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Wave-adjusted boundary condition for longshore current in finite-volume circulation models

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Abstract

Numerical modeling of coastal circulation encompassing the nearshore requires forcing by tide, surface gravity waves, and possibly other factors. In the nearshore, the wave-induced longshore current and setup are dominant hydrodynamic processes, and lateral boundary conditions representing tide and oceanic forcing typically do not include surface-wave contributions. Without proper boundary conditions, significant gradients in current and water level can occur that contaminate the solution in the internal domain. A standard strategy is to place the boundaries far from the site of interest, but this strategy greatly increases computational demands, and it may not be appropriate for long-term simulations. This paper describes a wave-adjusted boundary condition that accounts for wave-induced water level and current acting in combination with tidal forcing. The wave-adjusted boundary condition is demonstrated for an idealized case of a parallel-contour beach and for an engineering application at Ocean City, MD.

Keywords: Nearshore circulation; Longshore current; Wave setup; Boundary condition; Numerical modeling

1. Introduction

Circulation modeling for the nearshore, where depth-limited wave breaking occurs, has progressed to include coupled current, wave, and sediment transport processes. Early models of nearshore circulation (Longuet-Higgins, 1970a,b; Noda, 1974) incorporated

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forcing only by surface gravity waves. In coastal engineering applications, involving the nearshore, wide-scale modeling of coastal circulation and transport must represent tidal, surface wave, and other possible forcing simultaneously. Coupling of the acting hydrodynamic and morphologic processes allows simulation of flow and transport at and around inlets, navigation channels, structures, and in nearshore areas where waves break. In combined current and wave simulations, the radiation-stress fields associated with surface waves generate wave-induced currents and setup along coastal boundaries (Longuet-Higgins and Stewart, 1963) that can be much stronger than tidal and wind-induced flows.

Typically, the offshore boundaries of an oceanic circulation model are forced with water surface elevation information derived from tidal constituents, measured water-level time series, or from larger-scale regional circulation models. Such oceanic modeling boundary conditions will not be consistent with the interior solution for the nearshore if modification of the water level and current velocity by surface waves is included in the calculations. The inconsistency can produce large and unrealistic gradients in the water surface in surf zone areas where the ocean boundaries intersect the shore. Unrealistic gradients in water level at model boundaries extending seaward from the shoreline through the region of wave breaking induce large and anomalous currents that contaminate the solution in the interior domain. If sediment transport simulations are included, the anomalous currents can lead to severe transport gradients as well, and the unrealistic morphologic feedback to the circulation model at the boundaries can cause model instability.

Boundary forcing information that includes wave-driven processes across the surf zone is not available for typical applications. For this reason, practical application requires development of large domains for coupling circulation and wave models, so that boundary incompatibilities can be placed far away from the area of interest. However, for long-term simulations, mismatches at even apparently distant boundaries may contaminate the solution in the area of interest. In addition, variability in input wave conditions will modify the spatial extent of contamination.

An approach is presented here that adjusts the water-elevation boundary condition for the presence of wave-induced setup. The wave-adjusted boundary condition requires that (1) the radiation-stress gradient field obtained from a wave model overlap the circulation model boundaries, and (2) the lateral ocean boundaries are situated reasonably normal to the shoreline. One-dimensional (1D) continuity and momentum equations containing the radiation-stress gradients are solved along the axis normal to the boundary. Wave-induced setup along this axis is added to the prescribed water-elevation boundary forcing values to provide consistent water elevation values at the boundary and in the grid interior, which subsequently eliminates anomalous velocities. The wave-adjusted boundary condition is presented here as it was implemented in the depth-averaged finite volume circulation model M2D (Militello et al., 2004) for which it was originally developed. The method is generally applicable to both two- and three-dimensional circulation models.

2. Boundary adjustment formulation

Boundary forcing adjustment is accomplished by creating a surface deflection (setup and setdown) consistent with that of the interior solution so that flow generated by wave radiation stress gradients can move smoothly through the boundary. The method can be described in the context of the M2D circulation model, which computes water surface elevation and depth-averaged velocity components on a rectilinear C grid with staggered dependent variables. Water surface elevation is defined at the cell center and velocities are located at the cell faces as depicted in Fig. 1.

A typical application including surface wave forcing is depicted in Fig. 2, which shows a portion of a grid near the shoreline and ocean boundary. In this general representation, the shoreline is at the bottom, with $V_{1,1}$, $V_{1,2}$ and $V_{1,3}$ set to zero as boundary conditions. Water elevation boundary conditions are specified at cell centers for the leftmost column at $\eta_{1,1}$ and $\eta_{1,2}$. Velocity components along the left face of the leftmost column ($U_{1,1}$, $U_{1,2}$ and $U_{1,3}$) only enter the M2D solution algorithms in the advective terms. These velocity boundary values can be set to zero, specified from a regional model solution or extrapolated from the interior, although the later case can lead to unstable solutions.

