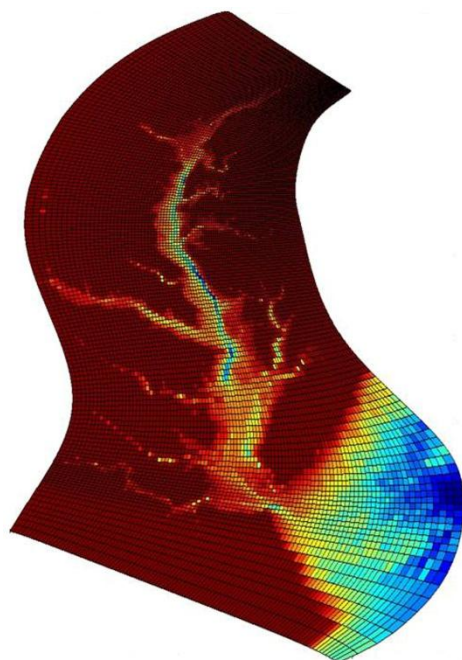


Chesapeake Bay Hydrodynamic Modeling

A Workshop Report by the Chesapeake Bay Program's
Scientific and Technical Advisory Committee



Workshop held June 9-10, 2011
Edgewater, Maryland

STAC Publication 11-04



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About the Scientific and Technical Advisory Committee

The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program (CBP) on measures to restore and protect the Chesapeake Bay. Since its creation in December 1984, STAC has worked to enhance scientific communication and outreach throughout the Chesapeake Bay Watershed and beyond. STAC provides scientific and technical advice in various ways, including (1) technical reports and papers, (2) discussion groups, (3) assistance in organizing merit reviews of CBP programs and projects, (4) technical workshops, and (5) interaction between STAC members and the CBP. Through professional and academic contacts and organizational networks of its members, STAC ensures close cooperation among and between the various research institutions and management agencies represented in the Watershed. For additional information about STAC, please visit the STAC website at www.chesapeake.org/stac.

Publication Date:

October, 2011

Publication Number:

11-04

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Executive Summary

There are currently multiple 3D hydrodynamic models running simulations in the Chesapeake Bay. Statistical comparisons of the relative skill of these models consistently demonstrate that many of these models perform as well as the existing CBP hydrodynamical model. Furthermore, these analyses also reveal that in general a multi-model average better matches observations than the results of any single model simulation.

Following distribution of the results of these model comparison efforts, discussion of what a “Next Generation Bay Model” should include was explored through a June 2011 Workshop hosted by the Chesapeake Bay Program’s Scientific and Technical Advisory Committee (STAC) and the Chesapeake Community Modeling Program (CCMP). The explicit workshop goal was to provide input to the Chesapeake Bay Modeling Team that can be used to inform selection of a future hydrodynamic model or models for assessing water quality and management impacts. In addition it is hoped that the information contained in this workshop report will provide the background needed for establishing an RFP that the CBP might consider issuing for the purpose of identifying and implementing a new hydrodynamic model or models for the Chesapeake Bay.

The workshop included overview talks on hydrodynamic model comparisons, as well as presentations on specific hydrodynamic models that the CBP could consider as alternatives or supplements to the existing CBP model. Talks on the sensitivities of these models to coastal boundary conditions and turbulence closure schemes were included on Day 2. At the conclusion of the workshop, the steering committee identified five recommendations for the CBP in regards to their future hydrodynamical modeling efforts:

- Use multiple models
- Use open source community models
- Assess model skill
- Implement models in a modular fashion
- Form a Chesapeake Modeling Laboratory to enable the above

Although these recommendations were specifically derived from the hydrodynamic model discussions at the workshop, these recommendations hold equally well for the CBP water quality and watershed models. The workshop steering committee urges the CBP to follow these recommendations as the CBP continues to refine their Chesapeake Bay modeling system and works towards implementing a new estuarine model by 2015.

1. Introduction

The Chesapeake Bay Program's Chesapeake Bay Modeling System consists of several coupled models that simulate water and nutrient transport and transformation within the Chesapeake airshed, watershed, and estuary. These coupled models work in series to estimate the impacts on water quality of nutrient management strategies within the Chesapeake watershed and are also used to help set Total Maximum Daily Loads (TMDLs). The estuarine model is comprised of a hydrodynamic sub-model and a water quality submodel. The hydrodynamic sub-model is based on a mechanistic hydrodynamic model called CH3D (Curvilinear-grid Hydrodynamics in 3D) that simulates the flow and mixing of waters in the Bay and its tidal tributaries. CH3D is a legacy code that is based upon the Princeton Ocean Model (POM). Although many state-of-the-art models have their roots in POM, CH3D has not enjoyed wide use or acceptance among the academic research community and documentation is not easily accessible, nor widely disseminated. In addition, the model has not been run for conditions past 2005, i.e. the most recent year of output available for model-data comparison is 2005.

The CBP is now at a point where they are considering seeking a new hydrodynamic modeling system, which will provide optimal results throughout the Chesapeake Bay, including the shallow-water, nearshore environment. The present CH3D model is potentially limited in this regard, as a result of its inherent horizontal and vertical grid structure. The current CBP plan is to immediately begin discussions of this "Next Generation Chesapeake Bay model", and to have a fully calibrated and operational Bay model in place by December 2015, for use in the 2017 reassessment. The Army Corps of Engineers (USACE) has suggested that the CBP transition to using the USACE Adaptive Hydraulics Model (ADH). (Currently ADH is a 2D model, however the USACE is investing \$2M to make it 3D within the next two years.) The transition from CH3D to ADH would be particularly convenient for the USACE because of the ease of using data already compiled by the USACE for running the current CH3D Bay model. However, there are several alternatives to ADH that should also be considered as a replacement for CH3D, and the organizers of this workshop felt it would be beneficial to the CBP and the larger restoration and management effort to seek input from the scientific and modeling community in regards to the pros and cons of the multiple hydrodynamic models available for use within the Chesapeake Bay. The Estuarine-Hypoxia team of the NOAA-funded U.S. IOOS Regional Testbed project is quantitatively comparing these multiple model simulations to those of the existing CH3D Bay model. In many cases these alternative models do quite well. With the results of these comparisons in hand, now is the ideal time to conduct an extensive community-wide discussion as to what a "Next Generation Bay Model" should entail.

To these ends, the CCMP convened a STAC sponsored two-day workshop on June 9-10, 2011 for the purpose of comparing state-of-the-art coastal and estuarine hydrodynamic models, reviewing the results of a recent study comparing the ability of several models (including CH3D) to simulate stratification and hypoxia in the Chesapeake Bay, and developing suggestions for a way forward for future CBP modeling efforts. An additional goal of this workshop was to provide the background needed for establishing an RFP that the CBP might consider issuing for the purpose of identifying, selecting, and implementing a new hydrodynamic model or models for the Bay.

2. Workshop presentations

The agenda for the workshop (see Appendix A) included an overview of CBP model needs, as well as a discussion of results from recent model comparison efforts in both Chesapeake Bay and Delaware Bay. These presentations were followed by talks discussing the pros and cons of six coastal/estuarine hydrodynamic models (CH3D, FVCOM, EFDC, sECOM, ADH and ROMS). Speakers were asked to specifically address the following questions during their talks:

1. How well does the model reproduce vertical stratification/mixing?
2. How well does the model accommodate complex geomorphology?
3. How well does the model conserve tracers?
4. Does the model include sediment transport?
5. Does the model include biogeochemistry and/or water quality?
6. Is the model computationally efficient?
7. To what degree is the model a “community model” (i.e., open source/open development and research community involvement)?

