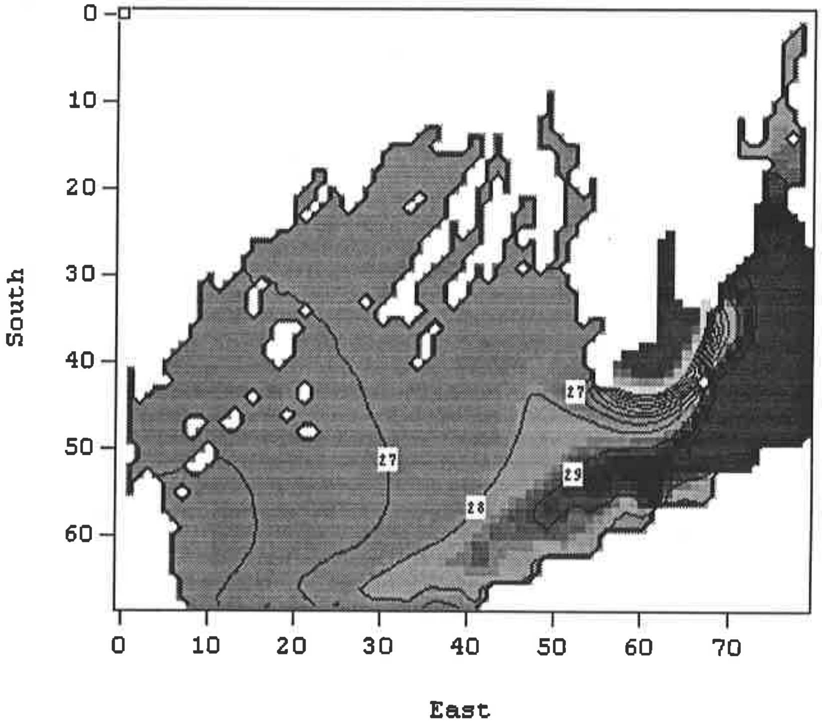


Figure 4.14 - Surface Salinity - 2 Days

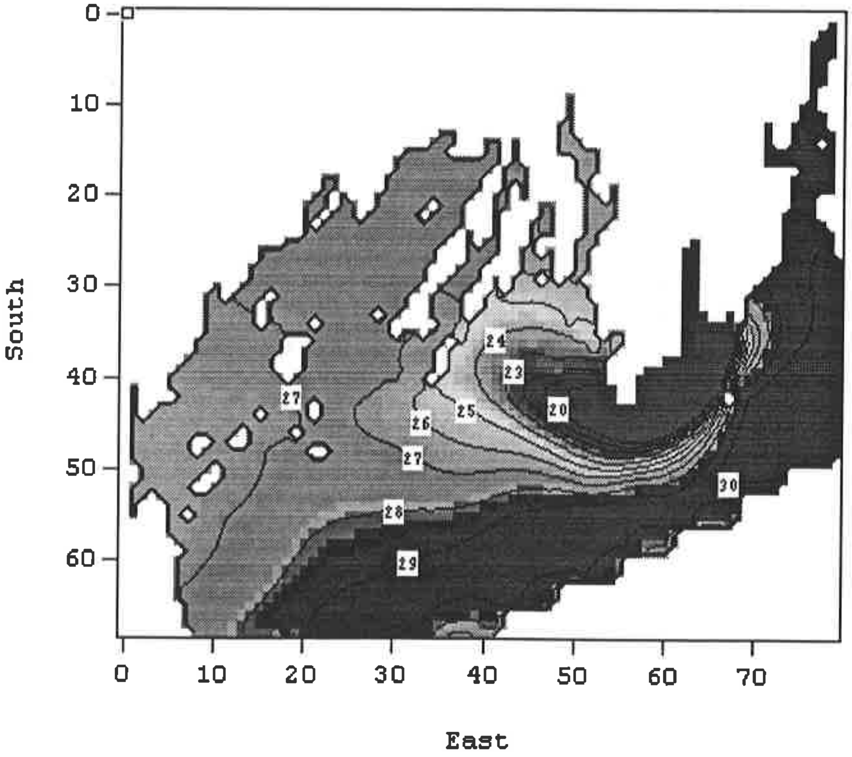


Figure 4.15 - Surface Salinity - 4 Days

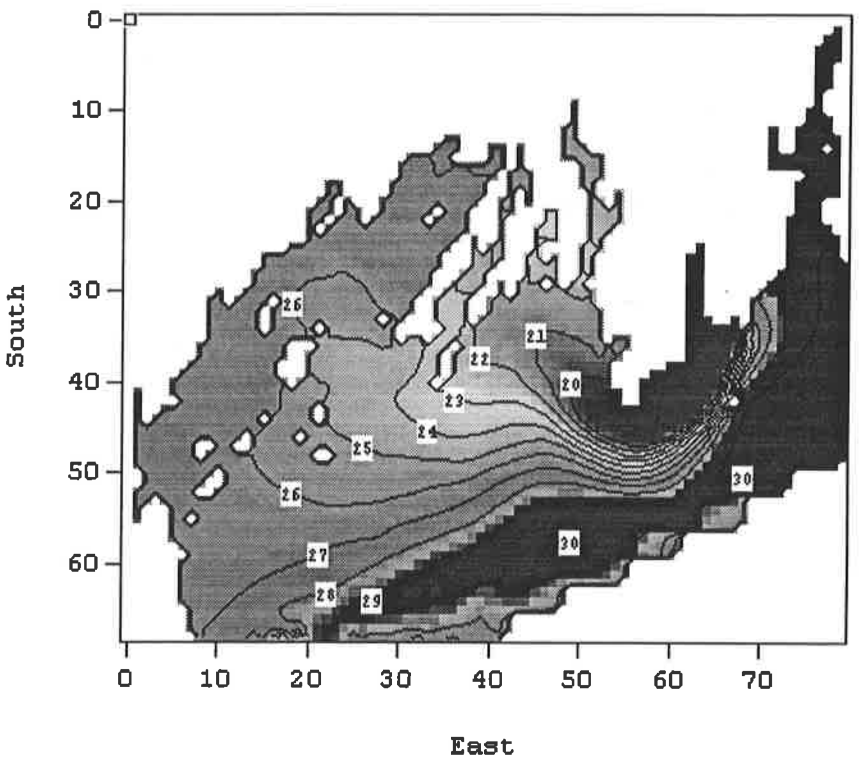


Figure 4.16 - Surface Salinity - 8 Days

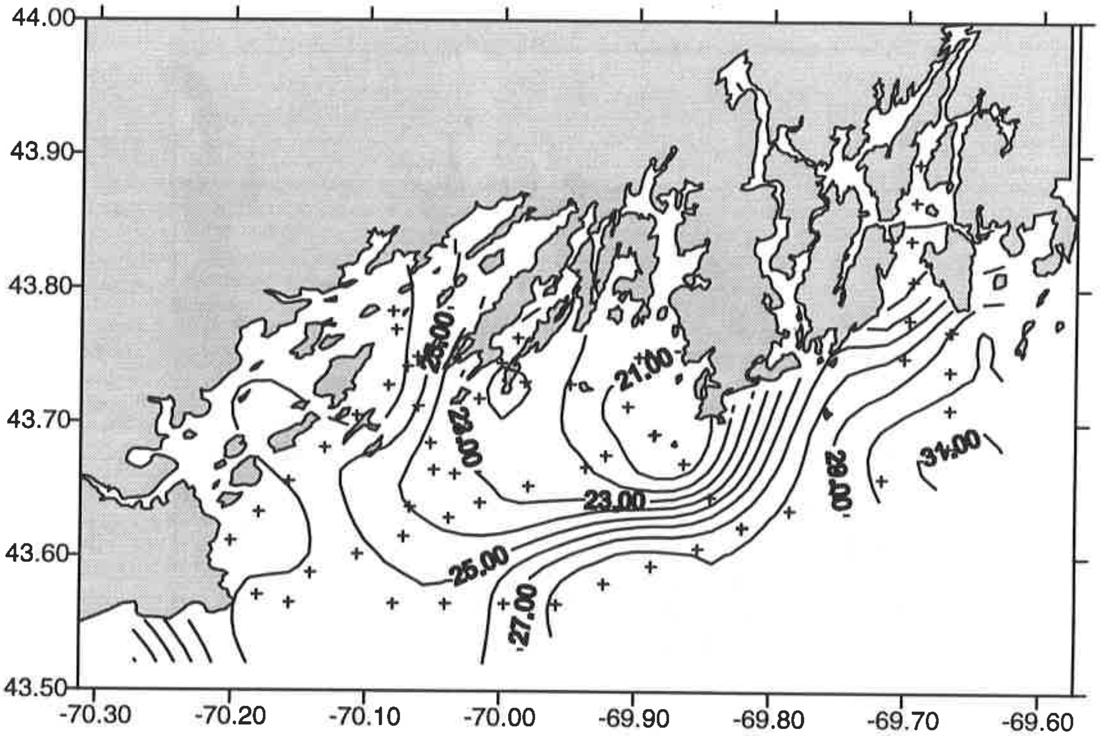


Figure 4.17 - Measured Salinities at High Tide

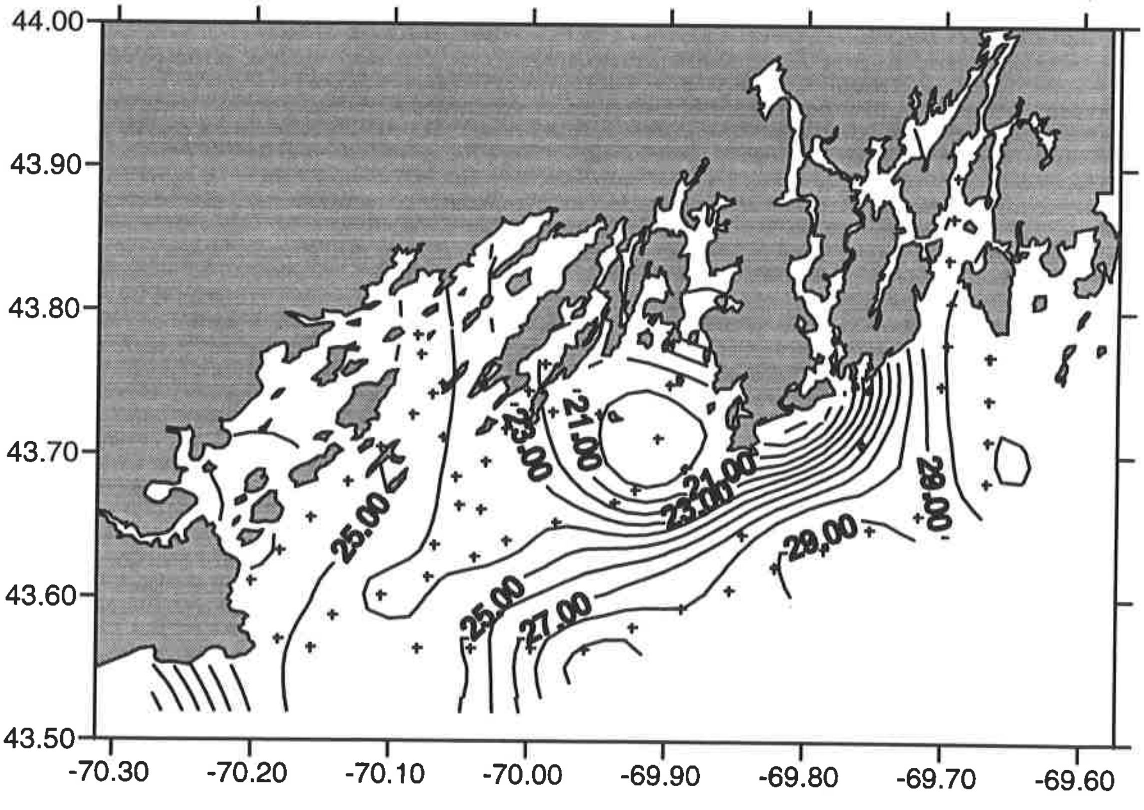


Figure 4.18 - Measured Salinities at Low Tide

4.6 Wind-driven Circulation

The relation between wind stresses and tidal forces is non-linear. The wind stresses can be added to the tidal model so that the flows are controlled by both wind and tide. However, the wind "contribution" cannot be distinguished in that situation. To examine the importance of wind driven circulation in Casco Bay the effect of wind was tested separately.

As an example, a uniform 10 m/s wind from various directions was chosen. The radiation condition was used for the ocean boundary condition as described in the CBM report, and the tidal amplitude was set to zero at the ocean boundary.

The wind-driven currents averaged over the total depth were shown in Figure 4.19. The maximum current is about 0.12 m/s. In this case, only flows around Cape Small and between islands are relatively large. The currents are very small, less than 0.02 m/s, over most of the region. A counterclockwise gyre is shown 7 km to the southwest of Cape Small. Interestingly, this gyre appears to be an artifact of the vertical averaging. Figure 4.20 has been constructed from the layer or layers containing the upper 10 meters of the water column. In this case we observe the more intuitive result that the surface currents are moving in the direction