Modeling the Tides of Massachusetts and Cape Cod Bays

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Abstract

A time-dependent, three-dimensional numerical modeling study of the tides of Massachusetts and Cape Cod Bays, motivated by construction of a new sewage treatment plant and ocean outfall for the city of Boston, has been undertaken by the authors. The numerical model being used is a hybrid version of the Blumberg and Mellor ECOM3D model, modified to include a semi-implicit time-stepping scheme and transport of a non-reactive dissolved constituent. Tides in the bays are dominated by the semi-diurnal frequencies, in particular by the M₂ tide, due to the resonance of these frequencies in the Gulf of Maine. The numerical model reproduces, well, measured tidal ellipses in unstratified wintertime conditions. Stratified conditions present more of a problem because tidal-frequency internal wave generation and propagation significantly complicates the structure of the resulting tidal field. Nonetheless, the numerical model reproduces qualitative aspects of the stratified tidal flow that are consistent with observations in the bays.

Massachusetts and Cape Cod Bays

Massachusetts and Cape Cod Bays (hereafter refered to simply as “the bays”), together, constitute approximately a 100 × 50 km semi-enclosed basin having an average depth of 35 m in the western Gulf of Maine (figure 1). The bays are used for a variety of potentially conflicting purposes including commercial and recreational fishing, shipping, recreational boating, swimming, and as a repository for sewage effluent and dredged sediments. At present, the Massachusetts Water Resources Authority (MWRA) is constructing a new sewage treatment plant for the city of Boston and 42 surrounding communities (Tarricone, 1992). The plant, when fully operational, will discharge 1.3 bgd (56 m³s⁻¹) of secondarily treated effluent, making it the second largest sewage treatment facility in the United States. The effluent will be discharged into Massachusetts Bay through a 14

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2323
Figure 1: Base map of the Massachusetts and Cape Cod Bay system showing proposed outfall location, bathymetric contours, and Stellwagen Bank.
km-long, 7.3 m-diameter, solid-rock tunnel (figure 1). The last two km of which contain a set of 80 .8 m-diameter risers used to transport the effluent to the seabed.

In order to help ensure that the discharge of effluent will have minimal effect on the shoreline residents and ecological resources of the bays, including the endangered North Atlantic Right Whale population that feeds on Stellwagen Bank (figure 1), a three-dimensional (3-d) numerical circulation model of the bays has been developed by the authors. The numerical model being used is based on the 3-d, time-dependent coastal circulation model, ECOM3D, developed by Blumberg and Mellor (1987). The model consists of fully nonlinear prognostic (i.e. predictive and interactive and thereby able to affect conservation of the other variables) equations for temperature, salinity, free-surface elevation and momentum. Vertical turbulent-mixing processes are parameterized by means of a turbulent closure submodel whose adjustable parameters are set to well-established laboratory values, thereby leaving the model free of tuning parameters. A complete description of ECOM3D, including discretization schemes, stability criteria and imbedded parameter values, is reported by Blumberg and Mellor (1987). The code has been modified recently to include a semi-implicit time-stepping scheme and the ability to transport a non-reactive dissolved constituent. The time-stepping scheme was added in order to allow model time steps that exceed the Courant-Fredrichs-Lewy condition (e.g. model results presented here are from runs with a time step of 621 seconds, implying a maximum of roughly 5 times the CFL criterion.) Details of the semi-implicit scheme are presented in the ECOM-si users’ manual (HydroQual,1991). This modified version of ECOM3D is known as ECOM-si (semi-implicit).

ECOM-si employs an orthogonal curvilinear coordinate system in the horizontal (figure 2) and a \( \sigma \)-coordinate system (a coordinate system having the same number of cells regardless of depth) in the vertical. The Massachusetts Bay model grid is 68 by 68 cells in the horizontal and has 11 equally-proportioned levels in the vertical. Minimum grid spacing is approximately 600m in the vicinity of Boston Harbor. Maximum grid spacing is approximately 6000m, along the offshore open boundary. Model grid bathymetry was interpolated from bathymetric soundings collected by the National Oceanic and Atmospheric Administration.