The second day of the workshop included talks on the sensitivities of the models to boundary conditions on the shelf and to various turbulence closure parameterizations. The final talk described the potential for new modular modeling approaches. A brief summary of each of these 12 talks is provided in Appendix B.

3. Panel Discussion

The workshop concluded with a panel discussion on the future direction of Chesapeake Bay modeling and focused on three main topics:

1. The Chesapeake Modeling Laboratory recommended in the NRC report "Achieving Nutrient and Sediment Reduction Goals in the Chesapeake Bay: An Evaluation of Program Strategies and Implementation"
2. The use of a modular framework when implementing model systems and the parallel issue of an ensemble approach to modeling
3. The importance of using models developed in an open source environment.

Chesapeake Modeling Laboratory - Most people in attendance were very supportive of a Chesapeake Modeling Laboratory (CML). While many agreed that an actual "brick and mortar" campus would be ideal, given the current funding environment it may not be realistic. An alternative could be a virtual laboratory where modelers at remote sites could collaborate over the internet, shared computer servers and interactive video networks. In this manner overhead costs would be kept to a minimum, while maintaining the benefits of these collaborations. The virtual CML could be based off of the existing community modeling infrastructure established by the Chesapeake Community Modeling Program.

Modular Approach - A driving force behind the general support at the workshop for a modular modeling approach is the current inability of non-CBP researchers to run CBP models themselves or to link them with other models. By inputting the CMP modeling system into a modular framework, the process of linking other models to one or all of the CBP modeling system components is simplified. One modular framework that might be considered is the Community Surface Dynamics Modeling System (CSDMS) (csdms.colorado.edu/wiki/Main_Page). CSDMS is a National Science Foundation project at the University of Colorado that has developed tools and methods to incorporate open source models in a modular framework. Once a model is in CSDMS it can interact with any of the other models in the framework. There was general agreement during the panel discussion that modular systems are the future of modeling and this should be considered in future CBP modeling efforts. A modular system would also simplify the process of ensemble modeling and the computation of multi-model averages.

Open Source - There was a strong consensus during the panel discussion that open source models are the only option. Being able to see the code and how the model operates is critical to the scientific modeling process. Additionally, by allowing others to collaboratively develop and modify model code in a structured community framework will benefit everyone in the Chesapeake modeling and management community.

4. Recommendations

Based on the panel discussion, the workshop presentations and the discussions they fostered, the workshop steering committee developed the following five recommendations for how the CBP should proceed with their future modeling efforts. It is sincerely hoped that the CBP will consider these issues as they begin to identify and implement a new hydrodynamic model or models for the Bay.

1) Use multiple models.

Analyses presented at the workshop specifically demonstrated that multiple hydrodynamic models provide more insight into system behavior and more confidence in model output than any one hydrodynamic model in isolation. Although the workshop focused mainly on hydrodynamic models, these conclusions hold for other categories of models as well, including watershed models and water quality models. There was a strong consensus among the workshop participants that the CBP must migrate to using an ensemble of multiple models in their assessment process.

2) Use open source community models.

The workshop highlighted the sizable communities that have organically formed in support of several scientifically vetted, open source models for estuarine hydrodynamics. Analogous communities are forming in support of open source watershed and water quality models. Because of the many and diverse researchers invested in community models, such models are more likely to adopt advantageous new computational approaches, potential model errors are more likely to be identified, and the general confidence in such models tends to be significantly higher. There was a strong consensus among the workshop participants that the CBP must use an open source model in their assessments.

3) Assess model skill.

It is crucial that the CBP use scientifically vetted models with quantitatively demonstrated skill. Analyses presented at the workshop demonstrated that it is relatively easy to systematically evaluate and compare the skill of multiple Chesapeake Bay hydrodynamic and hypoxia models, as long as the output is easily accessible in a standard format, and as long as additional model sensitivity runs are feasible. All present and future CBP models should be able to be openly and quantitatively assessed by the scientific community. There was a strong consensus among the workshop participants that any new models chosen to supplement or replace existing CBP models should demonstrate skill at least similar to the existing CBP models.

4) Implement models in a modular fashion.

An obstacle to the familiarity, use and testing of CBP models by the larger community has been the inability of non-CBP researchers to run CBP models themselves or to link them with other models. A recommended solution to this problem is to “modularize” both present CBP models and other models that may be adopted by the CBP in the future. The modularized components could then be easily interchanged within a community-supported testbed by modelers both inside and outside CBP. In this fashion, various ensembles of watershed,

hydrodynamic, water quality and other models could be more easily compared and tested.

5) Form a Chesapeake Modeling Laboratory to enable the above.

The Chesapeake Modeling Laboratory (CML) suggested in the NRC report "Achieving Nutrient and Sediment Reduction Goals in the Chesapeake Bay: An Evaluation of Program Strategies and Implementation" is a logical mechanism for carrying out the above recommendations. Given the current budget climate, however, a "brick and mortar" laboratory seems unlikely in the near future. The consensus of the workshop participants was that the CBP should immediately begin building off the existing community modeling infrastructure already focused on the Bay region to form a virtual CML with permanent funding. In the short-term an Ad-Hoc modeling advisory committee sanctioned by, but external to, the CBP should be formed to advise CBP on future modeling activities, and insure that the CBP seriously considers the recommendations listed above.

Appendix A. Workshop Announcement and Agenda

CCMP Hydrodynamic Modeling Workshop
June 9 – 10, 2011
Smithsonian Environmental Research Center
Edgewater, MD



A joint CCMP, CSDMS, CBP, and U.S. IOOS Modeling Testbed **Hydrodynamic Modeling Workshop** will be convened at the Smithsonian Environmental Research Center, June 9-10, 2011. The purpose of this workshop will be to review state-of-the-art coastal and estuarine hydrodynamic modeling and compare the strengths and weaknesses of different model grids and their ability to simulate physical properties such as temperature and salinity variability and stratification. A strong emphasis will be placed on how well these models perform in Chesapeake Bay with goals of informing simulations of water quality parameters (such as light, nutrients, chlorophyll, and oxygen concentrations). These modeled attributes plus accurate circulation computations obviously have important implications for other critical components of the tidal bay and tributaries such as larval and juvenile transport, habitat, inundation, and climate change. Quantitative comparisons of model performance in Chesapeake Bay will draw heavily from the on-going U.S. IOOS Modeling Testbed model intercomparison project. The overarching goals of this workshop will be to 1) review, summarize, and finalize the results from the U.S. IOOS Modeling Testbed model intercomparison project and 2) provide input to the Chesapeake Bay modeling workgroup that can be used to inform selection of a future hydrodynamic model or model ensemble for assessing water quality and living resource management impacts.

