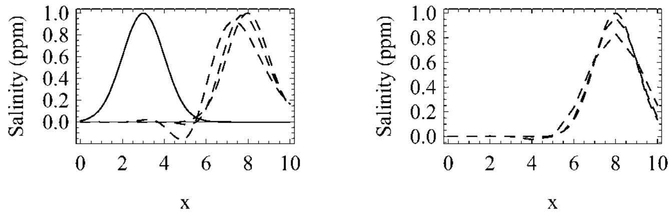

Figure 8 Convergence results for 1D SuPG transport formulation. Left panel: $\Delta t = 1.0$, 0.5 and 0.1 seconds. Right panel: $\Delta x = 1.0$, 0.5 and 0.1 m.

further resolution was not possible due to time constraints. However, the peak amplitude is 0.999 for the finest resolution and results indicate that the error is approaching zero.

Finally, we implemented the SuPG transport within the baroclinic ADCIRC *x*-*z* model. Figure 9 shows the front characteristics for these SuPG modifications. Again the bulk fluid motions are captured fairly well and there is a slight phase lead in the model results, when compared to the data. However, the front widths during the sloshing phase are much higher; although, the large spike in front widths is more closely captured (in magnitude) by the SuPG transport than it is in the existing ADCIRC formulation. Looking just at the linear portion of the results, we note that the front width behavior is correct although the magnitude is a bit high again. Additionally, the front speeds of the laboratory data and model results are comparable (lab speed = 0.077 m/s and model speed = 0.074 m/s). Furthermore, we note that global salinity mass balance was achieved throughout the simulation (to the 8th decimal place). Note that these results were obtained with a much coarser mesh than that used for the existing formulation results that were shown above in Figure 3. Due to time constraints, we were only able to use 38 horizontal elements and 11 vertical levels with the SuPG model (roughly one-third the resolution used in our previous work). Therefore, poor resolution is likely the cause of these discrepancies. Recall that the width and amplitude of the plume were artificially diffused in Figure 8 (due to the numerical diffusion added by the SuPG discretization) until adequate resolution had been achieved.

Table 2. Spatial convergence results for velocity 2:1 test (Δt=0.01).

Δx=Δz (m)	Location (m)	Amplitude (m)	Error
2.0	9/6	0.867	0.133
1.0	9/6	0.947	0.053
0.5	9/6	0.989	0.011
0.25	9/6	0.999	0.001

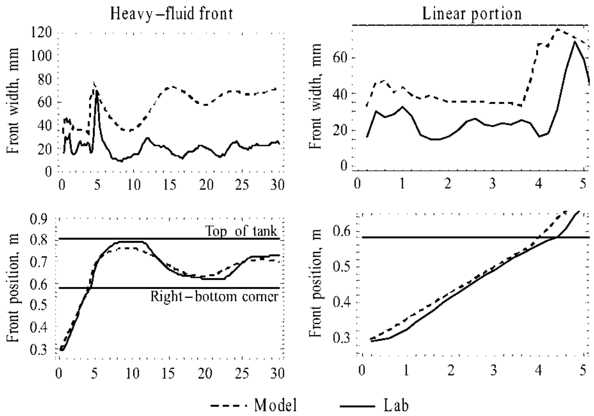

Figure 9 Comparison of front location and width versus time for the SuPG transport alternative baroclinic ADCIRC model against the laboratory lock-exchange data.

CONCLUSIONS

The simple upstream bias for advection terms did not improve stability, although it may provide a calibration parameter for capturing the front speed of the laboratory lock-exchange data. Furthermore, the SuPG transport alternative did not increase stability either. While the stand-alone SuPG transport model is promising (capable of matching the analytical solution and stable for pure-advection), when coupled with the varying ADCIRC hydrodynamics it does not perform as well. Future work includes further examination of the elemental velocity used in the SuPG weight functions (Equations (16) and (20)), as well as trying standard Galerkin weight functions for the intermediate diffusion variables, α and γ (Equations (22) and (23)). Additionally, we are examining the consistency of the SuPG transport model in light of the work of White (2007). Finally, the flux corrected transport does indeed allow for larger stable time steps, which may offset the use of two meshes (linear and quadratic). However, at this time, we are continuing to explore the SuPG alternative, as it best fits in the existing ADCIRC model framework.

