U.S. GODAE: GLOBAL OCEAN PREDICTION WITH THE HYBRID COORDINATE OCEAN MODEL (HYCOM)

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Award #: N00014-04-1-0676
http://www.hycom.org

LONG-TERM GOALS

A broad partnership of institutions is collaborating in developing and demonstrating the performance and application of eddy-resolving, real-time global and basin-scale ocean prediction systems using the HYbrid Coordinate Ocean Model (HYCOM). These systems are to be transitioned for operational use by the U.S. Navy at both the Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS, and the Fleet Numerical Meteorology and Oceanography Center (FNMOC), Monterey, CA, and by NOAA at the National Centers for Environmental Prediction (NCEP), Washington, D.C. The systems will run efficiently on a variety of massively parallel computers and will include sophisticated, but relatively inexpensive, data assimilation techniques for assimilation of satellite altimeter sea surface height (SSH) and sea surface temperature (SST) as well as in-situ temperature, salinity, and float displacement.

The partnership represents a truly broad spectrum of the oceanographic community, bringing together academia, federal agencies, and industry/commercial entities, spanning modeling, data assimilation, data management and serving, observational capabilities, and application of HYCOM prediction system outputs. The institutions participating in this Partnership have long histories of supporting and carrying out a wide range of oceanographic and ocean prediction-related research and data management. All institutions are committed to validating an operational hybrid-coordinate ocean model that combines the strengths of the vertical coordinates used in the present generation of ocean models by placing them where they perform best. This collaborative partnership provides an opportunity to leverage and accelerate the efforts of existing and planned projects, in order to produce a higher quality product that will collectively better serve a wider range of users than would the individual projects. In addition to operational eddy-resolving global and basin-scale ocean prediction systems for the U.S. Navy and NOAA, respectively, this project offers an outstanding opportunity for NOAA-Navy collaboration and cooperation ranging from research to the operational level.

This effort is part of a 5-year (FY04-08) multi-institutional National Ocean Partnership Program (NOPP) project which includes the Florida State University (E. Chassignet, A. Srinivasan), U. of Miami (G. Halliwell, M. Iskandarani, T. Chin, A. Mariano, Z. Garraffo), NRL/STENNIS (H. Hurlburt, A. Wallcraft, J. Metzger, B. Kara, J. Cummings, G. Jacobs, H. Ngodock, C.A. Blain, P. Hogan, J. Kindle), NAVOCEANO (F. Bub), FNMOC (M. Clancy), NRL/MONTEREY (R. Hodur, J. Pullen, P. May), NOAA/NCEP/MMAB (D.B. Rao, C. Lozano), NOAA/NOS (F. Aikman), NOAA/AOML (C. Thacker), NOAA/PMEL (S. Hankin), Planning System Inc. (O.M. Smedstad), NASA-GISS (R. Bleck), SHOM (R. Baraille), LEGI (P. Brasseur), OPeNDAP (P. Cornillon), U. of S. Mississippi (W. Schmitz), U. of N. Carolina (C. Werner), Rutgers (J. Wilkin, D. Haidvogel), U.

of S. Florida (R. Weisberg), Fugro-GEOS/Ocean Numerics (D. Szabo, R. Stephens), Horizon Marine Inc. (J. Feeney, S. Anderson), ROFFS (M. Roffer), Orbimage (L. Stathoplos), Shell Oil Company (M. Vogel), ExxonMobil (O. Esenkov).

OBJECTIVES

The partnership is addressing the Global Ocean Data Assimilation Experiment (GODAE) objectives of three-dimensional (3D) depiction of the ocean state at fine resolution in real-time and provision of boundary conditions for coastal and regional models. It will also provide the ocean component and oceanic boundary conditions for a global coupled ocean-atmosphere prediction model. It will make these results available to the GODAE modeling community and general users on a 24/7 operational basis via a comprehensive data management strategy.

APPROACH AND WORK PLAN

HYCOM development is the result of collaborative efforts among the University of Miami, the Naval Research Laboratory (NRL), and the Los Alamos National Laboratory (LANL), as part of the multi-institutional HYCOM Consortium for Data-Assimilative Ocean Modeling. This effort was funded by the National Ocean Partnership Program (NOPP) in 1999 to develop and evaluate a data-assimilative hybrid isopycnal-sigma-pressure (generalized) coordinate ocean model (Bleck, 2002; Chassignet et al., 2003; Halliwell, 2004). HYCOM has been configured globally and on basin scales at 1/12º (~7 km mid-latitude) resolution, and regionally at 1/25º (~3.5 km mid-latitude) resolution. More details can be found at http://www.hycom.org.