of the wind at some fraction of the wind speed. A common rule of "thumb" is that the surface currents are about 3% of the wind speed. Where the term surface is loosely defined but is taken to mean as close to the surface as can be measured. The actual surface currents vary rapidly with a logarithmic distribution, see for example Pearce and Cooper (1981). For the sake of argument we can take the surface to be the upper meter of the water column.

In Figure 4.20, 0.1 m/s would be 1% of the wind speed which means that the 10 meter average is less than 3% of the wind speed. Figure 4.21 shows the currents at the air-sea interface (Level 1) predicted by MECCA. This is the velocity at the top of the uppermost layer. The currents here are, perhaps, 1-3% of the 10 m/s wind speed and in lieu of extensive data for verification seem "reasonable". The reader interested in these details should reference section 8.4.1 in the MECCA Manual for a description of how the surface boundary condition is imposed. In particular, MECCA imposes a surface current that produces the specified shear stress over the top layer in the model. This means that the surface velocity may become unreasonable in deep waters if the surface layer becomes too thick.

With the surface flow to the west continuity would dictate that a return flow exist in the lower layers. This return flow can be seen in Figures 4.24 and 4.25. Note that 10 "layers" are bounded by 11 "levels" and that, for example, level 7 is between layer 6 and layer 7. Further examination indicates that, in fact, no gyre exists in any layer and perhaps emphasizes the importance of proper data interpretation whether prototype or computer generated.