Incompatibilities between the boundary and interior solution arise if wave forcing, as depicted in Fig. 2, is applied in a simulation in which ocean boundary forcing does not represent the hydrodynamic response of surface waves in the nearshore. In this situation, the model will correctly calculate the wave-induced setup at the interior points $\eta_{2,1}$ and $\eta_{2,2}$, and it will also correctly simulate the wave-induced currents (i.e. to the right) for most interior points (i.e. $U_{2,2}$ and $U_{3,2}$). However, velocities at the right face of the first column ($U_{2,1}$ and $U_{2,2}$), which are calculated by the M2D solution algorithm, will not be realistically represented because an anomalous surface gradient will develop between the first and second columns. This gradient occurs because the water elevations in the interior

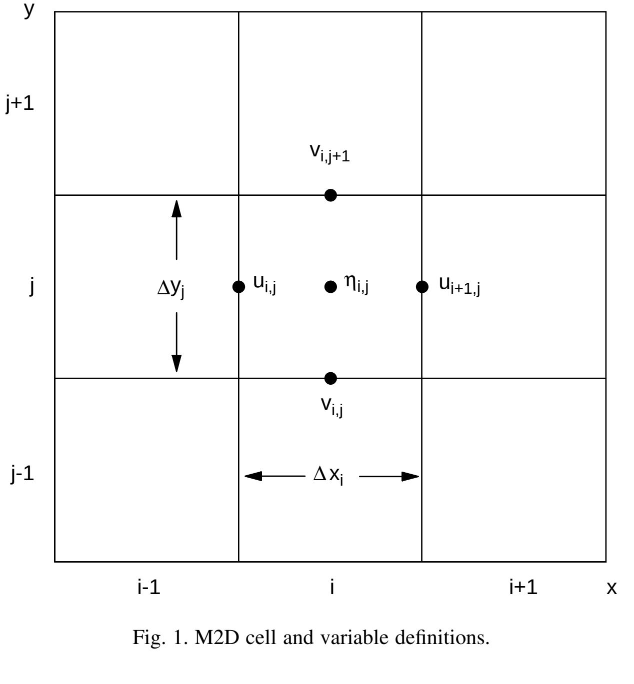

Fig. 1. M2D cell and variable definitions.

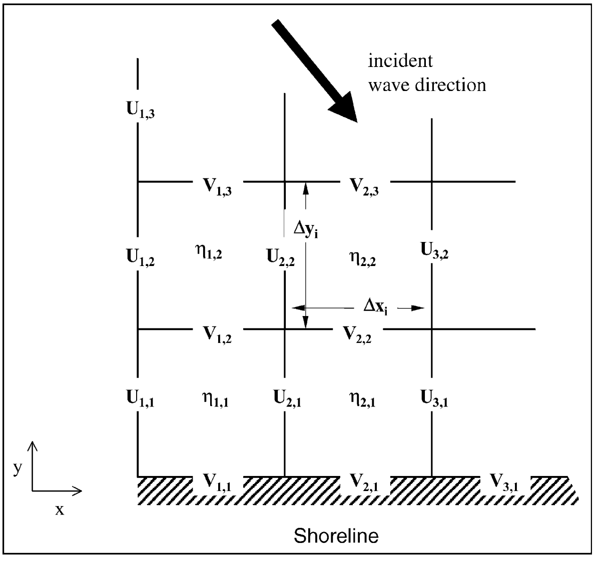

Fig. 2. M2D grid and variables near a shoreline.

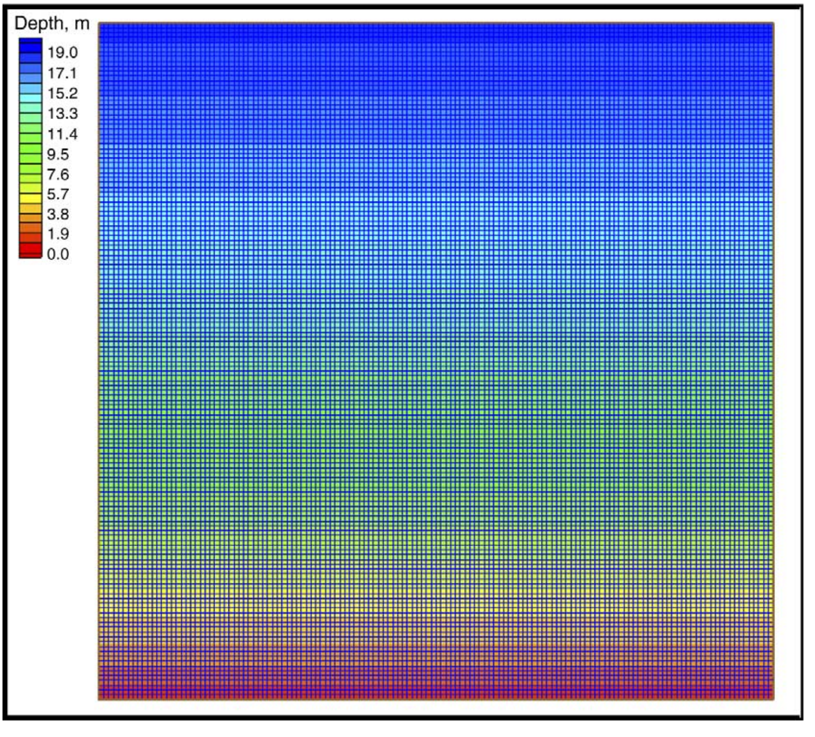

Fig. 3. Computational grid and bathymetry for idealized beach.