While HYCOM is a sophisticated model, including a large suite of physical processes and incorporating numerical techniques that are optimal for dynamically different regions of the ocean, data assimilation is still essential for ocean prediction a) because many ocean phenomena are due to flow instabilities and thus are not a deterministic response to atmospheric forcing, b) because of errors in the atmospheric forcing, and c) because of ocean model imperfections, including limitations in resolution. One large body of data is obtained remotely from instruments aboard satellites. They provide substantial information about the ocean's space-time variability at the surface, but they are insufficient by themselves for specifying the subsurface variability. Another significant body of data is in the form of vertical profiles from XBTs, CTDs, and profiling floats *(e.g.,* ARGO). Even together, these data sets are insufficient to determine the state of the ocean completely, so it is necessary to exploit prior knowledge in the form of statistics determined from past observations as well as our understanding of ocean dynamics. We combine all sources of information synergistically to produce the best possible depiction of the evolving ocean. Several techniques for assimilating data into HYCOM are either in place or under development.

In order to increase the predictability of coastal regimes, several partners within the HYCOM consortium are developing and evaluating boundary conditions for coastal prediction models based on the HYCOM data assimilative system outputs. The inner nested models may or may not be HYCOM, so the coupling of the global and coastal models needs to be able to handle unlike vertical grids. Coupling HYCOM to HYCOM is now routine via one-way nesting (Zamudio et al., 2006). Coupling HYCOM to other models, such as the Navy Coastal Ocean Model (NCOM) or the Regional Ocean Model System (ROMS), has already been demonstrated, while coupling of HYCOM to unstructured grid/finite element models is still in progress.

RESULTS

We report here on some of the progress made during FY 07.

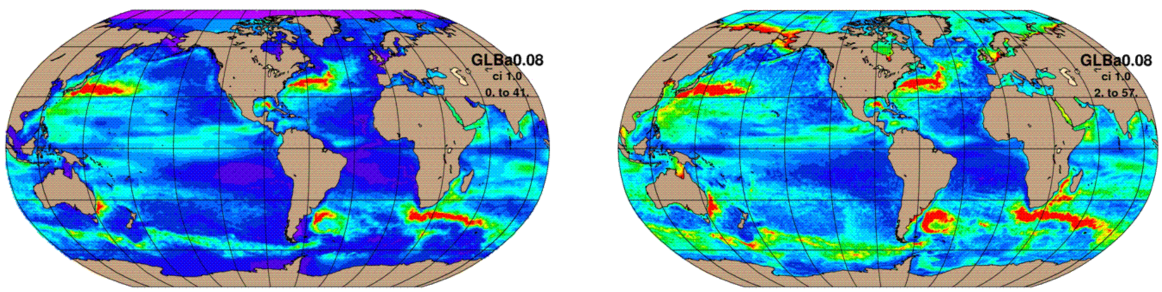
a) <u>Global U.S. Navy ocean forecasting system:</u>

NCODA Implementation:

The Navy Coupled Ocean Data Assimilation (NCODA) (Cummings, 2005) system is being used as the assimilation technique in the global HYCOM experiments. The NCODA system is a fully three-dimensional multivariate optimum interpolation system. The three-dimensional ocean analysis variables include temperature, salinity, geopotential and the vector velocity components (T, S, U, V), which are all analyzed simultaneously. In support of HYCOM, a new analysis variable was added to NCODA that corrects the model layer pressure of the hybrid vertical coordinates. The NCODA horizontal correlations are multivariate in geopotential and velocity, thereby permitting adjustments (increments) to the mass fields to be correlated with adjustments to the flow fields. The velocity adjustments are in geostrophic balance with the geopotential increments, and the geopotential increments are in hydrostatic agreement with the temperature and salinity increments. Either the Cooper and Haines (1996) technique or synthetic T & S profiles (Fox et al., 2002) can be used for downward projection of SSH and SST. The Cooper and Haines (1996) technique is used for downward projection of the SSH data in the experiments with the global model. The present implementation interpolates the HYCOM vertical coordinate to z-space, performs the NCODA analysis, and then maps the z-level NCODA T, S U, V and layer pressure analysis increments to the appropriate HYCOM vertical coordinate. The HYCOM update program applies the temperature and salinity analysis increments in the model mixed layer, and applies the layer pressure analysis increments in the isopycnal part of the domain to correct the model interface layer pressures. The incremental updating scheme is used so that a fraction of the analysis increments can be added to the HYCOM forecast variables at each model time step. Typically the increments are added over a 6 hour window. The NCODA analysis software has been upgraded so that it can run both in the Mercator and the bipolar Arctic part of the HYCOM domain, see below.