For more information, please contact **Dave Jasinski** – dave@communitymodeling.org
CCMP gratefully acknowledges funding support from:



DAY 1

Time	Title	Presenter
8:30	Introduction	Raleigh Hood, UMCES
9:00	CBP Model Needs	Lewis Linker, CBPO
9:15	US IOOS Modeling Testbed Comparisons: Hydrodynamics and Hypoxia	Marjy Friedrichs, VIMS
10:00	Delaware River and Bay Model Evaluation Experiment	Rich Patchen, NOAA
10:30	Break	
10:45	CH3D	Carl Cerco, USACE
11:30	FVCOM	Robert Beardsley, WHOI
12:15	Lunch	
1:00	EFDC	Jian Shen, VIMS
1:45	sECOM	Nickitas Georgas, SIT
2:30	ADH	Gaurav Savant, USACE
3:15	Break	

3:30	ROMS	Hernan Arango, Rutgers
4:15	Discussion	
5:00	Reception/Posters	

DAY 2

Time	Title	Presenter
8:30	Coastal Shelf Influences on Chesapeake Bay, from a Modeling Perspective	Wen Long, UMCES
9:15	Modular Modeling Approaches	Scott Peckham, CSDMS
10:00	Break	
10:15	Estuarine Turbulence Modeling	Malcolm Scully, ODU Dom Di Toro, U Del. & Carl Friedrichs, VIMS
11:00	Panel Discussion	
12:30	Lunch	
13:30	Panel Discussion (cont.)	
14:30	Wrap-up	Raleigh Hood, UMCES
15:00	Adjourn	

Appendix B. Summary of workshop presentations

1. Toward Modeling and Analysis Tools For the 2017 Mid-Course Reevaluation

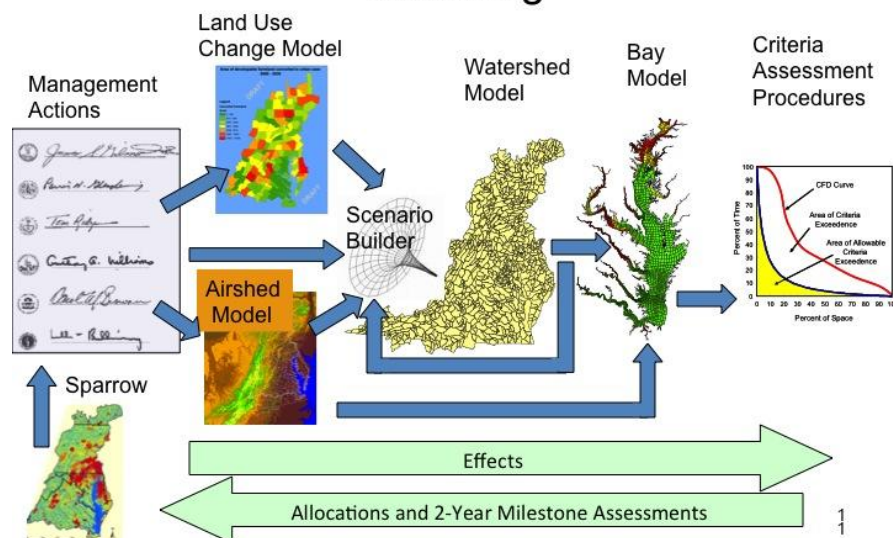
Lewis Linker

Environmental Protection Agency Chesapeake Bay Program Office

The CBP models guiding TMDL planning and implementation are well founded and fully suited to their current task. Nevertheless, over the last quarter century, the CBP has been committed to refinement of our watershed, estuary, and airshed analysis tools. Refinement of the CBP modeling tools has always been oriented to providing the best available scientific tools for use by CBP decision makers. To these ends, the CBP will implement a new estuarine model by 2015. Some of the elements to be considered for this new model include:

- Extend calibration period beyond 2005 to get more observed data and more recent data, particularly for shallow water monitoring that came on line from 2003 forward.
- Full sediment diagenesis with scour, resuspension, fate and transport of organic material.
- Represent shallows and embayments with a finer grid, perhaps with a ribbon model, perhaps with finite volume grid to better represent clarity SAV and open water DO.
- Refine chlorophyll simulation and assessment particularly in the James and DC waters.
- Consider including a simulation of estuarine wetlands.
- Consider keeping CH3D-ICM investment in menhaden, oyster, SAV, sediment transport while improving shallow water embayment issues of scale + understanding of shallow water dynamics.

Chesapeake Bay Program Modeling



2. U.S. IOOS Testbed Comparisons: Hydrodynamics and Hypoxia

Marjy Friedrichs

Virginia Institute of Marine Science, College of William & Mary

As part of the U.S. IOOS Modeling Tested project, the relative skill of five Chesapeake Bay hydrodynamic models and five dissolved oxygen models have been compared for both a wet and a dry year (2004 – 2005). The data used for comparison were profiles of temperature, salinity and dissolved oxygen collected by the EPA Chesapeake Bay Program at ~40 monitoring stations distributed throughout the Bay and sampled every 2 to 4 weeks. The five hydrodynamic models utilized are CH3D, EFDC, ChesROMS, CBOFS, and UMCES-ROMS.

Major results from the hydrodynamic model comparison for Chesapeake Bay include a demonstration that the five models all do reasonably well in capturing fundamental aspects of the hydrodynamics, although the precise depth and intensity of stratification at the pycnocline continues to be a universal challenge. Temperature was simulated very well by every one of the models. The CH3D and EFDC models did slightly better in reproducing bottom salinity and density stratification, whereas the CH3D and ChesROMS models did slightly better in reproducing pycnocline depth. All five models under-predict the strength and variability of salinity stratification. The 3 ROMS-based models (ChesROMS, UMCES ROMS, CBOFS) demonstrated remarkably similar skill in reproducing bottom salinity, stratification and pycnocline depth, indicating that this skill is not highly dependent on horizontal grid resolution, which differed substantially between these three models.

Major results of the dissolved oxygen model comparisons include a demonstration that the six model combinations tested to date all do reasonably well in capturing of the seasonal variability of the dissolved oxygen field. By a narrow margin, the EFDC-1eqn model performed best in reproducing bottom dissolved oxygen, whereas ChesROMS-1DD performed best in reproducing hypoxic volume in 2004 and ICM performed best in reproducing hypoxic volume in 2005. However, the differences in skill among the various hypoxia models were generally small, with the extremely simple constant respiration models performing nearly as well as the complex ICM model. Another significant finding with regards to future modeling strategies is the result that the multi-model hindcast for hypoxic volume was significantly more accurate than the hindcast from any one model alone.

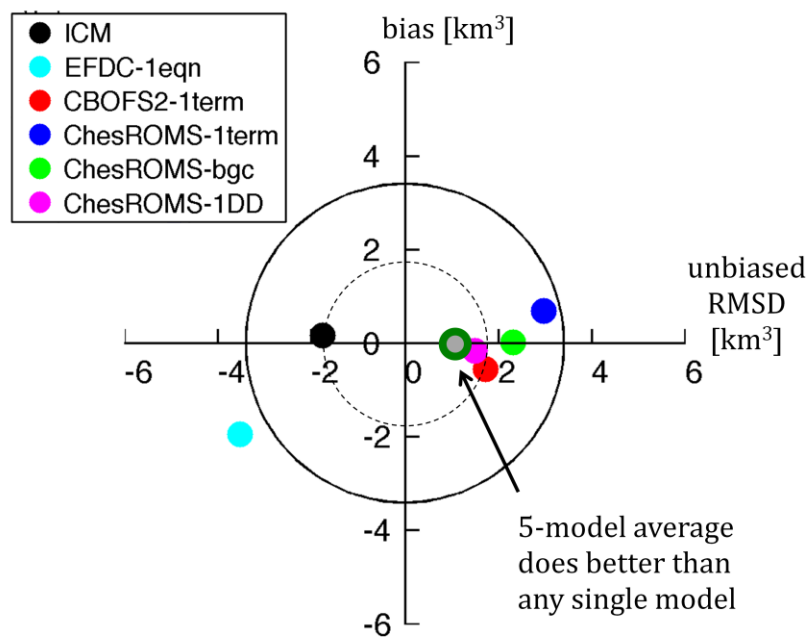
Scientifically, key results to date include the ability of models with highly simplified biology (e.g., a constant net respiration rate independent of nutrient input) to reproduce the seasonal hypoxia cycle about as well as much more complex, nutrient-dependent ecological models. Reproduction of seasonal variation in DO was found to not be dependent on the seasonal cycle in respiration rate, nor the seasonal cycle in fresh water input, nor the seasonal cycle in density stratification. In fact, all the models reproduced the observed

seasonal cycle in bottom DO better than they reproduced the seasonal cycle in observed stratification. Further sensitivity analyses are currently being conducted with this set of models in order to examine the sensitivity of seasonal variations in DO to wind speed and direction.