($\eta_{2,1}$ and $\eta_{2,2}$) are responding to the incident waves, whereas the boundary values ($\eta_{1,1}$ and $\eta_{1,2}$) are fixed at the prescribed levels.

A simple example is presented to demonstrate this result. A computational grid representing a longshore uniform beach with a linear slope was created (Fig. 3) having spacing of 50 m in each horizontal direction, and depths ranging from 1.13 m at the shoreline to 18.4 m at the seaward boundary. The steady spectral wave model STWAVE (Smith et al., 2001) was applied to calculate radiation-stress gradients for a 2 m wave with a period of 10 s and incident direction of 25° relative to shore normal. STWAVE simulations were conducted on an identical grid as the M2D simulations, and the STWAVE spectral spreading parameters were $\gamma=3.3$ and nn=4. M2D simulations consisted of a 12.5 h duration with 2 s time step and ramp duration of 0.02 day that was sufficient to provide steady conditions. All M2D ocean boundaries were prescribed constant water surface elevation values of 0 m.

Water surface elevation and velocity for the simulation are shown in Figs. 4 and 5, respectively. Setup is calculated at the shoreline, but decreases to zero at the lateral boundaries. An alongshore current develops in the nearshore as expected, but velocities at the lateral boundaries display unrealistic patterns. In the lower left corner, the flow is opposite to the expected direction, and in the lower right corner, the flow is accelerated. Just outside of the surf zone, a significant and anomalous flow into the grid is predicted, and propagates through the entire solution domain.

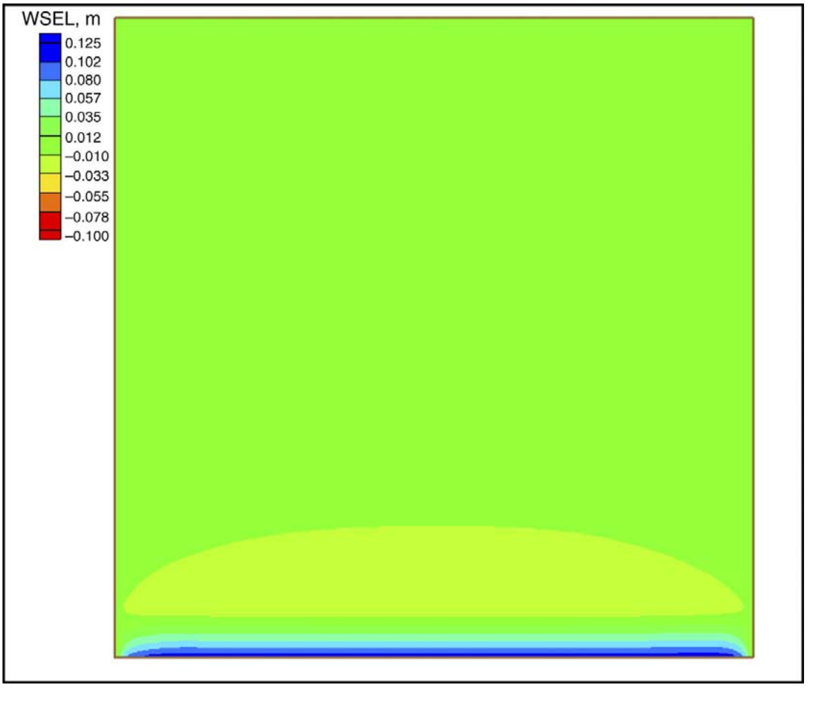

Fig. 4. Water surface elevation calculated with standard water surface elevation boundary condition.