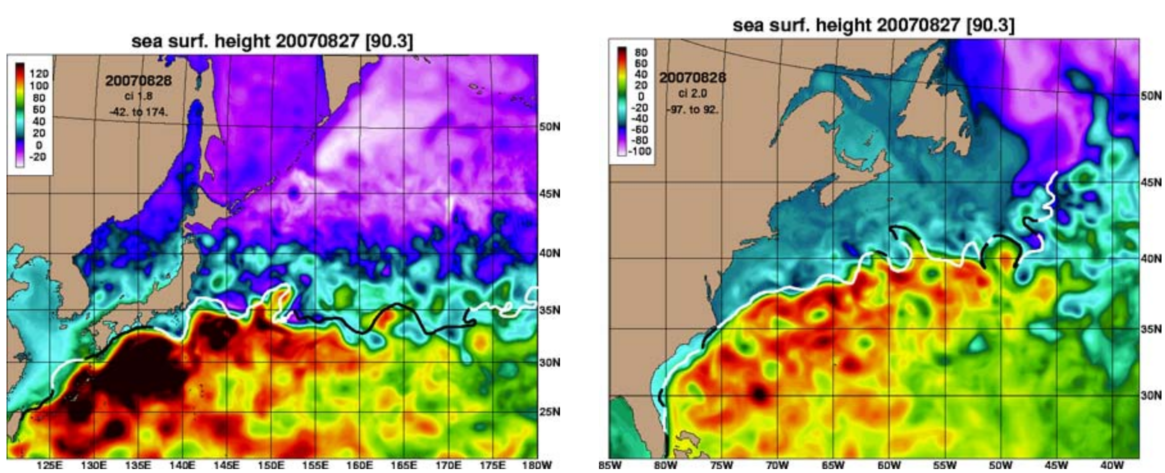
1/12º Global U.S. Navy HYCOM:

A pre-operational nowcast/forecast system using the 1/12º global HYCOM has been running in near real-time since 22 December 2006 and in real-time since 16 February 2007. The experiment was initialized on 2 November 2003 using a model field from a run without data assimilation. The model is running on 379 processors (24 nodes) on the IBM Power 5+ at the Naval Oceanographic Office using a part of the operational allocation on the machine. The daily run consists of a 5 day hindcast and a 5 day forecast and takes about ~15 wall clock hours. The NCODA analysis is performed at 18Z and the model is incrementally updated over the next 6 hours so that the data from the 18Z analysis is in the model at the 00Z nowcast. The NCODA analysis is therefore performed every 24 hours, assimilating all available observations within 12 hours of the analysis time except for the altimeter data where a 72 hour time window was used. In order to assimilate the altimeter anomalies from the satellite altimeters, it is necessary to have a mean sea surface height field. In the current system, a model mean from an atmospherically forced model experiment was used. The mean sea surface height was compared to available observations of the frontal location of the Kuroshio and the Gulf Stream and then modified using a rubber sheeting technique. It is extremely important to have an accurate frontal location for the assimilation to be successful in these regions. The model outputs from the hindcast experiment are available through the HYCOM consortium web page, http://www.hycom.org. A validation of the results from the hindcast run is underway with a on the large scale circulation features, sea surface height variability and eddy kinetic energy, mixed layer depth, vertical profiles of temperature and salinity, sea surface temperature and coastal sea levels. As an example of this validation, Figure 1a shows the SSH variability from the Modular Ocean Data Assimilation System (MODAS) analysis of altimeter observations and Figure 1b shows the variability from HYCOM over the three years of the assimilative hindcast experiment. The variability compares well with what is observed. An example of an independent observation comparison can be seen in Figure 2a-b. These figures show the SSH in the Kuroshio and Gulf Stream region, respectively. The white/black line represents the frontal analysis of MCSST observations performed at the Naval Oceanographic Office. A black line represents data more than four days old. The model is able to accurately depict the frontal position in these regions, showing most of the meanders indicated in the observations. Verification of 30-day ocean forecasts is discussed in Figure 3.