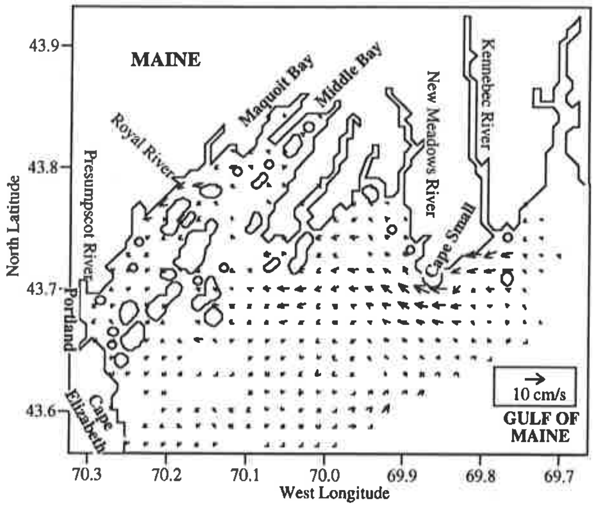


Figure 4.19 - Wind Driven Currents Averaged Over Depth

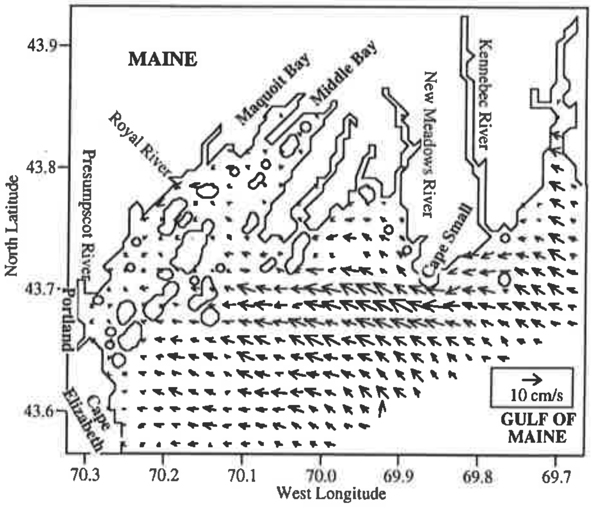


Figure 4.20 - Wind Driven Currents - Averaged Over Top 10 Meters

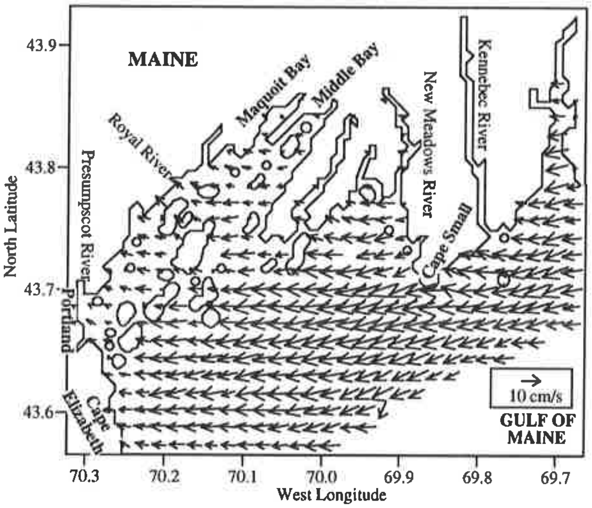


Figure 4.21- Wind Driven Currents - Level 1 (Sea Surface)

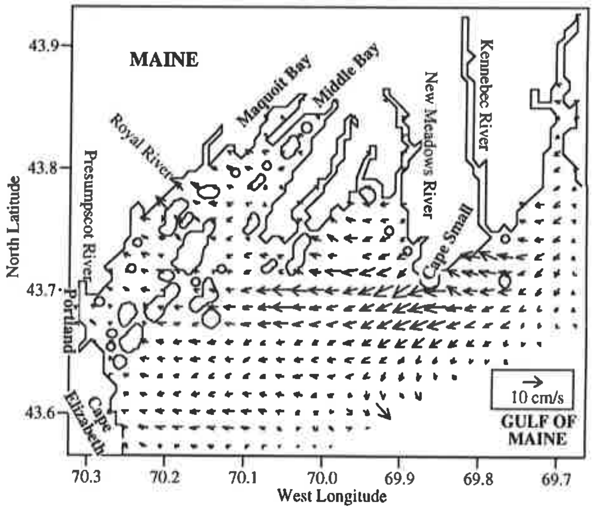


Figure 4.22 - Wind Driven Currents - Level 3

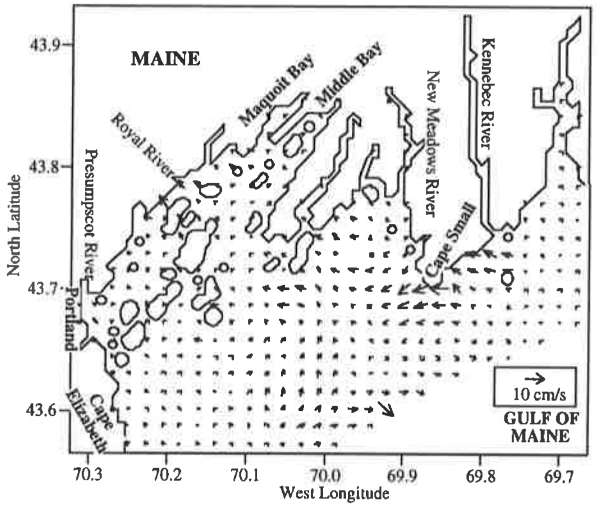


Figure 4.23 - Wind Driven Currents - Level 5

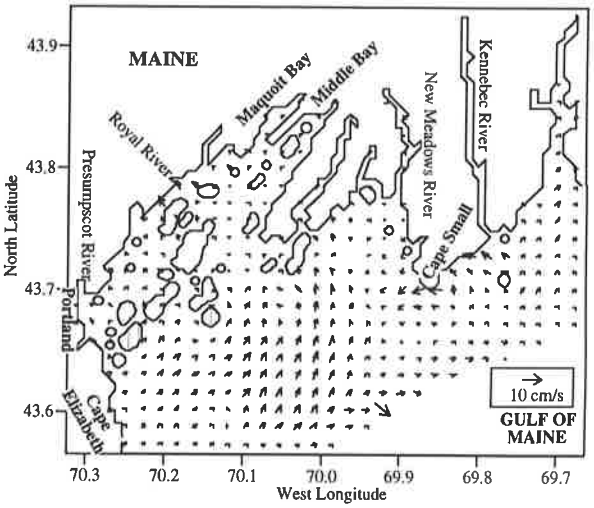


Figure 4.24 - Wind Driven Currents - Level 7

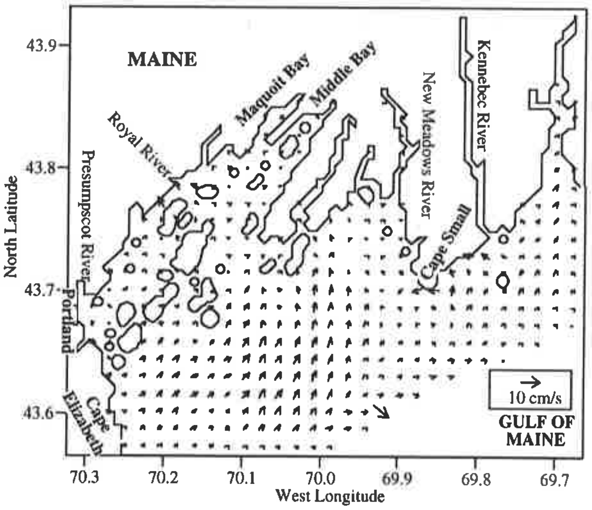


Figure 4.25 - Wind Driven Currents - Level 9

CHAPTER 5
SUMMARY

A numerical model of Casco Bay was established using a model developed by NOAA called MECCA. MECCA uses the semi-implicit ADI numerical scheme to lessen the computational effort needed by the model. In addition MECCA allows for an arbitrary number of layers as well as flows driven by density differences in the fluid. A possible drawback is the use of the sigma coordinate system for the vertical coordinate. The sigma coordinate system can produce unrealistic results in strongly stratified areas. Further interest in developing a prognostic solution as the spring freshet develops, for example, might warrant modifying MECCA to use uniform layers instead of the current sigma system. A recent paper by Mellor (1994) indicates that the problem is not severe in relatively shallow near shore areas and that it can be "fixed".