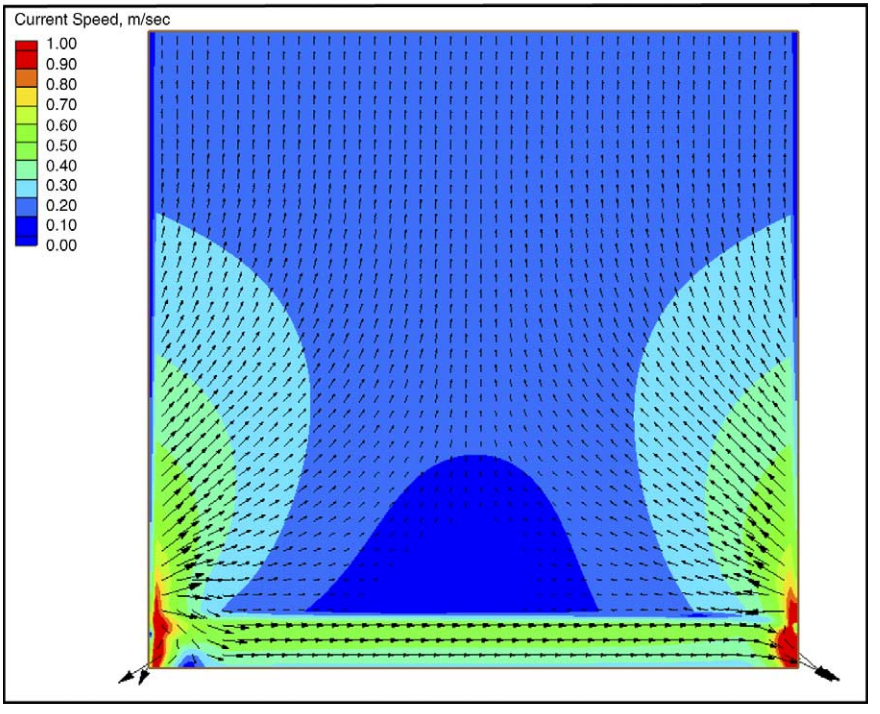

Fig. 5. Velocity calculated with standard water surface elevation boundary condition.

A conceptually simple method has been developed to alleviate the artificial water surface gradients and associated anomalous current pattern. This method consists of adding an adjustment to the prescribed water elevations at the forcing boundaries. Adjustments to the prescribed boundary conditions are calculated by solving the 1D continuity and momentum equations normal to the boundary, in which the radiation-stress gradient is included in the momentum equation. For a grid system with the *y*-axis aligned perpendicular to the shoreline, the 1D equations are

$$\frac{\partial(h+\eta_{\mathrm{b}}+\eta')}{\partial t}+\frac{\partial Q'_y}{\partial y}=0 \tag{1}$$

$$\frac{\partial Q'_y}{\partial t}+\frac{\partial v'Q'_y}{\partial y}+\frac{1}{2}g\frac{\partial(h+\eta_{\mathrm{b}}+\eta')}{\partial y}=-\tau_{\mathrm{by}}+\tau_{\mathrm{wy}}+\tau_{\mathrm{Sy}} \tag{2}$$

where t is time, y is the independent spatial variable, h is the still-water depth, η_{b} is the prescribed boundary condition, η' is the water elevation adjustment, Q'_y is the flow along the y direction, v' is the velocity adjustment, τ_{by} is the y-component of the bed stress, τ_{wy} is the y-component of the wind stress and τ_{Sy} is the radiation-stress gradient along the y direction. The flow Q'_y is defined as

$$Q'_y=v'(h+\eta_{\mathrm{b}}+\eta') \tag{3}$$

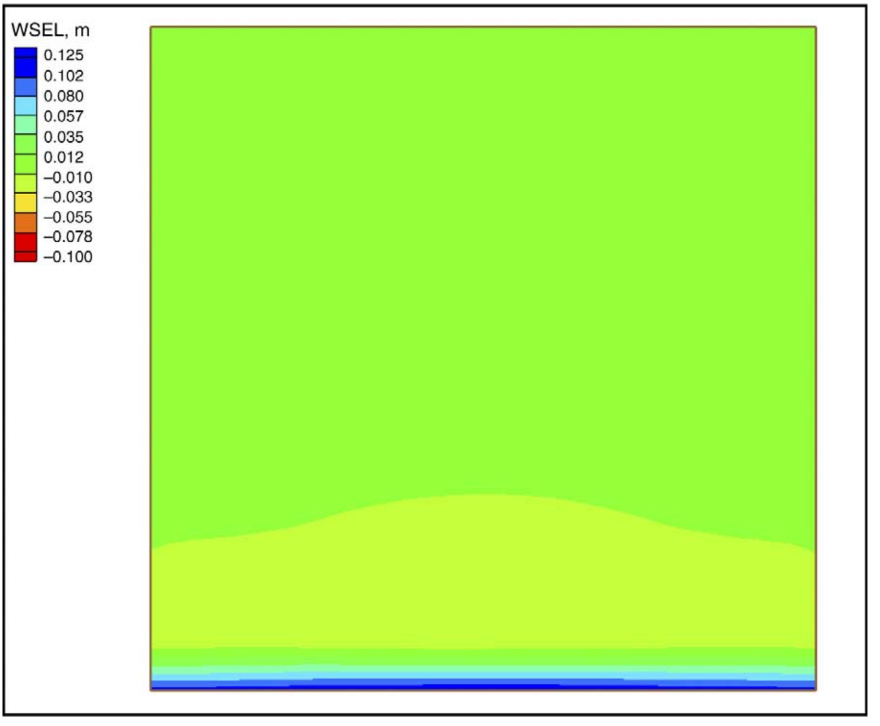

Fig. 6. Water surface elevation calculated with wave-adjusted boundary condition.