(a) (b)

Figure 1. (a) The SSH variability from the MODAS analysis of available satellite altimeter observations for the period 1993-2006 and (b) the SSH variability from the 1/12º Global HYCOM domain over the time period 2004-2006, the three years of the assimilative hindcast.



(a) (b)

Figure 2. The SSH field from the 1/12º Global HYCOM domain on 27 August 2007 in the (a) Kuroshio region and (b) Gulf Stream region. The black line represents the frontal analysis of MCSST observation performed at the Naval Oceanographic Office. A black line represents data more than four days old.

Subregion	Latitude range	Longitude range
World Ocean	45°S - 45°N	all
Gulf Stream region	35°N - 45°N	76°W - 40°W
Equatorial Pacific	20°S - 20°N	109°E - 77°W
NW Arabian Sea and Gulf of Oman	15°N - 26°N	51°E - 65°E
Hawaiian Islands	18°N - 23°N	159.5°W - 153.5°W
Yellow and Bohai Seas	30°N - 42°N	118°E - 127°E

Table 1: Subregions depicted in Figure 4.

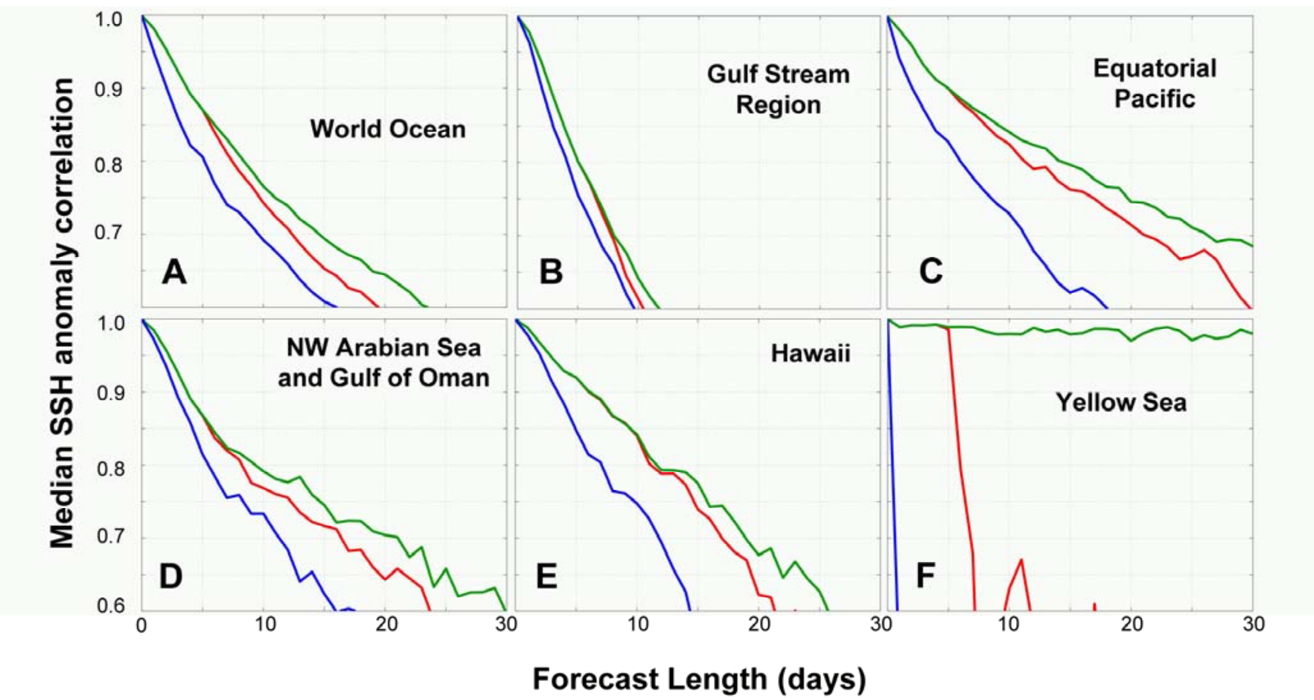


Figure 3: Verification of 30-day ocean forecasts: (a-f) median SSH anomaly correlation vs. forecast length in comparison with the verifying analysis for (a) global HYCOM/NCODA (45°S-45°N) and five subregions (b-f) defined in Table 1. The red curves verify forecasts using operational atmospheric forcing, which reverts toward climatology after five days. The green curves verify "forecasts" with analysis quality forcing for the duration and the blue curves verify forecasts of persistence (i.e. no change from the initial state). The plots show median statistics over twenty 30-day HYCOM forecasts initialized during January 2004 - December 2005, a period when data from three nadir-beam altimeters, Envisat, GFO and Jason-1, were assimilated.

The first hindcast experiment with the 1/12º Global HYCOM using NCODA as the assimilation technique has finished. In this experiment the NCODA analysis was split into 12 overlapping regions covering the Mercator part of the global HYCOM grid. A new set of 8 subdomains have been set up, see Figure 4, so that the NCODA analysis can run in all parts of the global HYCOM grid. The analysis is split in 8 domains for computational efficiency. Each domain is run on a fraction of the total number of available processors so that each domain finishes at about the same time. A