The Casco Bay simulation was established using depths from NOAA charts. This was, in sum, more expedient than using the digital NOAA data sets which were either uncontrolled[1] or too sparse at 15'. The simulation was constructed in two parts: the outer simulation which consisted of the entire Casco Bay region at a grid spacing of 600 meters and an inner simulation of Maquoit and Middle Bays at a grid spacing of 200 meters. The boundary conditions for the Casco Bay simulation are from a simulation of the entire Bay of Fundy and Gulf of Maine which used a 5 × 5.5 km grid spacing.

To obtain an indication of the accuracy of the simulation as a guide for tuning, the results were compared to prototype data: first for tides or sea surface elevations as a function of time, then for currents, and finally for salinities. In addition, vertically averaged currents are used as input to DETMOD which provides a simple user interface to allow easy examination of the circulation patterns in Casco Bay.

5.1 Data Comparisons

Data as well as the simulation results indicate that the general circulation in Casco Bay is dominated by tide and bathymetry. That is, the tide signal dominates other processes, such as wind and density. A comparison of calculated surface elevations (or tides) to field data has been presented in section 4.1. The data for Portland Harbor agrees to within 6 cm in amplitude and 1° in phase. The above comparison is for the M_2 or primary semi-diurnal component which compromises most of the tide signal in the Gulf of Maine. Additional comparisons are carried out for the overall tidal range (with all components) for a variety of stations around Casco Bay. Model tuning could undoubtedly bring the model range and the measured ranges closer into agreement. However, the model comparison is made using a harmonic analysis of the model results to provide the amplitude of the M_2 component at the grid cell used for comparison. Since the prototype data contain all the components a more instructive course of action would be to obtain the amplitude and phase of the M_2 component wherever possible and then tune the model. These data were not available at the time of this report but it is recommended that this be part of any follow on study.

The tidal currents flow into and out of the bay in a reversing pattern (Figures 4.1 and 4.2). Specifically, the flood currents flow toward the wide open basin area from the Gulf of Maine and then, are "squeezed" into the inner bays via the narrow channel, Broad Sound, at reasonably high speed. The currents inside the inner bays are largely "up and down" and constrained by the bathymetry. The magnitude of the tidal currents at Broad Sound as calculated by MECCA is in the order of 40 cm/s. Currents elsewhere in the bay are smaller than this. In section 4.3,

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[1] Data from various cruises are used without regard to accuracy or bias.

MECCA results are compared to the data from Parker (1982) (Figures 4.8 to 4.12). Both tide and current comparisons show that the simulation matches well enough inside Casco Bay AND that further tuning would be suspect without additional data. Outside Casco Bay the comparisons indicate, at least during the time the data was taken, a net drift in addition to the tidal signal. Two possible causes for this seem likely. The first possibility is tidal rectification and the resultant overall circulation in the Gulf of Maine. In addition, the spring freshets along the coastal areas tend to form a current more or less from northeast to southwest.

In principle, the 3DENS simulation of the entire GOM includes tidal rectification. If it is necessary to obtain better comparisons in the outer bay region it will be necessary to provide boundary conditions in such a way that the density driven currents are produced in the model. An alternative would be to model the entire GOM with a finer resolution. The 3DENS simulation contains approximately 10,000 grid cells. With computers getting faster this may be the most reasonable way to obtain the needed simulation. Remember, however, that comparisons inside the bay are in reasonable agreement.

Clearly wind stresses modify the current regime. It is difficult, however, to tell how much of the net drift is generated by wind since the wind-generated portion is much smaller than the tidal portion. To examine the wind effects in the bay, several examples are presented. Wind was assumed uniform over the entire bay with a speed of 10 m/s. Because of the sigma coordinate system the thickness of a layer varies with the total depth. The results are shown in Figures 4.19 to 4.25. Note Figure 4.20 which shows the velocities for the upper ten meters regardless of the layer thickness. Velocity fields at different levels (Figures 4.21 to 4.25) show that the wind-generated currents in the top two or three levels flow in the same direction as the wind with a magnitude of about 2% of that of the wind, while, currents below those levels flow in the opposite direction with a smaller magnitude. The presence of the return flow is intuitive and has been measured at a variety of locations.

To test if the model conserves mass (or water), the discharge across the entire ocean boundary was calculated for the case of an east wind and no tide. After 20 hours of simulation the resultant discharge for all 100 boundary cells was:

$$Mass\_Flux = \sum_{i=1}^{100} (U_i x H_i x \Delta L) = 5.569 m^3 / \sec ,$$

where U_i is the vertically averaged velocity normal to the ocean boundary at the i^{th} cell, H_i is the total depth at the i^{th} cell, and ΔL is the grid cell size, either ΔX or ΔY (=600m). Considering the entire ocean boundary, the discharge, 5.569 m^3/s, is very small and essentially zero. To calculate the equivalent normal velocity across the boundary we estimate the average depth at 40 m and obtain:

$$\frac{5.569 m^3 / \sec}{100 x 600 m x 40 m} = 2.32 x 10^{-6} m / \sec$$

We see that the surface flow and return flow are very nearly in equilibrium after 20 hours and, for all practical purposes, this equilibrium indicates that the model conserves mass.

The land boundary condition has been corrected to conserve salt. Once MECCA was corrected to eliminate diffusive flux through the land boundary we were able to provide a preliminary test run of prognostic salinity calculations. In the original version of MECCA approximate salinities were specified around the boundary to eliminate the problem as much as possible. For the Casco Bay simulation this did not work well and had to be corrected. As Figure 4.17 and 4.18 indicate the comparisons to field data are reasonable. Comparison at depth indicates, however, that the model apparently allows for too much vertical mixing. It is also possible that since the present version of the model allows only for the input freshwater to be distributed over the entire water column that this initial distribution is contaminating the results. In any event MECCA has evolved into a useful model and one future task should be to get MECCA to agree with the data for the lower layers as well.

An additional problem with Mecca is the way diffusion is handled at the ocean boundary. With a straight line or rectangular boundary Mecca conserves salt. For a diagonal specification salt is not conserved, however. In the application to Casco Bay with MECCA, about one third of open boundary cells belong to this case. A careful examination of Figures 4.14, 4.15, and 4.16 show some small perturbations of salinity near the ocean boundaries. They do not however, seem to have any effort on the overall solution and for the present it seems prudent to concentrate effort on other areas. The modifications to MECCA to correct this were beyond the scope of the project.

5.2 Future Directions

To answer the question "Where do we go from here?" we must first answer the question "Where do we want to go?". As Yogi Berra said, "If you don't know where you are going you may end up somewhere else!". People's interests in Casco Bay seem to encompass all aspects of the water environment and it is impossible to solve all problems with "**the model**". A step of general interest would be to refine the grid or make the cells smaller. Casco Bay has a lot of islands and complicated bathymetry and a finer grid would provide for more detail in the solutions. Along these lines it may also be productive to investigate the use of a orthogonal curvilinear or "stretchy" grid. This would allow for grid cells of varying sizes which would allow for more grids in areas of interest. The latest version of the "Mellor" or Princeton Ocean Model allows for this.

Of the various topics of concern it appears that the currents, per se, are not as of as much interest as the long term transport of material. In particular, do "bad things" in the water from the Kennebec River get transported into Casco Bay. The latter question is, of course, far more difficult to answer than the former.

We have some indication from field data that water from the Kennebec heads west. The model run illustrated by Figure 4.16 predicts flow of material from the Kennebec into Casco Bay. A definitive field experiment with a suitable tracer is ultimately the only way to answer this question. However, modeling can expand on what field data we do have. Using MECCA, the authors were unable to reduce the mixed layer thickness to a reasonable level. In addition to further work with MECCA the authors also suggest that the Mellor model be used and compared to the current version of MECCA. This is particularly true for simulations of density driven flows where a more sophisticated turbulent closure may provide for a more realistic treatment of the mixed surface layer.