The model of the bays can be forced by freshwater inflows at the mouth of the Merrimack River and at the proposed outfall site; momentum can be introduced at the free surface by specifying a time-dependent wind speed and direction; heat can be introduced at the free surface by specifying a time-dependent atmospheric heat flux; and, most importantly for the tidal problem, energy can be introduced at the open boundaries by specifying space- and time-dependent elevations. Partially clamped elevation boundary conditions with an arbitrary user-specified relaxation time are also available in ECOM-si for situations when wind, tide, atmospheric
Figure 2: Model grid for the three-dimensional circulation model, ECOM-si, of Massachusetts and Cape Cod Bays. The curvilinear orthogonal grid allows the mesh resolution to vary spatially, having a minimum grid spacing of 600 m and a maximum grid spacing of 6000 m. There are 11 vertical $\sigma$-levels, evenly distributed throughout the water column.
heating and freshwater inputs are simultaneously important (See Blumberg et al., 1993 for discussion of these cases.).

The Tides of Massachusetts and Cape Cod Bays

The tidal response of the bays is dominated by the semi-diurnal frequencies, in particular, by the $M_2$ tide (Irish and Signell, 1992). The average tidal range in the bays is 2.6 m. The average $M_2$ tidal range in the bays is roughly 2.45 m, implying that the diurnal and overtide sea surface responses are negligible. Based on extensive analysis by Irish and Signell (1992) of bottom pressure records collected at numerous points in the bays, tidal range is basically constant throughout the bays with slight amplifications of roughly 10% in Boston and Provincetown Harbors. Predominance of the semi-diurnal response in the bays is due to the fact that the Gulf of Maine is strongly resonant at the semi-diurnal frequencies causing the semi-diurnal tidal wave to propagate easily into the bays.

Irish and Signell (1992) also demonstrate that tidal currents are predominantly semi-diurnal, with the diurnal signal representing even a smaller portion of the flow than does the sea surface elevation. Despite the dominant frequencies being constant baywide, the velocity amplitudes, and hence the tidal excursions, vary significantly. Amplitude variations are due to basin slope and bathymetric variability. The strongest currents in the bays are found in the channel between Race Point and Stellwagen Bank. Tidal velocities as large as 1 knot and excursions as large as 12 km are not uncommon. Minimum tidal excursions of less than 2 km are found in the deep central part of Massachusetts Bay. Tidal excursions at the proposed outfall site are roughly 2 km.

Currents at tidal frequencies vary seasonally within the bays. Irish and Signell (1992) showed that internal waves with periods matching those of the tides are observed in the spring and summer when the bays are stratified. Stratification, and thus internal wave activity, disappears in the winter when surface cooling and storms completely mix the water column.

Modeling Tides in Massachusetts and Cape Cod Bays

As stated previously, tides in the bays are driven almost exclusively by the $M_2$ tidal response of the Gulf of Maine. Therefore, because of limited space, the results presented herein focus only on the response of the bays to forcing at the $M_2$ frequency. This forcing is introduced along the model’s open eastern boundary by specifying $M_2$ amplitudes and phases for sea surface elevation. These data were obtained from a tidal model of the Gulf of Maine (Naimie and Lynch, 1991) which has been finely-tuned to reproduce observations in the gulf.