Discussion Points and Recommendations:

- A set of metrics now exist to test the skill of CB hydrodynamic models. Metrics such as these need to be used to test potential new CBP models
- This analysis clearly demonstrates the utility of multi-model averages. The CBP needs to consider using input from multiple models in the future.
- A CB Modeling Center, such as suggested by a recent NAS report on CBP, would be useful for further developing multiple CB models and model comparisons as described here

Hypoxic Volume



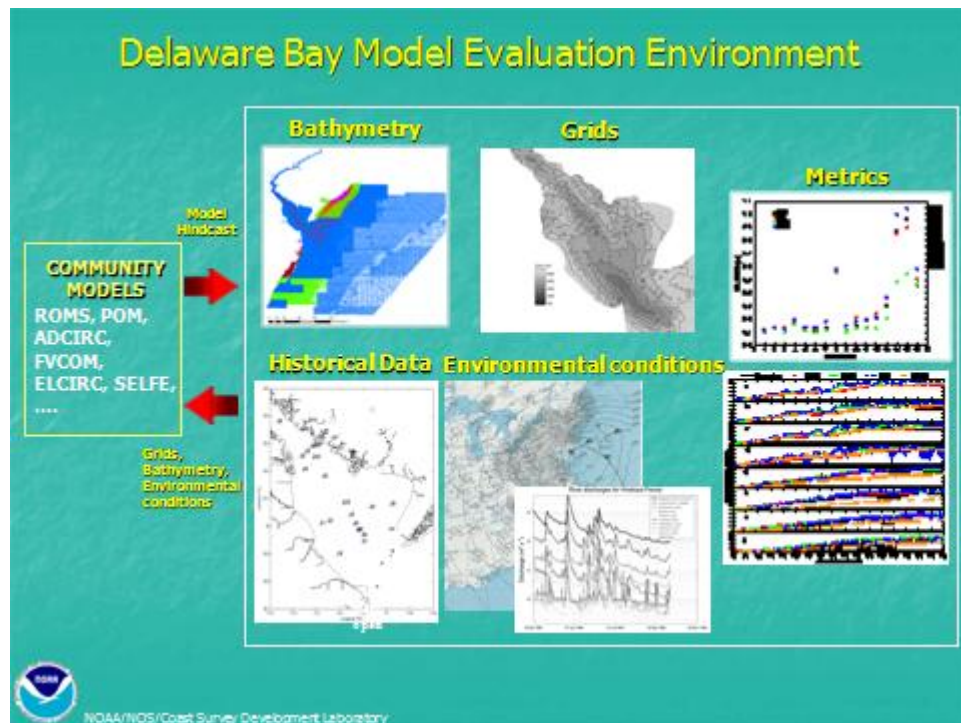
Several simple DO models reproduce seasonal variability of hypoxic volume about as well as ICM

3. Establishment of a Delaware Bay Model Evaluation Environment

Richard Patchen

National Oceanic and Atmospheric Administration, National Ocean Service,
Coast Survey Development Laboratory

The Office of Coast Survey's Coast Survey Development Laboratory (CSDL) within National Ocean Service established a Model Evaluation Environment (MEE) for the Delaware River and Bay and adjacent shelf. The purpose of the MEE was to establish a framework to evaluate available candidate circulation models to support the NOS modeling backbone to provide operational circulation forecasts in U.S. Coastal waterways. The presentation describes the various elements that comprise what is needed to establish the MEE. The presentation concluded by providing examples of MEE products for the six community models that were evaluated. The six community models include both 2-D and 3-D models that are formulated on both structured (orthogonal) or unstructured (highly variable triangular elements) grids. The models were: the Princeton Ocean Model (POM), the Regional Ocean Model System (ROMS), the Finite Volume Coastal Ocean Model (FVCOM), the Advanced Circulation Model (ADCIRC), the Eulerian-Lagrangian Circulation Model (ELCIRC), and the Semi-implicit Eulerian-Lagrangian Finite Element Model (SELFE).



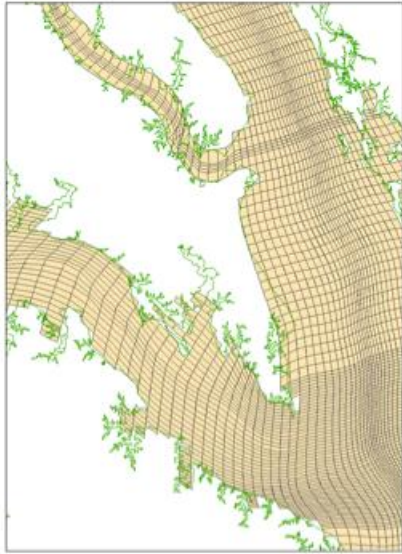
4. CH3D-WES

Carl Cerco
United States Army Corps of Engineers

The CH3D-WES hydrodynamic model has seen application to Chesapeake Bay on multiple grids since 1987. CH3D (Computational Hydrodynamics in Three Dimensions) was developed in 1986 by Peter Sheng and associates. The model was substantially modified at the US Army Engineer Waterways Experiment Station and this version is referred to as CH3D-WES. The model is coded in FORTRAN 77 and provides computations of surface elevation, velocity in three dimensions, vertical diffusivity, salinity, and temperature. The computational grid, as employed in Chesapeake Bay, incorporates several unique features. The first is the use of non-orthogonal curvilinear coordinates in the surface plane, which provide excellent conformation to the complicated geometry of Chesapeake Bay and major tributaries. The second is the use of a Z-grid in the vertical dimension, in which variations in depth are represented by variation in the number of vertical layers. The Z-grid replaced the original sigma coordinates in CH3D to improve computation of vertical stratification. The Z-grid also reduces computational time since fewer cells are employed in shallow regions versus deeper regions of the system.

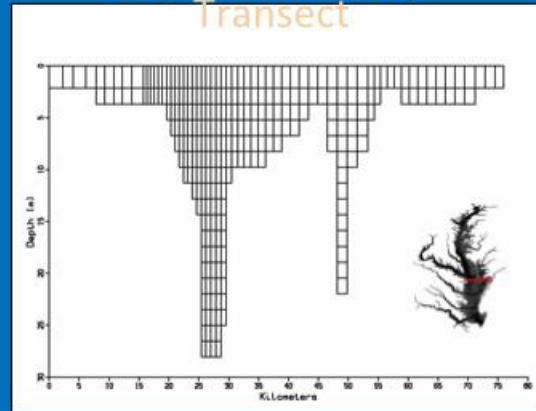
In its present application to Chesapeake Bay, CH3D-WES operates on a grid of 56,000 cells (11,000 surface cells by 1 to 19 vertical cells). Surface cells are roughly 1 km x 1 km x 2 m. Thickness varies in response to forcing from tide and wind. Sub-surface cells have a constant thickness of 1.5 m. The model employs a 90-second time step and requires 5 to 20 hours cpu per simulated year, depending on computer hardware. Hydrodynamic computations are stored at one-hour intervals for subsequent use by the independent CE-QUAL-ICM eutrophication model. Simulations are available for the years 1985 – 2005.

CH3D is a robust, proven tool for providing hydrodynamics for eutrophication computations in Chesapeake Bay and major tributaries. However, the model has its limits for application in small, shallow embayments with complicated geometry. Although the model grid can be refined for application to these systems, the use of quadrilateral cells is a limitation, as is the use of a Z-grid. Absence of wetting and drying is an additional limitation. As the interest of the Bay Program moves to smaller systems and the littoral zone, employment of an alternate model in these regions should be considered.