ACKNOWLEDGEMENTS

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DEVELOPMENT AND APPLICATION OF THE COUPLED HYCOM AND ADCIRC SYSTEM

Kendra M. Dresback[1], Randall L. Kolar[1], Cheryl Ann Blain[2], Christine M. Szpilka[1], Anthony M. Szpilka[3], Richard A. Luettich[4] and Thomas Shay[4]

ABSTRACT

To accurately capture the fluid dynamics present in shallow straits and near-coastal zones, development efforts have centered around enhancing the 3D baroclinic capabilities of the coastal model, ADCIRC. The scale of resolution necessary to resolve shallow straits and coastal zones is not practical with structured global/regional models, such as HYCOM. However, ADCIRC utilizes an unstructured grid, which can capture complicated topography and coastal fluid dynamics. Typically, the barotropic ADCIRC domain encompasses large portions of the ocean; however, in baroclinic simulations, we restrict the domain to the region of interest due to computational demands. Consequentially, the open boundary is placed in an area dominated by complex, nonlinear processes, so proper specification of the open boundary conditions is difficult. Hence, one solution is coupling the offshore conditions provided from HYCOM to the near-coastal model, ADCIRC. This paper examines the coupling protocol needed to interface ADCIRC and HYCOM and provides preliminary results.

INTRODUCTION

Complex, near-coastal hydrodynamics interact nonlinearly with ocean basin scale flows, which dictates that accurate, three-dimensional, baroclinic models must resolve flows of widely-differing spatial and temporal scales. These flows occur in the intricate coastlines, shallow straits and underwater canyons that must be resolved to accurately predict the hydrodynamics within the coastal regions. However, the combined demands of three-dimensional flow, high resolution in coastal regions, and extensive spatial coverage precludes the use of a single, comprehensive model. The

1. Natural Hazards and Disaster Research - National Weather Center, School of Civil Engineering and Environmental Science, University of Oklahoma, 202 W. Boyd St, Room 334, Norman, OK, 73019, PH: 405-325-5911, Fax: 405-325-4217, emails: dresback@ou.edu, kolar@ou.edu, cmszpilka@ou.edu
2. Ocean Dynamics and Prediction Branch, Oceanography Division (Code 7322), Naval Research Laboratory, Stennis Space Center, MS 39529-5004, email: cheryl.ann.blain@nrlssc.navy.mil
3. Department of Natural Sciences, Carroll College, 1601 N. Benton Ave, Helena, MT, 59625, email: aszpilka@carroll.edu.
4. Institute of Marine Sciences, University of North Carolina - Morehead City, 3431 Arendell St., Morehead City, North Carolina 28557, emails: rick_luettich@unc.edu, tom_shay@unc.edu

scale of resolution necessary to resolve these shallow straits and coastal zones is not practical with structured global/regional models, such as the HYbrid Coordinate Ocean Model (HYCOM) (Chassignet et al 2003 and 2006). However, the ADvanced 3D CIRCulation Model (ADCIRC) (Luettich et al 1992 and 2004; Kolar et al 1994a) utilizes an unstructured grid, thus giving it the ability to map intricate coastlines and the corresponding topography that is needed to resolve the complex fluid dynamics. In two-dimensional barotropic applications, such as hurricane storm surge, the ADCIRC model domain can encompass large portions of ocean basins; however, in the high-resolution, three-dimensional, baroclinic simulations there is a significant increase in the computational demands due to the refinement in the vertical direction, so the model domain for these applications is restricted to smaller regions. Thus, this places the open boundary in a zone dominated by complex, nonlinear processes, such that proper specification of the open boundary conditions is difficult. One solution is to couple, or nest, models that specialize in simulating a specific flow regime or spatial scale.

The work presented herein couples the structured grid HYCOM, which is more suited for the deeper ocean regions, with the unstructured grid ADCIRC model, which is best suited to capturing the geometrically intricate coastal regions. Herein, we examine coupling these models in a one-way fashion where information from the outer model (HYCOM) is fed to the inner model (ADCIRC) through both the initial and boundary conditions via the temperature, salinity, velocity and surface elevations. Model coupling, which also goes by several other names, including nested modeling and downscaling/upscaling, has seen frequent application in many near-coastal simulations, where a larger scale ocean-basin model is used to determine boundary conditions for a higher resolution near-coastal model (Barth et al 2005; Codron et al 2000; Greatbatch et al 2004; Pinardi et al 2003; Sheng et al 2005).