Figure 3 contains a comparison of eight modeled and measured surface tidal current ellipses for well-mixed conditions — at sites identified as U2, U3, U6, U7, RP, MN, BB and BS in figure 3 (See Irish and Signell, 1992, or Geyer et al., 1992, for details of measurements). It should be noted that the orientation and
Figure 3: Comparison of modeled and observed surface $M_2$ barotropic tidal currents in the bays. Shown are tidal ellipses, which indicate the observed velocities over the tidal cycle. They also represent the excursions water parcels would make if they moved with the tidal currents observed at the mooring. For clarity, these tidal excursions are shown at three times actual scale.
amplitude of the ellipses varies substantially throughout the bays. In the figure, the size of the ellipse not only represents the current velocity but also the tidal excursion at the measurement site. The ellipses are scaled to represent 3 times the observed tidal excursion at the measurement sites.

The model reproduces both amplitudes and orientations of the tidal ellipses very well. Comparisons similar to those shown in Figure 3, but for other depths in the water column, show that the model reproduces the barotropic M₄ tide very accurately throughout the water column everywhere in the bays for well-mixed conditions. There is some difference in ellipticity between the modeled and observed currents at the station located between Race Point and Stellwagen Bank — identified as RP in figure 3. The modeled flow appears to be too rectilinear. This can be attributed to insufficient model grid resolution at the measurement location (figure 2). Rapid changes in bathymetry in this area cause secondary flows which increase the cross-channel amplitude of the tidal ellipse. The model appears to underresolve these secondary flows. This assertion was confirmed by doubling the model grid resolution and observing a significant improvement in agreement between modeled and observed ellipticity.

Comparisons similar to those shown in figure 3, but for stratified periods, are, in general, less accurate than for well-mixed periods. Experimentation with different degrees of stratification indicates that these results are extremely sensitive to the density structure of the water column. Therefore, additional effort continues to be placed on the development of accurate temperature and salinity open-boundary conditions, as well as physically realistic atmospheric heat flux surface-boundary conditions for the model. Figures 4 and 5 are included here to illustrate qualitatively the differences in tidal behavior between well-mixed winter conditions and stratified summer ones. Each figure contains contours of uₓ, the square root of the maximum kinematic bottom stress amplitude (see Blumberg and Mellor, 1987, for a description of ECOM-si's bottom stress formulation). Figure 4 represents well-mixed wintertime conditions and figure 5 represents stratified summertime conditions. The summertime conditions shown are maximum uₓ values after 3 tidal cycles for which the model was initialized everywhere using the maximum stratification profile observed in Stellwagen Basin during 1990 and for which temperature and salinity were treated prognostically in the model.

Spatial scales of the contours in the wintertime scenario are much larger than those of the summertime scenario indicating much less high wavenumber variation in bottom stress. The implication of this is that internal waves are present in the latter. Measurements (Irish and Signell, 1992) indicate the presence of internal waves in much of the bays during the stratified season, including the presence of a nearly-classic first-mode internal wave in Stellwagen Basin. It is interesting to note that magnitudes of bottom stress can be either reduced or increased by the presence of internal waves, depending on the whether they interfere constructively or destructively with the barotropic tide. Whether internal waves are present or not and the manner in which they interact with the M₄ tide, if present, is
Figure 4: Maximum $u_*$ due to forcing the model’s open boundary with $M_2$ tides under well-mixed conditions. Contours are in units of cm/s and represent the square root of the kinematic bottom stress. Areas of intense currents between Race Point and Stellwagen Bank and in the mouths of Boston and Plymouth Harbors are clearly visible.
Figure 5: Maximum $u_*$ due to forcing the model’s open boundary with $M_2$ tides under stratified conditions. Contours are in units of cm/s and represent the square root of the kinematic bottom stress amplitude. The model was initialized with the maximum summertime stratification observed in Stellwagen Basin in 1990, and was allowed to run for 3 tidal cycles treating temperature and salinity prognostically. The much finer spatial structure relative to that shown in figure 4 is an indication of the presence of internal waves.
determined by the complex bathymetry of the bays. Studies to further improve the modeling of tides in the bay under stratified conditions and to investigate the interaction between the tides and other important flows in the bays, such as wind-driven flows or those initiated by impulses of freshwater, are currently underway.

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