hindcast experiment using the new regions is underway. The first experiment will be a repeat of the previous hindcast experiment for the year 2005. The latest version of the HYCOM code is also used in this experiment. The new code can use a baroclinic time step that is twice as long as in the old version. The results from this experiment are in the process of being validated against observations as well as compared to the results from the initial hindcast.

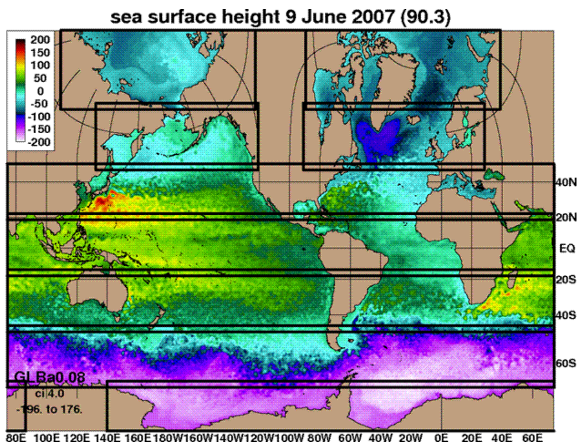


Figure 4. (a) The figure shows the SSH field from the 1/12º Global HYCOM domain on 9 June 2007 with the 8 regions for the NCODA analysis covering the global HYCOM grid.

b) NOAA Real Time Ocean Forecast System for the Atlantic (RTOFS):

The NOAA ocean forecast system (http://polar.ncep.noaa.gov/ofs/) for the Atlantic (25°S-76°N) is run daily with one-day nowcasts and five-day forecasts. Prior to June 2007, only the SST was assimilated. In June 2007, NOAA implemented 3-Dvar data assimilation of i) sea surface temperature and sea surface height (JASON and GFO), ii) temperature and salinity profile assimilation (ARGO, CTD, moorings, etc., and iii) GOES data (for this dataset a bias removal was implemented). As part of this operational implementation, NOAA has improved the specification of data streams and model parameters for i) external mode open boundary conditions, ii) the vertical hybrid grid parameters (25 to 26 layers with better resolution in the coastal areas, and resolution of important water masses in the interior); and iii) river outflow data derived from USGS. For model algorithms, NOAA now employs a surface initialized Montgomery potential, modify the specification of sigma star for stability, and allow the freshening of the water column at river outflows. THE NOAA Operational products are now distributed (http://polar.ncep.noaa.gov/ofs/download.shtml) via operational grain ftp server, and for selected products they reside in the data server NOMADS.

c) Data management:

The HYCOM Data Distribution System effort (S. Hankin, A. Srinivasan, P. Cornillon) has had to address a number of distinct but coupled tasks: receiving model outputs from data providers; converting between formats as needed to meet data serving needs; providing data subsets to internal