Non-Orthogonal Curvilinear Coordinates

Z-grid at Mid-Bay Transect



5. Finite Volume Coastal Ocean Model (FVCOM) Development and Applications

Changsheng Chen (UMASSD) and Robert C Beardsley (WHOI)

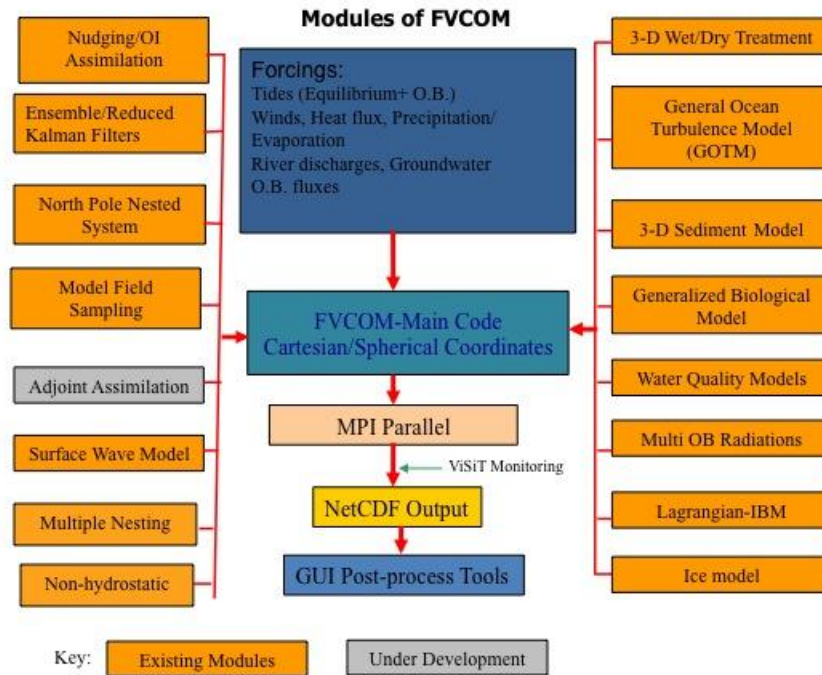
FVCOM is a prognostic, unstructured-grid, finite-volume, free-surface, 3-D primitive equation coastal ocean circulation model developed by UMASSD-WHOI joint efforts. The model consists of momentum, continuity, temperature, salinity and density equations and is closed physically and mathematically using turbulence closure submodels. The horizontal grid is comprised of unstructured triangular cells and the vertical grid features a generalized terrain-following vertical coordinate to follow bottom topography. The Smagorinsky turbulent closure scheme is used in the horizontal and FVCOM features the General Ocean Turbulent Model (GOTM) to provide optional vertical turbulent closure schemes.

FVCOM is solved numerically by a second-order accurate discrete flux calculation in the integral form of the governing equations over an unstructured triangular grid. This approach combines the best features of finite-element methods (grid flexibility) and finite-difference methods (numerical efficiency and code simplicity) and provides a much better numerical representation of both local and global momentum, mass, salt, heat, and tracer conservation. The ability of FVCOM to accurately solve scalar conservation equations in addition to the topological flexibility provided by unstructured meshes and the simplicity of the coding structure has made FVCOM ideally suited for many coastal and interdisciplinary scientific applications.

FVCOM is an open community model system with more than 1000 registered users around the world. The new FVCOM version 3.1.5 is ideally suited for applications within the Chesapeake Bay system. Key features for these applications include 1) wetting/drying, 2) capability for representing sea walls and dikes, 3) automatic multi-grid nesting, 4) capability to nest with other models (e.g., ROMS, HYCOM, etc.) to obtain open boundary conditions, 5) Lagrangian particle tracking capability, 6) module for sediment transport based on the Warner et al Community Sediment Transport Model, 7) an finite-volume, unstructured-grid version of the surface wave model SWAN, 8) option for coupled wave-current dynamics, and 9) a set of finite-volume, unstructured-grid biological and water quality models. These latter models include 1) the Generalized Biological Module (GBM) that allow users to select either a pre-built biological model (such as NPZ, NPZD, etc.) or construct their own biological model using the pre-defined pool of biological variables and parameterization functions, 2) UG-RCA, which we converted directly from the structured-grid RCA (version 3) for Mass/CC Bays developed by HydroQual, 3) FVCOM-WQM, a water quality model based on the EPA Water quality Analysis Simulation Program (WASP), and 4) an unstructured-grid finite-volume version of CE-QUAL-ICM, the Army Corps of Engineers structured-grid water quality box model.

FVCOM version 3.1.5 will be released publically at our next open workshop this fall when the new User's manual is completed. See <http://fvcom.smast.umassd.edu/FVCOM/index.html>

For more information about FVCOM and some of the many successful applications of FVCOM to learn more about our coastal ocean environment.



Solver: Mode-split or semi-implicit; 2-D and 3-D,
 Types: Research version (FVCOM-v2.7) and Forecast version (FVCOM-v3.0).

6. Features of the Environment Fluid Dynamics Computer Code (EFDC)

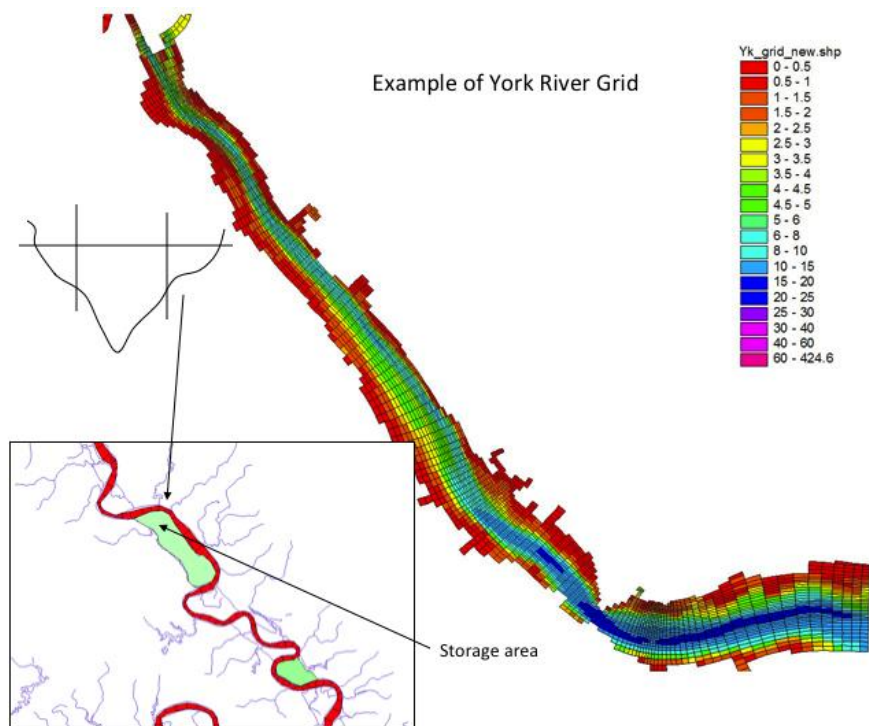
Jian Shen

Virginia Institute of Marine Science, College of William & Mary

EFDC was developed at the Virginia Institute of Marine Science (College of William & Mary) by John Hamrick with primary support from the Commonwealth of Virginia. The eutrophication sub-model was integrated to the EFDC model in 1996. Subsequently, the suspended sediment and toxic sub-models have been integrated to the EFDC model. EFDC is presently maintained by Tetra Tech, Inc. with ongoing development support from the US EPA ORD, OST, and Regions 1&4.