MODEL BACKGROUNDS - ADCIRC AND HYCOM

ADCIRC

ADCIRC is based on the full nonlinear shallow water equations, using the traditional hydrostatic pressure and Boussinesq approximations. A full development of the equations and model can be found in Luettich et al (1992 and 2004) and Westerink et al (1994). As with nearly all prominent 3D near-coastal circulation models (Blumberg and Mellor 1987; Haidvogel and Beckmann 1999), ADCIRC uses a mode-splitting technique to solve the resulting balance laws: the external mode solves the depth-averaged continuity equation for the free surface elevation; the surface elevation forces the internal mode solution, which resolves the horizontal velocity field using a stretched sigma-coordinate system; and the 3D continuity equation is solved for the vertical velocity, subject to kinematic boundary conditions (Luettich et al 2002; Muccino et al 1997). Further discussion of the generalized sigma or stretched coordinate system can be found in Luettich and Westerink (2004) or Dresback (2005).

For the baroclinic simulations, ADCIRC solves the time-dependent scalar transport equation for salinity and temperature, which, through an appropriate equation of state, obtains a density field. Herein, ADCIRC employs an equation of state described in McDougall et al. (2003) and uses the temperature, salinity and pressure in determining the density field. From this information, we calculate the baroclinic pressure gradients and the density field within ADCIRC using σ_t values, which can be obtained from $\sigma_t = \rho - 1000\ \mathrm{kg/m^3}$ (Pickard and Emery 1964). In order to avoid spurious currents for stably-stratified flow, the baroclinic pressure gradients are evaluated in a level coordinate system, and they are fed back into the momentum equation through the buoyancy term (Dresback et al 2004; Dresback 2005). Validation of the code against process-oriented tests demonstrated that baroclinic ADCIRC could accurately model front propagation and shape for the difficult "lock-exchange" test (Kolar et al 2009). The equations are discretized in space using linear triangular finite elements and in time using Crank-Nicholson (Lynch and Gray 1979; Kinnmark 1986; Luettich et al 1992 and 2004; Kolar et al 1994a and 1994b, and Westerink et al 1994). Baroclinic ADCIRC can be executed on parallel architectures. ADCIRC does have the capability to evaluate river discharges in barotropic mode; however, work towards the addition of the river evaluation in baroclinic mode is ongoing.

HYCOM

HYCOM is a general ocean circulation model that uses the primitive form of the shallow water equations and was developed from the Miami Isopycnal Coordinate Ocean Model (MICOM, Bleck 1978). HYCOM is a regional/global ocean model and employs a structured grid, the Arakawa "C" grid with curvilinear coordinates. The unique feature of the HYCOM model is its hybrid vertical coordinate approach that consists of three coordinate systems: isopycnal coordinates in the deep, stratified waters; sigma coordinates in the shallower, un-stratified waters; or z-level coordinates in the surface mixed layer or other un-stratified layers (Bleck 1978 and 2006; Chassignet et al 2003 and 2006). Layer type and thickness vary in time and space throughout a HYCOM model simulation. For the temporal discretization, HYCOM uses a leap-frog scheme with a time filter for the baroclinic portion of the solution. For the barotropic portion, it employs a split explicit free surface scheme that is shifted in time (Griffes et al 2000; Haidvogel and Beckmann 1999). Currently, HYCOM does not include tidal effects but does utilize winds and surface heat flux. HYCOM implements rivers into the model as precipitation, which is a separate monthly climatological field from the standard precipitation field; it is treated as a mass source into the system. Like ADCIRC, HYCOM can be executed on parallel architectures.

Data Extraction From HYCOM To ADCIRC

To accurately utilize the HYCOM information within the ADCIRC domain, we must obtain both the initial conditions, which serves to set up the baroclinic fields in ADCIRC, along with the boundary conditions, which allows the model to bring in the outside state of the ocean. Due to the global nature of the HYCOM model, along with its structured grid and the typically coarser resolution, the coastlines cannot be as finely defined, as is common with unstructured triangular meshes. Consequently, often the smaller interior water bodies, such as back bays, inlets and marshes are not encapsulated by the HYCOM grid. In fact, often they are designated as dry or unsubmerged areas (considered "inactive") in the HYCOM model and do not have valid data. Figure 1 shows this contrasting horizontal resolution of the HYCOM and ADCIRC models in the northeast Gulf of Mexico, with the gray dots showing the resolution of the ADCIRC model and the black squares showing the extent of the wetted or "active" nodes of