The adjusted water elevation η_{adj} is

$$\eta_{\mathrm{adj}} = \eta_{\mathrm{b}} + \eta' \tag{4}$$

and this value is applied at the boundary in place of the prescribed boundary value η_{b}. If the boundary is specified as a mixed water surface elevation and velocity boundary, then the v component of velocity assigned at the boundary is adjusted accordingly

$$v_{\mathrm{adj}} = v_{\mathrm{b}} + v', \tag{5}$$

where v_{adj} is the applied velocity at the boundary, and v_{b} is the prescribed velocity.

The finite-volume equations implemented in the M2D model for momentum are

$$\begin{aligned}&\frac{\Delta q_{y_{i,j}}}{\Delta t}\Delta x_i \Delta y_j + (G^k_{x_{i+1,j}} - G^k_{x_{i-1,j}})\Delta x_i + \frac{1}{2} g\left[(h_{i,j} + \eta^k_{i,j} + \eta'^k_{i,j})^2\right.\\ &\quad \left.-(h_{i,j-1} + \eta^k_{i,j-1} + \eta'^k_{i,j-1})^2\right]\Delta x_i = -\tau^k_{\mathrm{by}_{i,j}}\Delta x_i \Delta y_j\\ &\quad + \tau^k_{\mathrm{wy}_{i,j}}\Delta x_i \Delta y_j + (\tau_{\mathrm{S}y})^{k+1}_{i,j}\Delta x_i \Delta y_j\end{aligned} \tag{6}$$

where $\Delta q_{y_{i,j}} = q_{y_{i,j}}^{k+1} - q_{y_{i,j}}^{k}$, and

$$F_{y_{i,j+1}}^{k} = \bar{v}_{i,j+1}^{k} q_y^{*}, \quad \bar{v}_{i,j+1}^{k} = \frac{q_{y_{i,j}}^{k} + q_{y_{i,j+1}}^{k}}{2\left(h_{i,j} + \eta_{i,j}^{k}\right)}, \quad \begin{array}{ll} q_y^{*} = q_{y_{i,j}}^{k} & \text{when} \quad \bar{v}_{i,j+1}^{k} > 0 \\ q_y^{*} = q_{y_{i,j+1}}^{k} & \text{when} \quad \bar{v}_{i,j+1}^{k} < 0 \end{array}$$

and

$$q_{y_{i,j}} = v'_{i,j}(h_{i,j} + \eta_{\mathrm{b}_{i,j}} + \eta'_{i,j})$$

and for continuity is

$$\frac{\Delta \eta_{i,j}}{\Delta t} \Delta x_i \Delta y_j + (q_{y_{i,j}}^{k+1} - q_{y_{i,j+1}}^{k+1}) \Delta x_i = 0 \tag{7}$$

These equations are solved in time by the time-staggered algorithm applied in the M2D numerical solution (Militello et al., 2004).

The idealized beach simulation was run with the wave-adjusted boundary condition to assess its effectiveness as compared to the previous simulation. Results of the simulation with the wave-adjusted boundary condition are shown in Figs. 6 and 7. Improved setup calculated at the shoreline is evident in Fig. 5 and extends nearly uniformly across the entire grid. A well-developed and uniform longshore current forms in the nearshore area, both near the lateral boundaries and in the interior. Currents in the offshore region are

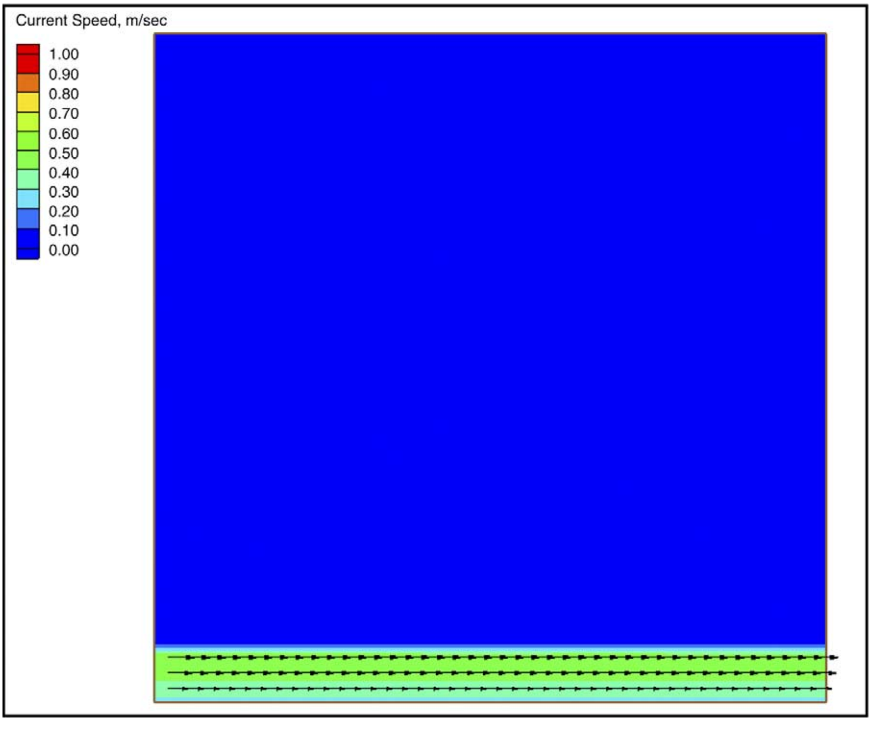

Fig. 7. Velocity calculated with wave-adjusted boundary condition.