EFDC hydrodynamics feature 3-dimensional with 2-D and 1-D options and is functionally equivalent to POM/ECOM CH3D-WES and TRIMM. Eutrophication sub-model features:

- Based on CE-QUAL-IC (Chesapeake Bay WQ Model) Kinetics
- Directly coupled to hydrodynamics
- 22 water column state variables including multiple classes of algae, organic carbon, nitrogen and phosphorous, and macroalgae
- Optional 27 State Variable Sediment Diagenesis Sub-model
- Reduced Number of State Variable Version Equivalent to WASP
- Data assimilation for water quality model (kinetic parameters and pollutant sources (VIMS' version, HEM3D))
- Decouple of kinetic update from transport
 - Kinetics can be computed every half to one hour

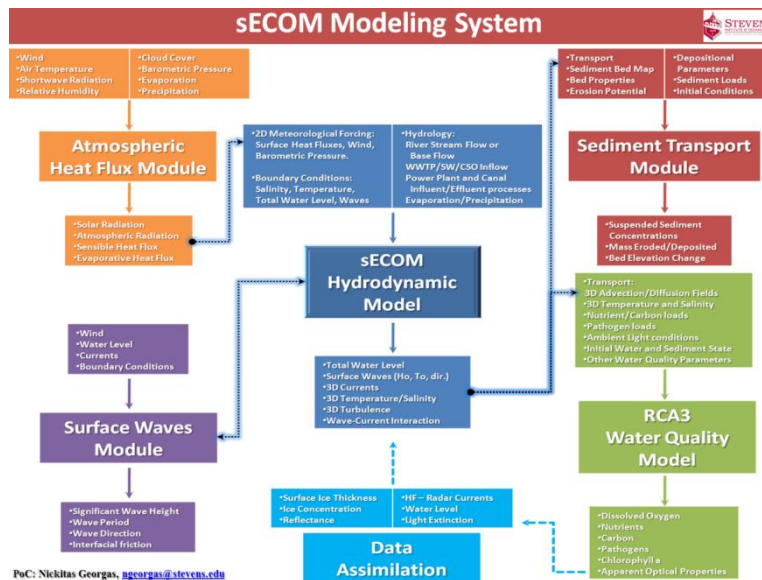


7. Stevens Estuarine and Coastal Ocean Model (sECOM)

Nickitas Georgas and Alan Blumberg
Stevens Institute of Technology

sECOM is a three dimensional, free surface, hydrostatic, primitive equation estuarine and coastal ocean circulation model. Prognostic variables include water level, 3D circulation fields (currents, temperature, salinity, density, viscosity, and diffusivity), significant wave height and period. It is the successor model to the ECOM/POM combination that is in use by almost 3000 research groups around the world with over 600 papers having been published with them as the modeling engine. Its operational forecast application to the New York / New Jersey Harbor Estuary and surrounding waters (NYHOPS) is found online (<http://www.stevens.edu/maritimeforecast>) dating back to 2006, and includes forecasts of chromophoric dissolved organic matter and associated aquatic optical properties through coupling to an RCA-based water quality model.

The recursive MPDATA advection-antidiffusion algorithm is used to solve the



thermodynamic (T, S, turbulence) advection-diffusion equations. ECOM/POM incorporates the Mellor-Yamada 2.5 level turbulent closure model that provides a realistic parameterization of vertical mixing processes, and a version of the Smagorinsky (1963) horizontal mixing scheme for subgrid scale horizontal shear dispersion. The model is forced in the open ocean lateral boundaries by total water level, waves, and long-term thermohaline conditions, at the surface with a two-dimensional meteorological wind stress and heat flux submodel, and internally with thermodynamic inputs from river, stream, and water pollution control plant discharges, and thermal power plant recirculation cells. Quadratic friction is applied at the bottom based on internally calculated friction coefficients that include wave boundary layer effects, and at the free surface through assimilation of surface ice cover friction.

The code is written in standard FORTRAN 77, and can be easily modified. Significant developments not included in the original ECOM/POM, such as robust explicit wetting-and-drying (W&D) and thin-dam (obstruction grid) formulations, new coupled wave and atmospheric modules, surface ice cover friction, and complete Climate and Forecasting Conventions (CF 1.4) compliance of the NetCDF outputs have been included. The code employs a mode-splitting technique to integrate in time the barotropic (2D) primitive shallow water equations separately from the baroclinic (3D) advection-diffusion equations that may run on a larger timestep. The “external” barotropic mode time step is restricted by the Courant-Friedrichs-Levy-(CFL-) stability-criterion and is set to 1s in NYHOPS. The “internal” baroclinic mode can usually converge with a larger time step (10s for NYHOPS), saving computational time. The two time steps are seamlessly integrated with a leap-frog scheme.

In its NYHOPS application to the waters of New York and New Jersey, the computational domain is discretized on an Arakawa “C” finite-difference grid (147x452 horizontal cells, 15,068 of which are designated as water). A system of curvilinear coordinates is used in the horizontal direction, allowing for a smooth and accurate representation of variable shoreline geometry. A high-resolution curvilinear model grid is used to encompass the entire Hudson-Raritan (New York/New Jersey Harbor) Estuary, the Long Island Sound, and the New Jersey and Long Island coastal ocean. The resolution of the grid ranges from approximately 7.5km at the open ocean boundary to less than 50m in several parts of the NY/NJ Harbor Estuary. In order to resolve coastline features that could not be resolved on a grid cell scale, most notably the NJ Atlantic coast barrier islands, 96 cell interfaces across which transport or mixing is disallowed (“thin dams”) have been defined. In the vertical, the model uses a sigma-coordinate system with bathymetrically-stretched sigma layers to permit better representation of bottom topography. The current vertical resolution of the grid is 10 sigma (bottom-following) layers at depths shallower than 200m, providing forecasts at 150,680 points averaged every 10 minutes.

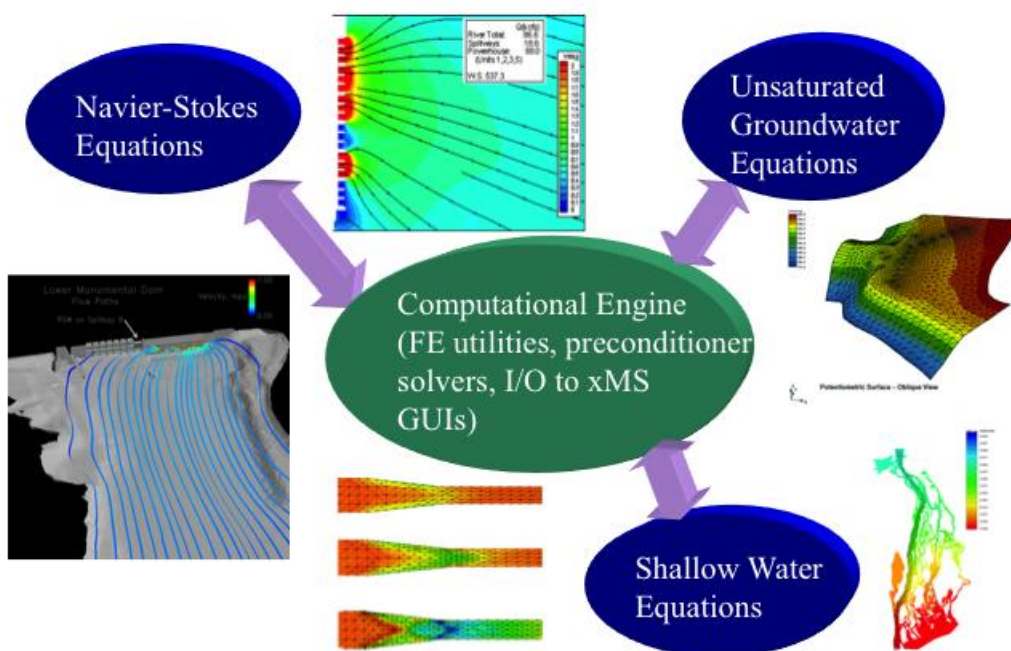
After many years of continuous model development, the accuracy and applicability of sECOM has improved markedly. Several comprehensive skill assessment studies have been carried out and in each case sECOM’s performance has been exemplary. Today the model is used in the NYHOPS domain with confidence to address the emergency issues as we safe navigation, water quality concerns, and beach erosion and flooding. It has been used in rescue efforts including US Airways Flight 1549 and to assist with water level forecasts associated with Hurricane Irene (<http://www.cnbc.com/id/15840232?play=1&video=300004196>). sECOM’s forecasts are shared daily with the NWS, USCG, and NOAA OR&R. They are also now being used effectively by the recreational community - sailors, power boaters, swimmers, and fishermen.