HYCOM Consortium modelers for purposes of forcing downscaled (coastal) models; providing access to HYCOM outputs for interdisciplinary science and education needs in a variety of formats; providing an on-line environment to assist with validation and intercomparison of model runs. The main goal is to develop and implement a comprehensive data management and distribution strategy that allows easy and efficient access to HYCOM-based ocean prediction system outputs to (a) coastal and regional modeling sites, (b) to the wider oceanographic and scientific community including climate and ecosystem researchers, and (c) the general public especially students in middle and high schools. The basic idea consists of the setup of a web server that acts as a gateway to backend data management, distribution and visualization applications. These applications enable end users to obtain a broad range of services such as browsing of datasets, gif images, NetCDF files, FTP request of data etc. The HYCOM Data Sharing System is built upon two existing software components: the Open Project for a Network Data Access Protocol (OPeNDAP) and the Live Access Server (LAS). These tools and their use to distribute the data are described below. In the current setup, the OPeNDAP component provides the middleware necessary to access distributed data, while the LAS functions as a user interface and a product server. The abstraction offered by the OPeNDAP server also makes it possible to define a virtual data set that LAS will act upon, rather than physical files. An OPeNDAP "aggregation server" utilizes this approach to append model time steps from many separate files into virtual datasets.

The Hybrid Coordinate Ocean Model (HYCOM) consortium's data service provides at the present time access to the following datasets:

1) 1/12 Global HYCOM simulation (Free run - currently the daily oputputs of years 2003-2006 are available; will soon be extended to 2007)
2) 1/12 Global U.S. Navy HYCOM daily hindcasts using the NCODA analysis (years 2003 to present)
3) 1/12 Global U.S. Navy HYCOM+NCODA real time daily 5-day forecast.
4) Near real-time 1/12° U.S. Navy Atlantic Ocean prediction system output (June 2003 – Present)
5) Monthly mean 1/12° Pacific Ocean Simulation output (1978-2003)
6) Monthly mean 1/3° Atlantic Ocean simulation output (1980-2000)
7) Several 1/12° Gulf of Mexico simulations for inter-comparing data assimilation schemes (HYDAE)

The HYCOM Data service has been in operation for the last four years and has seen a steady increase in the user base. In the last year the service received approximately 20,000 hits per month. In addition to the numerous requests from educational institutes and researchers this service has been providing near real-time data products to several private companies in France, Portugal and the USA. A Storage Area Network (SAN) consisting of three servers consisting of 4 AMD dual core Opteron CPUs attached over fibre channel to 100 TB of SATA based storage has been recently purchased. In this system, the servers are configured in a high availability mode and runs a Global file system which will allow concurrent read/write requests from all the attached 24 CPU's. The server design and overall operational philosophy includes high availability and high reliability features to allow for uninterrupted use.

d) <u>Boundary conditions for regional/coastal models</u>

The horizontal and vertical resolution chosen for the above forecasting systems marginally resolves the coastal ocean (7 km at mid-latitudes, with up to 15 terrain-following (σ) coordinates over the shelf), but is an excellent starting point for even higher resolution coastal ocean prediction systems. The resolution should increase to 1/25º (3-4 km at mid-latitudes) by the end of the decade. An important attribute of the data assimilative HYCOM simulations is therefore the capability to provide boundary conditions to regional and coastal models. In order to increase the predictability of coastal regimes, several partners within the HYCOM consortium are developing and evaluating boundary conditions for coastal prediction models based on the HYCOM data assimilative system outputs. As stated above, coupling HYCOM to other models, such as the NCOM or ROMS, has already been demonstrated and is now routine, while coupling of HYCOM to unstructured grid/finite element models is in progress.

During this past year, the U. of North Carolina group focused on two aspects: an improvement of the finite element mesh used to nest their coastal domain in the HYCOM solution (i.e., forced by HYCOM in a downscaling mode) and acceleration of the transition of the coastal circulation model from Quoddy to ADCIRC.