Finally, to further develop the current study it will be necessary to include the entire Gulf of Maine into the modeled region. It is apparent that the external boundary conditions are important to what is happening inside the Casco Bay model. In other words, it is not possible to completely isolate Casco Bay form the rest of the Gulf of Maine.

BIBLIOGRAPHY

Abarbanel, Henry D.I. and W.R. Young. 1987. General Circulation of the Ocean. Springer-Verlag New York Inc. 1987.

Bigelow, H. B. 1927. "Physical Oceanography of the Gulf of Maine". Bull. U.S. Bur. Fish., 40, 511-1027, 1927b.

Brooks, D. A. and L. U. Churchill. 1992. "Experiments with A Terrain-following Hydrodynamic Model for Cobscook Bay in the Gulf of Maine" Proceedings of the 2nd International Conference (Tampa, Florida). Estuarine and Coastal Modeling: 215 -- 226. 1992.

Csanady, G.T. 1973. Turbulent Diffusion in the Environment. Geophysics and Astrophysics Monographs, Vol. III. D. Reidel Publishing Company.

Hess, K. W. 1986. "Numerical Model of Circulation in Chesapeake Bay and the continental shelf" NOAA Technical Memorandum, NESDIS AISC 6, National Environmental Satellite, Data, and Information Service, NOAA, U.S. Department of Commerce, 47 pp.

Hess, K. W. 1989. MECCA Program Documentation. NOAA Technical Report NESDIS 46, Washington, D.C. September, 1989.

Leendertse, J. J. and S. K. Liu. 1975. "A Three-dimensional Model for Estuaries and Coastal Seas" Vol. II, aspects of computation. Report R-1764-OWRT, Rand Corp., Santa Monica, CA, 123 pp.

Madela, R. V. and S. A. Piacsek. 1977. "A Semi-implicit Numerical Model for Baroclinic Oceans" J. Comp. Phys. 23, 167-178 pp.

Marchuk, G.I. and A.S. Sarkisyan. 1988. Mathematical Modelling of Ocean Circulation. Springer-Verlag Berlin Heidelberg. 1988.

Mellor, G. L., T. Ezer, and L.-Y. Oey, (1994) “The Pressure Gradient Conundrum of Sigma Coordinate Ocean Models”, Journal of Atmospheric and Oceanic Technology, Vol 11, 1126-1134.

Neumann, G. and W. J. Pierson, Jr. (1966). Principles of Physical Oceanography. Prentice-Hall, Inc. (1966).

Parker, C. E. (1982). "The Currents of Casco Bay and the Prediction of Oil Spill Trajectories" Technical Report No. 28, Bigelow Laboratory for Ocean Sciences, West Boothbay Harbor, Maine. November 1982.

Pearce, B. R. and C. K. Cooper. 1981. "Numerical Circulation Model for Wind Induced Flow". J. Hydraulics Division. ASCE, Vol. 107: 285-302. March, 1981.

Pettigrew, N. R. (1995) In preparation.

Phillips, N. A. 1957. "A Coordinate System Having Some Special Advantages for Numerical Forecasting" J. Met. 14, 184-185.

Pickard, G. L. and W. J. Emery. 1989. Descriptive Physical Oceanography. Pergamon Press. 4th Edition. 1989.

Pond, S. and G. L. Pickard. 1983. Introductory Dynamical Oceanography. Pergamon Press. 2nd Edition. 1983.

Sommerfeld, A. 1949. PDE, Lectures in Theoretical Physics. Vol. 6, Academic, 1949.

Sucsy, P., B. R. Pearce and V. G. Panchang. 1991. 3DENS: A Three-dimensional Tide and Wind Model for Coastal Applications. Technical Report, Department of Civil Engineering, University of Maine. 1991.

Sucsy, P., B. R. Pearce and V. G. Panchang. 1993. "Comparison of Two- and Three-Dimensional Model Simulation of the Effect of a Tidal Barrier on the Gulf of Maine Tides". J. Physical Oceanog. Vol. 23, No. 6: 1231 - 1248. June 1993.

Tide Tables (1993) East Coast of North and South America. U.S. Department of Commerce, NOAA, National Ocean Service. Pages 209 - 210.

Tan, Weiyan. 1992. Shallow Water Hydrodynamics. Water & Power Press, Beijing. Elsevier Science Publishing Company, Inc. Elsevier Oeanography Series, 55. 1992.

Vreugdenhil, C. B. 1989. Computational Hydraulics: An Introduction. Springer-Verlag Berlin Heidelberg. 1989.

Wu, J. 1975. "Wind-stress Coefficients over Sea Surface Near Neutral Conditions - A Revisit" J. Phys. Oceanog. 10, 727-740.

Appendix

DETMOD

Desktop **E**nvironmental **T**ransport **MOD**el

Operation Manual:

Introduction:

DETMOD is a model which is designed to allow study of the transport of waterborne substances within estuaries and other nearshore marine environments. Its primary features are Graphical User Interface and "Real Time" display of model results. At present, it consists of a particle tracking diffusion model and an oil spill model, both rely on a velocity and water depth data set produced by the flow model described in the body of this report. An important feature us to allow the user to view the model output.

Installation & Setup:

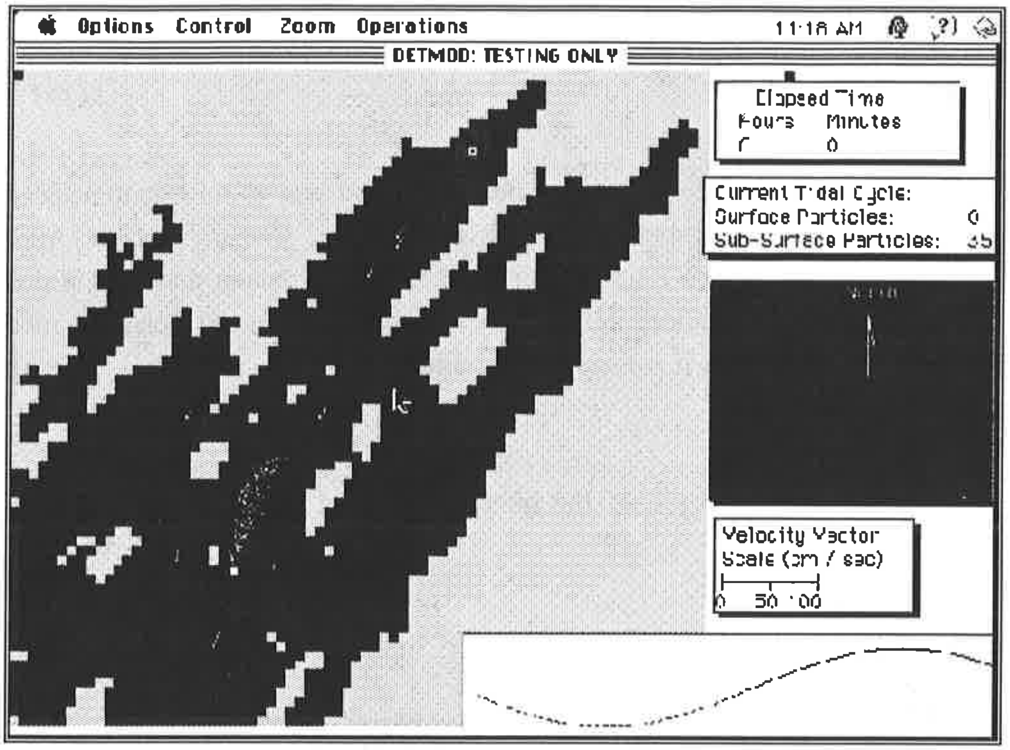
The Model requires a Macintosh computer with at least 7 megabytes of RAM and a high resolution color monitor with a 13", or larger, screen. The program and its data files will take up only 4.5 Mb of disk space.