8. Adaptive Hydraulics Model (ADH)

Gaurav Savant, Charlie Berger, Jennifer N. Tate and Gary L. Brown
United States Army Corps of Engineers

ADH is an implicit, Finite Elements based unstructured grid model developed at the US Army Corps of Engineers Engineer (USACE) Research and Development Center (ERDC). ADH is a modular numerical code and features the ability to solve the unsaturated groundwater equations, **3D Navier-Stokes equations, as well as 2D and 3D shallow water flow equations. The groundwater and shallow water modules are linked and can be solved together for surface water and groundwater exchange problems.** The grid is unstructured for all modules of ADH resulting in quick and accurate representation of the underlying problem bathymetry and shoreline features. The 3D shallow water module utilizes the Smagorinsky turbulent closure scheme in the horizontal and the Mellor-Yamada closure schemes in the vertical.

ADH Philosophy



ADH solves the conservative form of the continuity equation and guarantees fluid and constituent mass conservation to machine precision. ADH refines the base grid depending upon problem physics thereby providing targeted mesh resolution in regions of change of interest. This higher resolution is transient and is added as well as removed as and when required. The mesh adaption feature is particularly suited for estuarine and coastal problems where sediment plumes

and salinity intrusion are frequent. Adaption helps capture the plume or the salt wedge as it traverses through the domain.

ADH is a robust model with a large developer (Federal, University and Private) and user (Federal, Universities, Private and International) base. ADH is a USACE model and therefore is more likely to be available and supported for a long duration as opposed to university or privately held models that might be dependent upon funding levels.

ADH can handle super and subcritical flow within the same domain at the same time, this unique capability is particularly useful when modeling storm surges and resulting levee overtopping or sea level rise scenarios.

ADH is ideally suited for application to the Chesapeake Bay system. Key features for this application include 1) mass conservative wetting/drying, 2) adaptive refinement to accurately represent salt water intrusion fronts, sediment plumes or water quality indicator plumes etc, 3) implicit time stepping resulting in fast simulations, 4) Adaptive time stepping resulting in targeted time step sizes that guarantee convergence of the solution 5) capability to represent structures such as sea walls, dikes etc, 6) links to sediment transport and bedload libraries/processes, 7) links to water quality libraries such as CE-ICM and CE-NSM, 8) link to ecological libraries such as CASM, 9) links to STWAVE for wave stresses, 10) links to ADCIRC.

ADH has been applied to study problems in , among others too numerous to list, Galveston Bay (TX), San Pedro Bay (CA), San Diego Harbor (CA), Columbia River Estuary (WA), Mobile Bay (AL), Mississippi River Delta (LA), Breton Sound (LA), Cook Inlet (AK), St. Johns River Estuary (FL), Biscayne Bay (FL), Chesapeake Bay Sea Level Rise (MD), West Bay Diversion (LA), Suisun Bay (CA), Sacramento-San Joaquin Delta (CA), South Bay (CA), Great Lakes, Missouri River, Indus River (Pakistan), Dam Breaks (Afghanistan, Pakistan, Nepal, N. Korea etc).

Additional Information about ADH can be accessed via the internet at <http://adh.usace.army.mil> (outside DOD users have to use <https://adh.usace.army.mil>). A comprehensive list of publications on ADH is also available at the website under the publications tab.

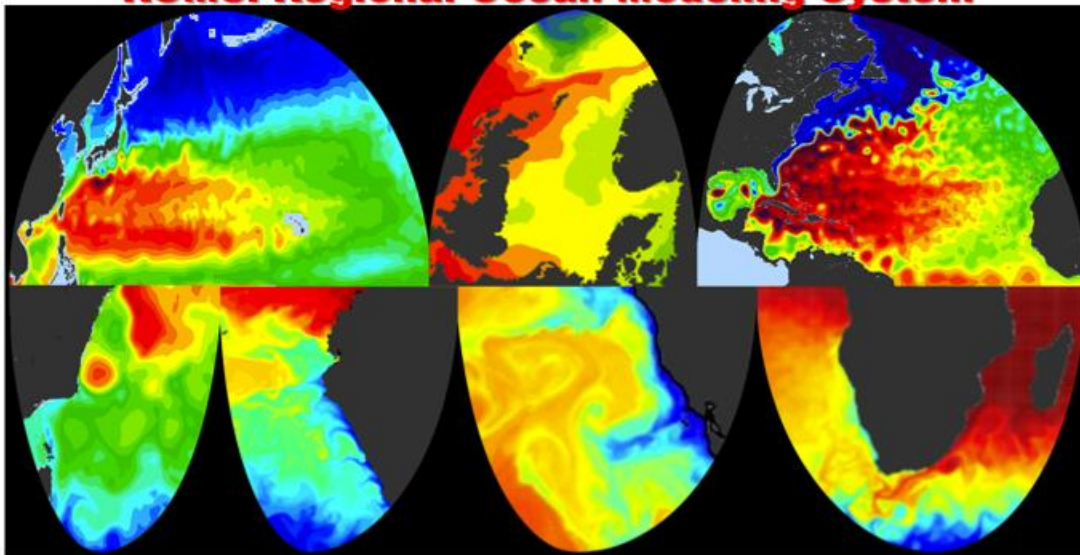
9. The Regional Ocean Modeling System (ROMS)

Hernan G. Arango

Institute of Marine and Coastal Sciences, Rutgers University

The Regional Ocean Modeling System (ROMS), currently available online at www.myroms.org, is a well established and widely accepted open source community ocean model based on primitive variables and first principle equations of geophysical fluid mechanics. The model solves for basic hydrodynamic quantities including sea surface height, 3D velocities, density, and turbulent kinetic energy using a terrain-following S coordinate in the vertical dimension and a staggered orthogonally curvilinear grid in the horizontal dimensions. The underlying assumptions include hydrostatic pressure, Boussinesq assumption of density variation, Coriolis effect as well as incompressible flow. The model bears the merits of incorporating most turbulence models for ocean flow, having a number of biogeochemical models inherently coupled with hydrodynamics, being open source, using modern parallel-computing code and allowing flexible user-specific configuration. Perhaps most importantly, ROMS comes with a large user and developer community. Latest developments of ROMS include sophisticated data assimilation schemes, sediment transport, flexible grid nesting capabilities and coupling with modern hydrology and meteorological models. Several ROMS model configurations and applications have been developed successfully for the Chesapeake Bay.