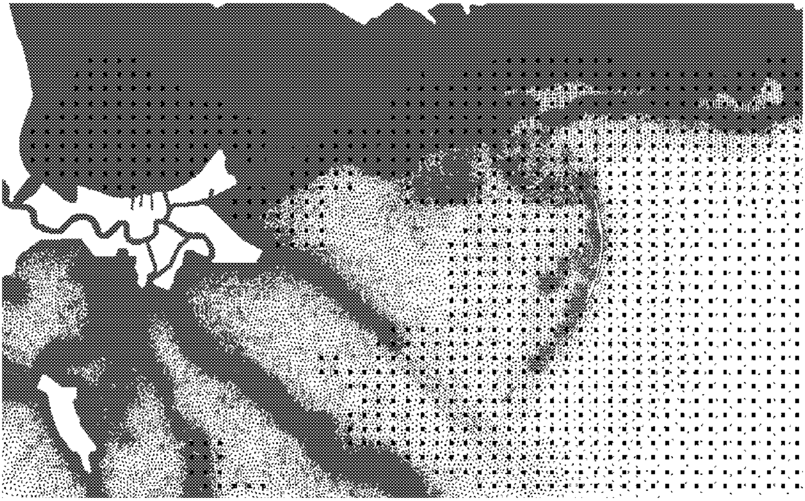

Figure 1 Example of the contrasting resolutions between HYCOM and ADCIRC in the northeast Gulf of Mexico. The gray dots shown are node points from the ADCIRC model, while the black squares indicate where HYCOM's 1/25 degree model has values that are not designated as dry or unsubmerged areas.

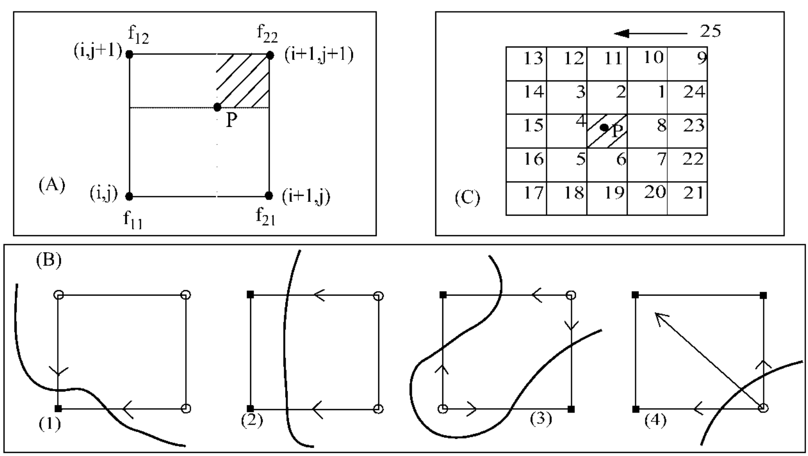

Figure 2 Horizontal interpolation or extrapolation methods for data extraction from HYCOM: (A) Sample grid cell for bilinear interpolation; (B) Four basic HYCOM grid configurations with at least one dry grid point (represented by black squares): (1) one vertex on land, (2) two adjacent vertices on land, (3) two opposite vertices on land, (4) three vertices on land; The thick black line indicates where the water line is located in the square and the open circles indicate wet grid points; (C) Spiral search pattern to find nearest wet node.

HYCOM. Thus, to obtain both the initial and boundary conditions in ADCIRC, we must either interpolate or extrapolate the HYCOM information to the ADCIRC domain. The methods used to interpolate or extrapolate HYCOM results is summarized herein; a full discussion of the methods can be found in Dresback et al (2010).

In the initial step of the horizontal interpolation/extrapolation methods, we determine within which grid cell of HYCOM an ADCIRC node lies. We do this using Mercator projection, which allows us to determine the x and y coordinates of a point, given its latitude and longitude, and the following equations: $x = \lambda - \lambda_0$ and $y = \ln(\tan(\pi/4 + \varphi/2))$; where (λ,φ) are the longitude and latitude of the point and λ_0 is the starting longitude value of the origin of the HYCOM grid. Thus using Mercator projection and the fact that HYCOM grids use a constant longitudinal grid spacing in degrees and the latitudinal spacing varies by its cosine to give the square grid cells, we then can determine the x and y coordinates of an ADCIRC node (shown as P in Figure 2). This allows us to efficiently determine in which HYCOM grid cell the ADCIRC grid point lies without searching through all the nodes in the HYCOM grid.