To install the model, copy the file *DETMOD.sea* into a folder on the hard drive. Double click on the file to start the extraction process. *DETMOD* is the application file and comprises the executable portion of the model. The velocities and water depths are in the file named *Velocities.d.* The data is in a straight binary format to facilitate loading and is not viewable or editable without the use of a hexadecimal editor.

There is nothing that need be done prior to running the model. To start the model double click on the application file.

Operation:

To run the model, double-click on the Application File named *DETMOD*. The model's default window will appear and will remain blank while the input data set is loaded. The model will start running using the default or chosen values for operational parameters.



Elapsed Time
Hours Minutes
0 0

Current Tidal Cycle:
Surface Particles: 0
Sub-Surface Particles: 35

Velocity Vector
Scale (cm / sec)
0 50 100

Figure 1 - Overview of Model Screen Showing Graphical Displays and Menus.

Control of the model is via four pull down menus located at the upper portion of the computer's monitor (see Figure 1.). The Options: menu allows the location of the source to be changed, and the model run to be terminated. The Control menu contains commands to display water depths, show false color concentration plots, allow selection of locations for velocity vectors, control the display of those vectors, and allow changing of operational parameters. The Zoom menu activates the zoom feature. The Operations menu activates the Residence Time feature for the Maquoit Bay simulation.

NOTE: The model looks for external events (i.e. Key Presses and Mouse Button Clicks) at the end of each time step while the model is running. This means that the mouse button must be held down until the end of the current time step, anywhere from 1 to 40 seconds. While the model is halted it is looping through only the event manager routines and will respond with little or no delay.

Communication from the model to the operator is conducted via the graphic display. Major areas of the screen are: The pull-down menus; The model area; The graphic &

numeric time display; The elapsed time display; And the wind direction & velocity display (see Figure 1.).

If it is desired to reset and restart the model, the easiest way to do it is to select "Oil Spill Control" from the Control menu and click on the "OK Restart" button. Another method is to select "New Source Location" from the Options: menu and simply double click on the existing source location. All the other menu selections suspend the model's execution which is resumed, as if uninterrupted, after the menu command's function is completed.

In the following sections each of the menu commands will be described in more detail:

Options: Menu (Figure 2.)

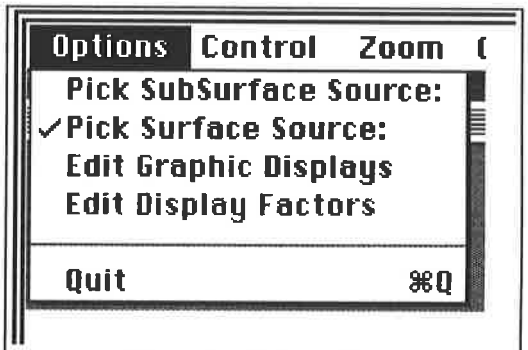


Figure 2 - Options Menu

Pick Subsurface Source: Allows the operator to select the location of the source of material in the water column. The particles representing the material in the water column is shown in white. Model execution is halted and the grid cell containing the current source is highlighted. The operator is prompted to select a new location which is done by clicking on the desired location on the screen. If the location highlighted is not desired a new location can be chosen any number of times. Once the correct location is highlighted the operator double-clicks on the highlighted cell and the model's operating parameters are reset and a new run is started.

Pick Oil Source: Allows the operator to select the location of the source of the spilled oil. The particles representing the material floating on the surface is shown in red. Model execution is halted and the grid cell containing the current source is highlighted. The operator is prompted to select a new location which is done by clicking on the desired location on the screen. If the location highlighted is not desired a new location can be chosen any number of times. Once the correct location is highlighted the operator double-clicks on the highlighted cell and the model's operating parameters are reset and a new run is started.

Edit Graphic Displays: Allows the user to control the whether a display is active and its location. (Figure 3)

Quit: Halts execution of the model and returns control to the Macintosh Operating System's Finder.

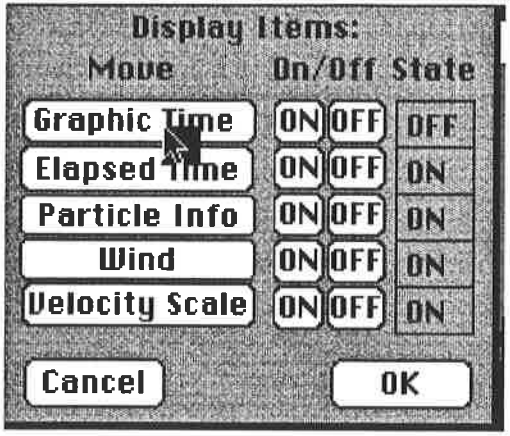


Figure 3 - Graphic Display Dialog

Control Menu (Figure 4.)

Display Bathymetry: Model execution is halted and a false color display of the water depths for the current time step is displayed. The display remains until the operator reselects the menu item. At that time the default screen is redrawn and model execution is resumed as if uninterrupted.

Pixel Concentrations: Displays a false color image of concentrations represented by the subsurface particle distribution. Similar to Oil Quantities below.

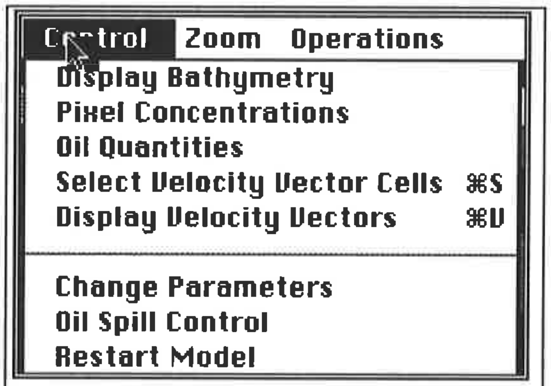


Figure 4 - Control Menu

Oil Quantities: Model execution is halted and a false color display of the quantity of oil contained in the area of each pixel is calculated and displayed. The range of values displayed as well as the number of color steps used to display the range are adjustable by numerical fields in Dialog Windows The operator continues the model run by reselecting the menu item.

Select Velocity Vector Cells: (Figure 5.) Model execution is halted and the operator is prompted to select locations for the display of velocity vectors. If a single water cell is selected it is highlighted and added to the display list. If a previously selected cell is clicked on, then the cell is un-highlighted and removed from the display list. Clicking and dragging will select or deselect rectangular and linear areas

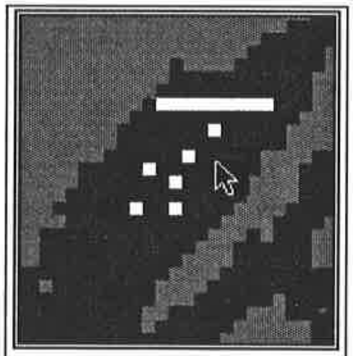


Figure 5 - Selecting Cells for Display

depending on the state of the cell first clicked on. This function allows full editing of vector display locations at any time of the operators choosing. When the selection editing process is complete the model run is resumed by reselection of the menu item.

Display Velocity Vectors: (Figure 6.) When selected, this menu item toggles the display of velocity vectors either on or off depending on the current state. When on, vectors are recalculated and displayed at the end of each time step. They may be turned on or off at any time. The locations selected remain until the run is terminated.