ROMS: Regional Ocean Modeling System



- Free-surface, Hydrostatic Primitive Equation Model
- Generalized Terrain-Following Vertical Coordinates
- Boundary-fitted Orthogonal Curvilinear Coordinates on an Arakawa C-grid: Cartesian, Spherical, and Polar
- Multiple Grid and Model Coupling (MCT, ESMF)
- High-order Numerical Schemes
- Shared- and Distributed-memory (OpenMP, MPI)
- F90/F95, C-preprocessing, NetCDF I/O
- Tangent Linear, Representer, and Adjoint Models
- Adjoint-based Algorithms for 4D-Var data assimilation, Ensemble Prediction, Adaptive Sampling, Sensitivity Analysis, and Generalized Stability Theory Analysis
- Tides, Ecosystem, Sediment, Sea Ice Models
- Various Vertical Mixing Schemes and Bottom Boundary Layer Parameterizations
- Web-Based Documentation and Distribution: www.myroms.org, www.myroms.org/wiki

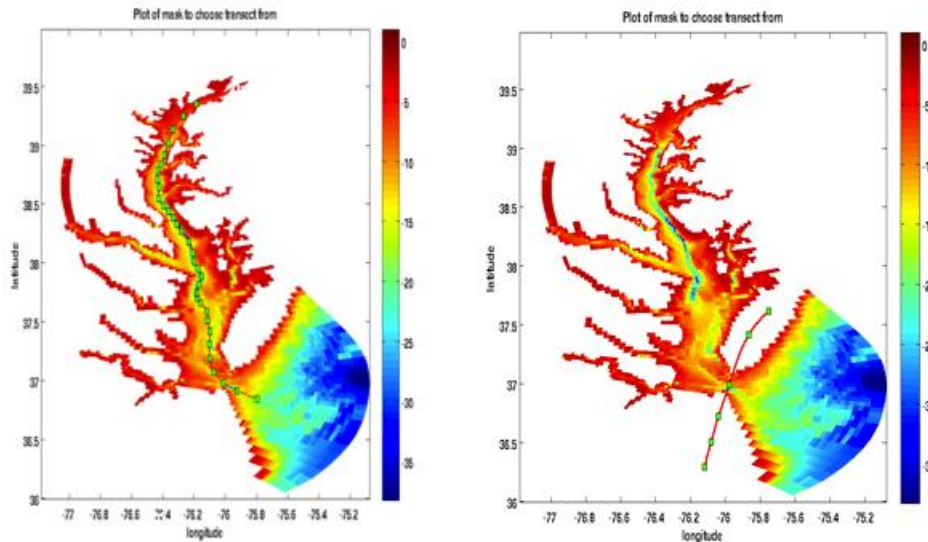
10. Coastal Shelf Influences on Chesapeake Bay, from a Modeling Perspective

Wen Long

University of Maryland Center for Environmental Science

ChesROMS (Chesapeake Bay Regional Ocean Modeling System) is developed based on the ROMS model as an open source community model. Extensive validation and hindcast simulations have been carried out. ChesROMS also consists of a built-in biogeochemical module for water quality simulations. Since reproducing salinity stratification is crucial for reproducing hypoxia in the Chesapeake Bay, we conducted sensitivity tests of salinity structure by perturbing the external forcing in various ways. Year 2005 was used as the baseline case and perturbations to river flow, wind speed on the shelf, and open boundary T and S forcing in May of 2005 were carried out to pinpoint the difference compared to the baseline case. Aggregated total salinity in the Bay, salt flux through a Bay mouth transect (right panel of the figure below) as well as EOF analysis of salinity structure along a centerline Bay transect (left panel) were performed to detect these sensitivities.

Results indicate that the salinity structure and salt budget in the Bay are much more responsive to changes in river discharge than to changes in open ocean (shelf) temperature, salinity and wind magnitude. The relative response of the circulation in the Bay to changes in shelf wind direction and sub-tidal water level changes is under further examination.



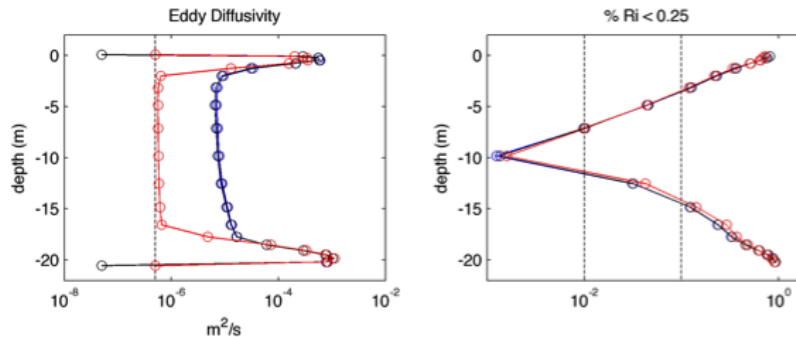
11. Estuarine Turbulence Modeling

Malcolm Scully

Center for Coastal Physical Oceanography, Old Dominion University

- Most two-equation turbulence models capture the essential behavior of stratified turbulence: a) they limit the turbulent length scale under stratified conditions; b) turbulent mixing is extinguished once a critical value of the gradient Richardson number is exceeded; c) they account for non-local turbulent mixing (advection and diffusion of TKE).
- Most commonly used 2-equation models are structurally the same and model results are largely insensitive to choice of second turbulent quantity.
- Stability functions of Canuto et al. (2000) generally result in more mixing because they allow mixing to occur at higher Richardson number.
- Model results are sensitive to the value of background diffusivity that is used.
- Specified background diffusivities are only achieved by the models when the minimum value of TKE is sufficiently low.
- In order to capture the strong density gradients in the pycnocline, low values of background viscosity are needed (molecular values?).
- In order to use low background diffusivities, models must resolve the spatial scales that are important to turbulence generation (shear).

Importance of setting appropriate minimum value for TKE



$$Kz_{\min} = 5 \times 10^{-7} \quad TKE_{\min} = 7.6 \times 10^{-6}$$

$$Kz_{\min} = 5 \times 10^{-8} \quad TKE_{\min} = 7.6 \times 10^{-6}$$

$$Kz_{\min} = 5 \times 10^{-7} \quad TKE_{\min} = 7.6 \times 10^{-8}$$

Only when only the minimum value of TKE is sufficiently low, can model achieve the specified background diffusivity!!

12. Component-based Ocean Modeling with the Community Surface Dynamics Modeling System (CSDMS)

Scott Peckham

University of Colorado

Key advantages to using Component based models:

- Components can be written in different languages and still communicate (via language interoperability).
- Components can be replaced, added to, or deleted from an application at runtime via dynamic linking (as precompiled units).
- Components can easily be moved to a remote location (different address space) without recompiling other parts of the application (via RMI/RPC support).
- Components can have multiple different interfaces.
- Components can be “stateful”; that is, data encapsulated in the component is retained between method calls over its lifetime.
- Components can be customized at runtime with configuration parameters.

Building a Modeling Framework

CSDMS has integrated a variety of powerful, open-source tools to build its modeling framework, such as:

Babel – Language interoperability (C,C++,Java,Python,Fortran)

Bocca – Component preparation and project management

Ccaffeine – Low-level model coupling (parallel environ.)

ESMF Regrid – Multi-processor spatial regriding

OpenMI Regrid – Single-processor spatial regriding

OpenMI – Component interface standard (1.4 and 2.0)

NetCDF – Scientific data format (self-describing, etc.)

VisIt – Visualization of large data sets (multi-proc.)

We greatly extended the original *Ccaffeine GUI* to create our **CSDMS Modeling Tool** for interactive model coupling.