After identifying this HYCOM grid cell, we then determine whether the HYCOM grid vertices are "active" or "inactive". If all four HYCOM vertices are active, then we use bilinear interpolation to assign a data value to the ADCIRC node (point P). Bilinear interpolation in effect weights a grid point with the area of the opposite quadrilateral divided by the area of the entire cell. Figure 2(A) shows a sample of the bilinear interpolation with the hashed area representing one section of the calculation. The equation for bilinear interpolation shown in Figure 2(A) is as follows:

$$f(x, y) = \frac{(x - x_i)(y - y_j)}{\Delta x \Delta y} f_{i+1, j+1} + \frac{(x_{i+1} - x)(y - y_j)}{\Delta x \Delta y} f_{i, j+1} + \frac{(x - x_i)(y_{j+1} - y)}{\Delta x \Delta y} f_{i+1, j} + \frac{(x_{i+1} - x)(y_{j+1} - y)}{\Delta x \Delta y} f_{i, j} \qquad \textbf{(1)}$$

When the vertices of the HYCOM grid cell includes both active and inactive nodes, we employ either averaging or substitution of the values from the active nodes to the inactive nodes. There are four basic cases, shown in Figure 2(B), of the HYCOM grid cell having active and inactive nodes where averaging or substitution of the values are utilized to obtain the value for the ADCIRC node. In Figure 2(B), the active nodes are shown as open circles, while the inactive nodes are shown as black squares, and the black line indicates where the water line is in the grid cell. The arrows in the figure indicate that information is passed (or substituted) from wet grid points to the dry grid points. For the case of one inactive node, which is shown in Figure 2(B1), the inactive grid cell value is replaced with the average of the two adjacent wet grid cell values. For the case of two inactive nodes that are adjacent to each other, which is shown in Figure 2(B2), the two inactive grid cell values are replaced with the value of the two adjacent wet grid cells. For the case of two inactive nodes that are diagonal to each other, which is shown in Figure 2(B3), the inactive grid cell values are replaced with the average of the two wet grid cells that are diagonal to one another. Lastly, for the case of three inactive nodes, shown in Figure 2(B4), the inactive grid cell values are replaced with the value of the one wet grid cell. Once, we have substituted the values for the inactive grid cells, the value of the ADCIRC node (point P) is calculated using bilinear interpolation, as shown in Figure 2(A).

The final case for the horizontal interpolation/extrapolation methods is when the vertices of the HYCOM grid cell are all inactive nodes. In this case, we extrapolate the value to the ADCIRC node by searching the nearby HYCOM grid cells for active (wet) values. This is done by employing a spiral search outward from the initial HYCOM grid cell, which is shown in Figure 2(C) following the numerical sequence indicated. The spiral search is done in "rings" around the ADCIRC node and continues searching outward until an active value is found in a ring. If only one active HYCOM grid cell is found in a given ring, then its value is assigned to the ADCIRC node. If more than one active HYCOM grid cell is found in a given ring, then the value of the closest grid point is assigned to the ADCIRC node.

The last step in the data extraction from HYCOM is to obtain the vertical variation of the salinity, temperature or velocity fields. This is done through a three step process, which is illustrated in Figure 3: we map the HYCOM vertical information from an element-based grid to a intermediate nodal-based grid and then to the vertical z-layers of the ADCIRC grid. Initially, we extract the HYCOM information for the layer thicknesses, salinity, temperature and the velocity fields onto an element-based grid, which is shown on the far right hand side of Figure 3. The HYCOM information is mapped from the element-based grid to a nodal-based intermediate grid, shown in the middle of Figure 3 (e.g., arrows from HYCOM information to intermediate grid). For the different HYCOM fields, we have to assign or average the fields onto the intermediate grid. We use the first and last elemental values as the surface and bottom nodal values, respectively. For all other nodal values, we average the two elemental values from the HYCOM information (e.g., arrows from HYCOM information to intermediate grid). Next, we linearly interpolate the information from the intermediate grid onto the vertical layers of the ADCIRC grid. To interpolate the values, we have to determine the actual depth values based on the bathymetry of the ADCIRC grid, and then we can compare these ADCIRC depths to the depths given in the intermediate grid based on the HYCOM information (e.g., point *a* on the ADCIRC grid falls between the top two points of the intermediate grid). After the depths are determined, we can linearly interpolate the values for salinity, temperature or velocities to the ADCIRC vertical grid (e.g., values for salinity, temperature and velocities for point *a* on the ADCIRC grid are determined from the top two points of the intermediate grid). When an ADCIRC vertical node falls below the HYCOM vertical grid due to the different bathymetric databases used by the models, we assign values from the closest vertical node above it on the ADCIRC vertical grid. Thus, we are not linearly extrapolating any values in the vertical grid. By utilizing this procedure, the vertical interpolation scheme can accommodate a variety of vertical layer distributions, such as uniformly distributed, log distributed or distributed based on a sine function.

Figure 4 shows the initial conditions for the surface temperature values for April 13, 2004 in the Northern Gulf of Mexico, one of our study areas. The surface temperature values taken from HYCOM are shown in Figure 4a with the boundaries of the ADCIRC grid shown as a black line. As can be seen in the figure, the HYCOM infor-