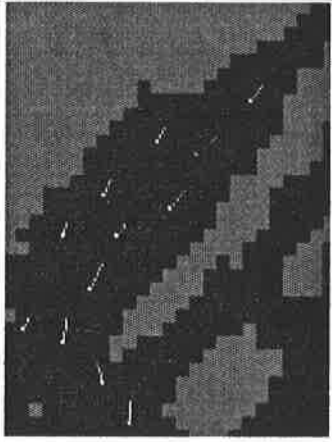


Figure 6 - Displaying Velocity Vectors

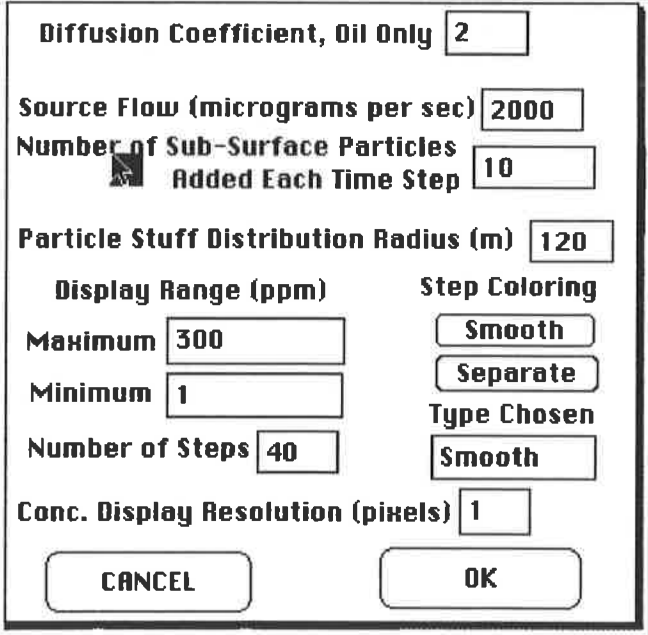
Change Parameters: Model execution is halted and a Dialog Window is presented. A description of each field and button within the dialog is contained in a following section.

Oil Spill Control: Model execution is halted and a Dialog Window is presented. A description of each field and button within the dialog is contained in a following section.

Change Parameters Dialog Window:
(Figure 7.)

Diffusion Coefficient (Oil): Is used to represent the rate of spreading of oil on the water's surface. It can be adjusted to reflect different turbulent mixing rates (m^2/s).

Source Flow: Scale factor to establish correct concentrations. Enter rate material introduced into the model.


Diffusion Coefficient, Oil Only: 2

Source Flow (micrograms per sec): 2000

Number of Sub-Surface Particles Added Each Time Step: 10

Particle Stuff Distribution Radius (m): 120

Display Range (ppm)

Maximum: 300

Minimum: 1

Number of Steps: 40

Type Chosen: Smooth

Conc. Display Resolution (pixels): 1

Figure 7 - Change Parameters Dialog Window

Number Of Particles Added Each Time Step: The computation time required for a given time step is directly proportional to the total number of active particles within the model. Therefore the "speed" of the model is controlled by varying the number of particles added at the start of each time step. However it is also true that the accuracy of the simulation is a function of the total number of particles used and that for realistic results a large number must be used. If it is desired to observe the hydrodynamics of the estuary or to see in general where particles are likely to go, start the model with only 1 or 2 particles added each time step. If, on the other hand, it is desired to obtain accurate plots of concentrations as many as 100 or 200 particles may be needed per time step.

Particle Stuff Distribution Radius: Is one half the length of a square over which a particle's substance is distributed in the pixel concentration function (smoothing function).

Display Range: This section is used to control the display of the false color concentration plots. The *Maximum & Minimum* values allow unwanted data to be screened out (not shown) on the low end and set to the highest color on the high end. The *Number Of Steps* is the number of different colors that the range of values will be mapped to. A Legend Bar is displayed on the screen to allow interpretation of the displayed data.

Step Coloring: These two buttons, "Smooth" and "Separate", control the type of color gradation used to display the concentrations. If "Smooth" is chosen then a portion of the palette is used where the colors blend smoothly into each other. They start at a medium red and proceed through yellow into light green. The full range of colors is always used and the number of shades skipped between each step is varied to allow different numbers of steps to be selected. If "Separate" is chosen the number of steps is fixed at ten and the colors vary radically from one step to the next. The effect produced is somewhat similar to contours rather than clouds.

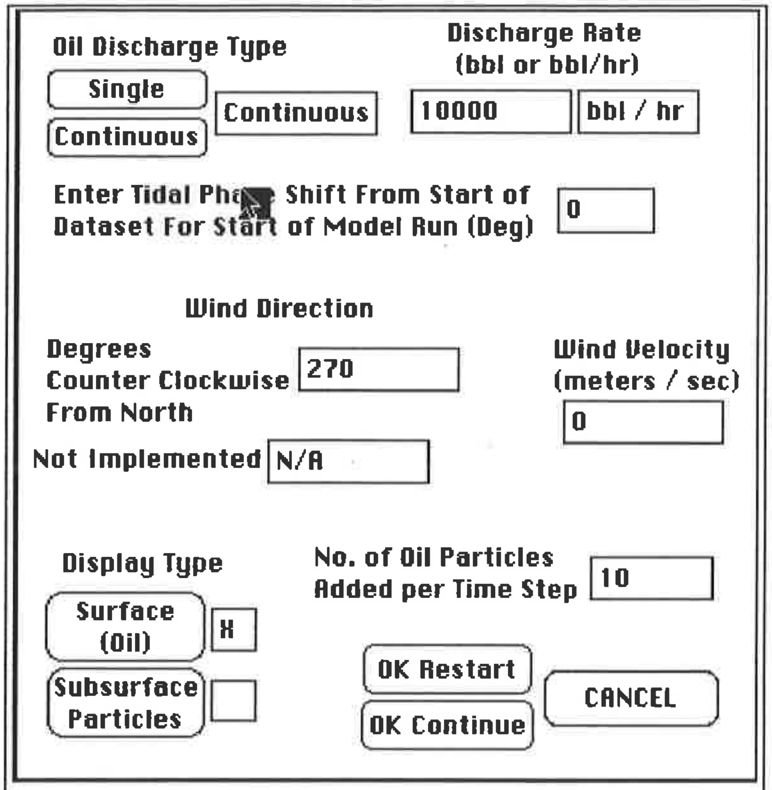
The *CANCEL* Button resets all values to their state when the dialog was opened, and restarts model execution as if uninterrupted.

The *OK* Button accepts the values as displayed and also resumes the model execution.

Oil Spill Control: Dialog Window (Figure 8.)

Oil Discharge Type: The Two buttons "Single" & "Continuous" allow the operator to select the type of discharge condition to be modeled. The current type in effect is shown in the boxed text field. Selection of a different type does not require the model to be restarted. This allows considerable flexibility in the entrance of oil to the model area. Examples following this section will provide more detailed explanation of how this can be accomplished.

Discharge Rate: Depending on the type chosen this field allows the operator to enter the quantity of oil discharged. The units field is appropriate to the type of discharge currently in effect.



Oil Discharge Type: Continuous

Discharge Rate (bbl or bbl/hr): 10000 bbl / hr

Enter Tidal Phase Shift From Start of Dataset For Start of Model Run (Deg): 0

Wind Direction

Degrees Counter Clockwise From North: 270

Not Implemented: N/A

Wind Velocity (meters / sec): 0

Surface (Oil): X

No. of Oil Particles Added per Time Step: 10

Figure 8 - Oil Spill Control Dialog

Tidal Phase Shift: This field allows the operator to alter the time within the tidal cycle at which the model run is started. The value is in degrees from the start of the tidal cycle as shown on the graphic tidal cycle display. For example, if the start of the cycle on the display is low tide and it is desired to start the model at Maximum flood stage, then the operator would enter 90 in the edit text field.

Wind Direction: Is the direction in degrees measured counter-clockwise from North that the wind is coming from. The wind is applied to the modeled area as a uniform vector field which does not vary with time.

Wind Velocity: Is the speed of the wind in meters per second.

Display Type: This function is not implemented in this version of the model.