weak and do not display the strong flows exhibited by the previous results. Because the boundary conditions were adjusted for the presence of wave forcing, the circulation patterns are realistic. Water can flow onto and off of the grid through the lateral boundaries without incompatibility between the boundary conditions and interior hydrodynamic processes.

3. Application of wave-induced boundary conditions at ocean city, MD Simulation

Application of the wave-adjusted boundary condition at Ocean City, MD, is provided to demonstrate the capability in a realistic modeling application. An M2D computational grid of the area was developed having cell spacing ranging from 50 to 148 m, with finest resolution at Ocean City Inlet (Fig. 8). Model bathymetry is shown in Fig. 9. A larger-domain STWAVE grid was developed so that radiation stress gradients would be calculated over the entire M2D computational domain. Cell spacing for the STWAVE model was specified as 100 m. Bathymetry for these grids was based upon the US Army

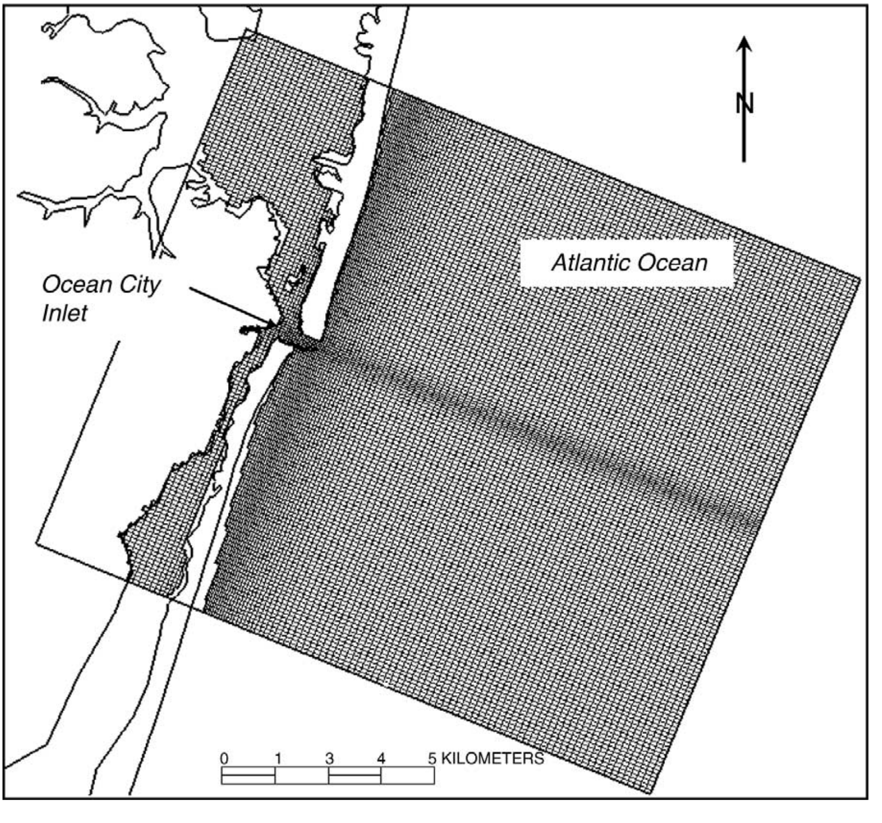

Fig. 8. Computational grid for Ocean City, MD, simulations.