No. of Particles Added per Time Step: Is an alternate method of controlling the number of particles added at the start of each time step. See the description of this option in the Change Parameters Dialog description above.

The *OK Restart* button: allows the values in the dialog to be entered into the model and the model is reset and restarted as a new run.

The *OK Continue* button: allows the values in the dialog to be entered into the model and the model run is continued as if uninterrupted, though with the changed values in place.

The *CANCEL* button: Allows the model run to proceed without changing any values. The state of all the model variables is as if the dialog had never been called up.

Zoom: Menu (Figure 9.)

Zoom In: To zoom in or make part of the screen look larger, select the "Zoom In" menu item. The cursor will appear as a cross-hair. With the cross-hair cursor select the portion of the screen to be zoom while holding the mouse button down. When the mouse button is released the selected region will fill the part of the screen reserved for the model output.

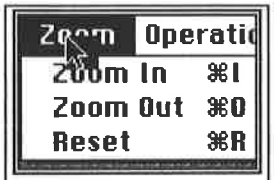


Figure 9 - Zoom Menu

Zoom Out: Zoom out automatically reduces the current screen by a factor of 2.

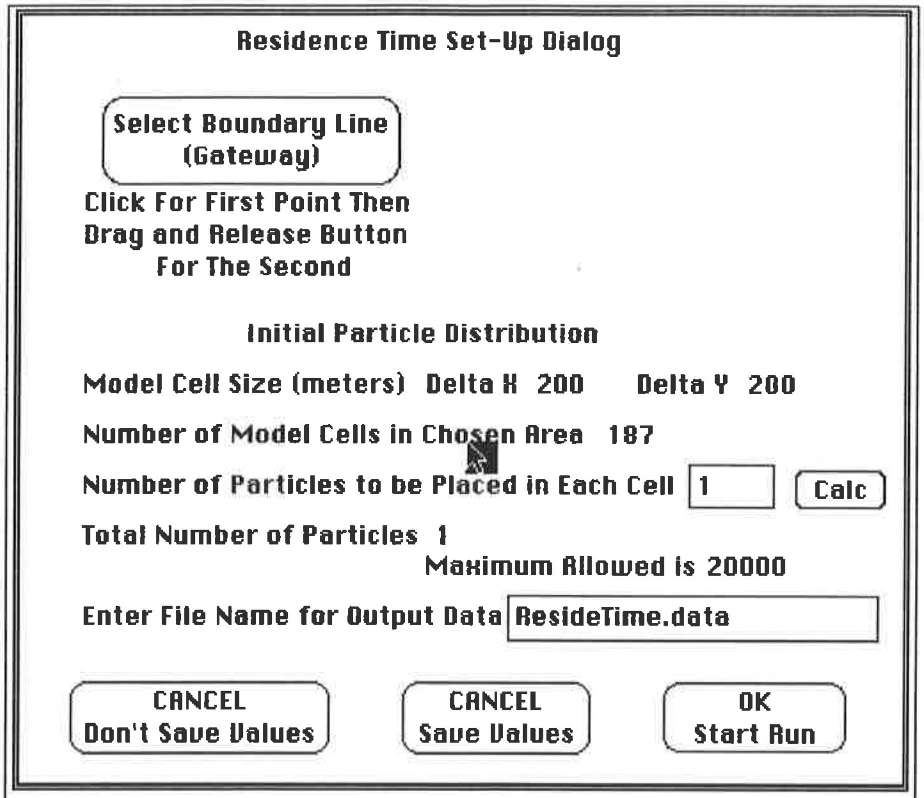
Reset: Reset sets the model portion of the screen to its original size.

Figure 10 - Operations Menu

Operations: Menu (Figure 10.)

Residence Time Set-Up: The Residence Time Set-Up menu item brings up the Residence Time Set-Up Dialog Window shown in Figure 11.

Select Boundary Gateway: The first action in investigating residence time is to select this item. The user action required is to select water cells on either side of a dead end water body. As shown in Figure 12 a double red line will appear. The user will be prompted to select side of the line that is of interest. After clicking with the mouse the region is highlighted in yellow and green (Figure 13). If the choice is correct then the area is filled with particles (Figure 14).



Residence Time Set-Up Dialog

Click For First Point Then Drag and Release Button For The Second

Initial Particle Distribution

Model Cell Size (meters) Delta X 200 Delta Y 200

Number of Model Cells in Chosen Area 187

Number of Particles to be Placed in Each Cell 1

Total Number of Particles 1

Maximum Allowed is 20000

Enter File Name for Output Data ResideTime.data

Figure 11 - Residence Time Set-Up Dialog

The dialog also displays the current grid size, the number of model cells chose, and allows for the user to input the number of particles to introduced per cell. The default is one. The user may also input a file name. The file will contain a list of times and number of particles during the run. This allows for a simple mechanism to plot the number of particles per unit time.

STOP Run: Stops the run.

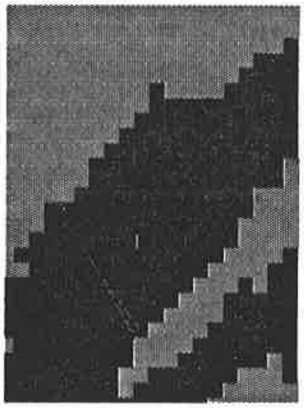
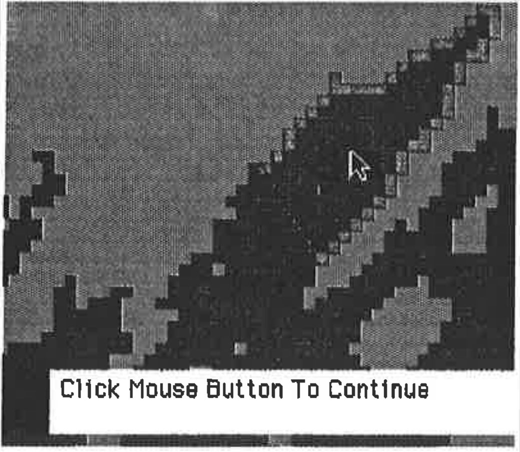


Figure 12 - Double Red Line



Click Mouse Button To Continue

Figure 13 - Region Outlined In Green

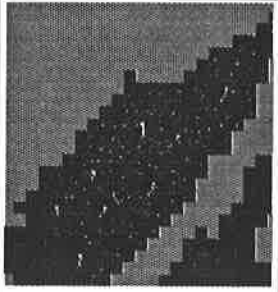


Figure 14 - Distributed Particles

Related Reports:

Kleinschmidt, David G. and B. R. Pearce, "DETMOD: A Desktop Estuarine Transport MODel." Proceedings of the First Congress on Computing in Civil Engineering, Washington, D.C. June, 1994. (Session Chairman)

Gong, B. and B. R. Pearce, "Circulation and Flushing in Casco Bay Maine" Proceedings of the First Congress on Computing in Civil Engineering, Washington, D.C. June, 1994. (Session Chairman)

Kleinschmidt, D. G. and B. R. Pearce "Microcomputer Based Tools for the Investigation of Coastal Hydrodynamic Systems", - *Proceedings, 2nd International Conference on Hydraulic and Environmental Modeling of Coastal, Estuarine, and River Waters*, University of Bradford, Bradford West Yorkshire, U.K., September 1992.

Pearce, Bryan R., D. L. Foster, V J. Schuler, P. V. Sucsy, and V. G. Panchang , "Numerical Thermal Plume Simulation Using a Lagrangian Tracer Technique", *Report - Department of Civil Engineering, University of Maine*, April 1991.

Kleinschmidt, D.G., Bryan R. Pearce, , "PARTOMATIC - A Lagrangian Heated Plume Model", *Proceedings of Estuarine and Coastal Modeling*, Nov. 1991, Tampa Florida.