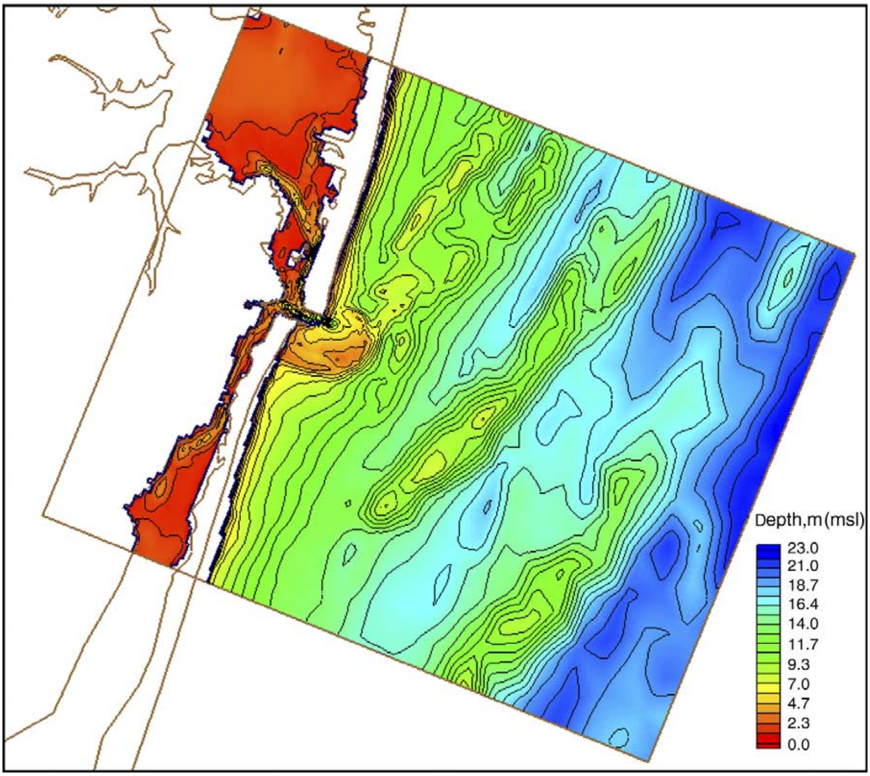

Fig. 9. Ocean City, MD, Bathymtery.

Corps of Engineers' Coastal Inlets Research Program (CIRP) regional ADCIRC (Luettich et al., 1992) model for the Delmarva Peninsula.

Forcing for the M2D simulation consisted of water surface elevation values applied at ocean boundaries and radiation-stress gradients mapped from STWAVE (Militello and Zundel, 2003). A global solution for tidal propagation calculated by the CIRP regional ADCIRC model was the source of water surface elevation values applied as M2D boundary conditions. Time histories of water level for each M2D boundary cell were interpolated from the nearest three ADCIRC node locations (Militello and Zundel, 2002). This interpolation process preserves the distribution of tidal elevation over the M2D forcing boundary, thereby retaining the spatial and temporal tidal phase variation over the model domain.

Input wave parameters for STWAVE were specified as significant wave height = 2.0 m, wave period = 8 s, and wave direction = 25° relative to shore normal. Radiation stress gradients calculated from the specified wave forcing were held constant for the M2D simulation.

The results of simulations with and without the wave-adjusted boundary conditions at the end of a 60-h simulation using a 2-s time step are provided for comparison. Figs. 10 and 11 compare the water elevation in the northeast corner of the grid for the situations

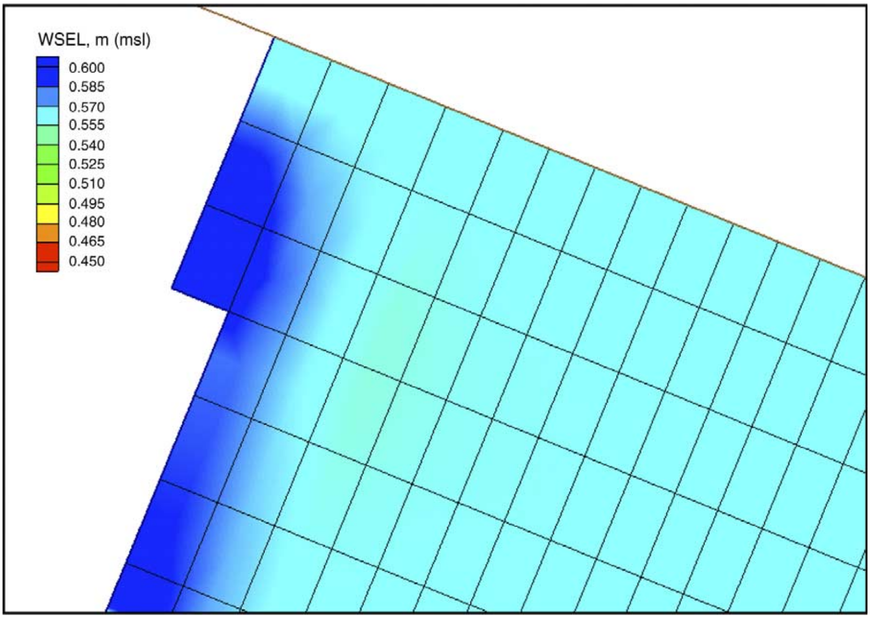

Fig. 10. Calculated water surface elevation with standard water surface elevation boundary condition.

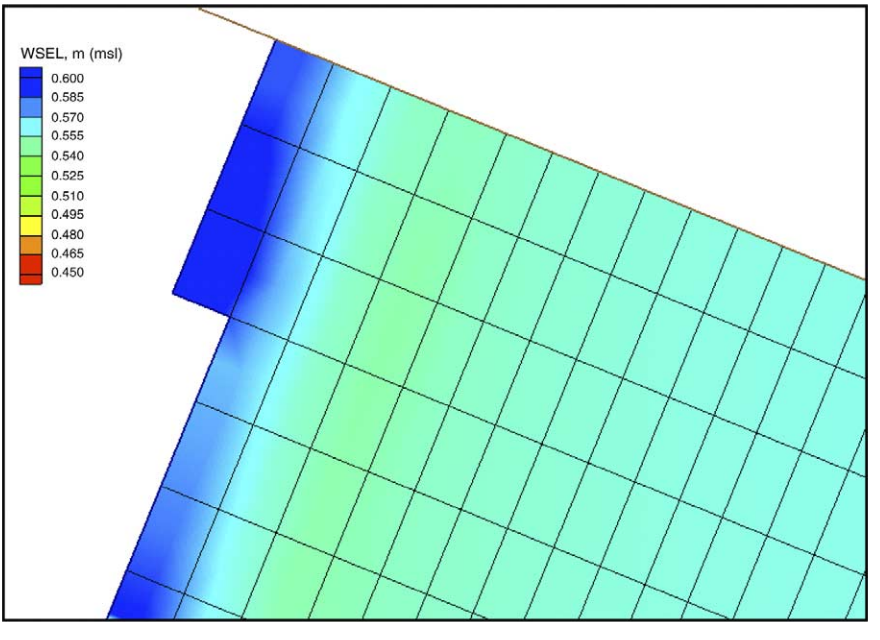

Fig. 11. Calculate water surface elevation with wave-adjusted water surface elevation boundary condition.

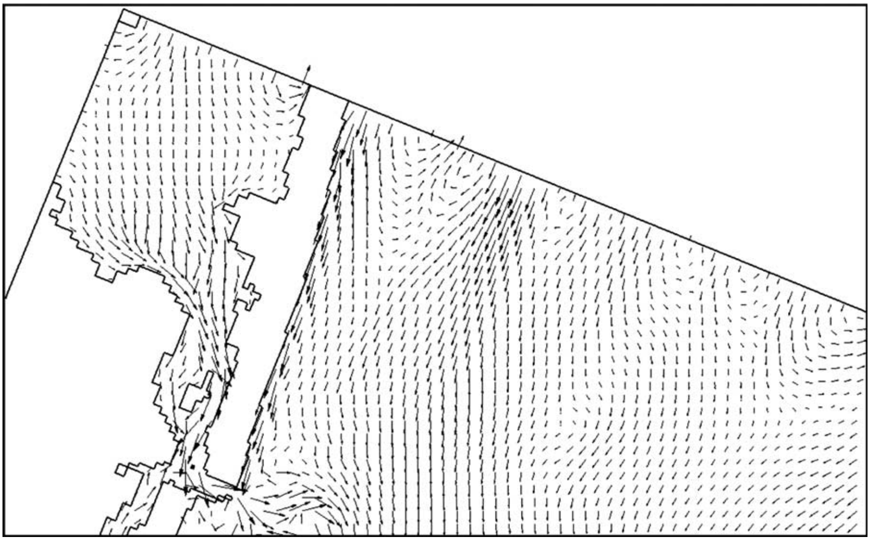

Fig. 12. Velocity calculated with standard water surface elevation boundary condition.

with the standard and wave-adjusted boundary conditions, respectively. In both plots, wave setup is calculated at cells adjacent to the shoreline, except at the lateral boundary cell for the standard boundary condition (Fig. 10). Velocities over a larger portion of the grid are shown in Figs. 12 and 13 for the standard and wave-adjusted boundary conditions, respectively. Both velocity plots show a well-developed longshore current. However, Fig. 12 displays unrealistic current patterns, such as the strong, jet-like influx seaward of

Fig. 13. Velocity calculated with wave-adjusted boundary condition.

the surf zone, as well as alternating reversals in flow direction along the lateral boundary. Current patterns in Fig. 13, calculated with the wave-adjusted boundary condition, exhibit realistic behavior with strong alongshore currents and weaker currents seaward of the surf zone.

4. Conclusions

A conceptually simple wave-adjusted boundary condition has been developed to reduce hydrodynamic incompatibilities near ocean boundaries when surface wave and tidal forcing are simultaneously represented in a circulation model application. The method was implemented into the M2D circulation model and successfully applied to both idealized and real modeling cases. The wave-adjusted boundary condition is generally applicable to other two- and three-dimensional models.

The method eliminates unrealistic gradients in water level at ocean forcing boundaries that have been shown to induce large and anomalous currents that contaminate the solution in the interior domain. This improvement in the overall hydrodynamic solution reduces requirements for large domain sizes specified to keep anomalous flows out of the subject study area. If sediment transport simulations are conducted, the wave-adjusted boundary condition will promote realistic calculations in long-term simulations, where the unrealistic morphologic feedback to the circulation model at the boundaries can cause model instability if boundary and interior incompatibilities are not treated appropriately.

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