1. Transition to new FEM mesh. UNC became concerned about the validity of their South Atlantic Bight (SAB) regional model simulations (currently done with Quoddy), primarily owing to insufficient resolution seaward of the continental shelf. They generated a new mesh such that:

- Minimum resolution will keep the 1/12-degree resolution of the HYCOM simulation. This is particularly important to prevent deep ocean mesoscale eddies properly captured in the HYCOM simulations from being aliased to larger features oscillating at inertial period in Quoddy simulations.
- Enhanced resolution near the shelf break.
- Northern boundary extended to include Chesapeake and Delaware Bays. We have included these in order to be able to include outflows from the Bays into the domain and to have better overlap with Harvey Seim's HFR surface velocities from Cape Hatteras to beyond the mouth of Chesapeake Bay.
- Northern boundary extending offshore far enough to capture the complete envelope of likely Gulf Stream exit from the domain.

Two versions of the new mesh were produced by Rick Luettich's group at UNC. The first mesh contains very high resolution along the coastline and includes estuaries, islands, and tidal inlets (Figure 5). The second is the same, except that it has a continuous coastline. UNC anticipates that these changes, together with algorithmic changes in the treatment of the open boundaries, will significantly improve the baroclinic Quoddy runs.

Once Quoddy is running reliably on the new mesh, the SAB nowcast/forecast system will be re-implemented. The new system will use the new mesh, the new global HYCOM 1/12-degree simulations, and new NCEP meteorological forcing products. This system will serve as the basis of the climatological studies outlined previously. This work will use the continuous shoreline (no inlets or estuaries) version of the new mesh.

2. Transition to ADCIRC. UNC plans to transition to the use of ADCIRC for our regional model as soon as feasible. They are collaborating with Luettich (UNC) and Randy Kolar (U Oklahoma) as they work to produce a 3D baroclinic version of ADCIRC. A 4-day diagnostic run has been completed, and surface density and velocity fields are shown in Figure 6 (on an earlier mesh). They will switch our nowcast/forecast system and climatological runs to ADCIRC on the high-resolution version of the new mesh (including the estuaries and inlets), taking advantage of the speed of ADCIRC's parallelized version to complete this work.

Figure 5. New finite element mesh of the South Atlantic Bight. Open-ocean resolution is a maximum of 1/12-degree and coastal islands, inlets and estuaries are resolved. A second version of this mesh with a continuous coastline will be used for Quoddy runs, and the full mesh will be used after the transition to ADCIRC.

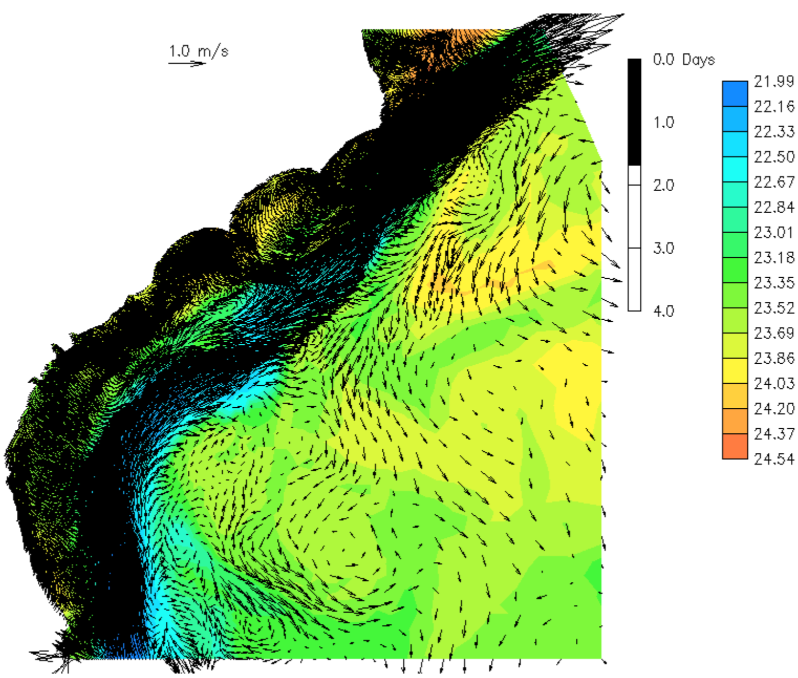


Figure 6. Top level velocity field 1.75 days into a 4-day diagnostic run of the 3D baroclinic version of ADCIRC. The color map shows top level density anomaly (density field held constant for the diagnostic run). Initial conditions are from the 1/12-degree Atlantic HYCOM simulation and the FEM mesh is the original HYCOM/Quoddy SAB mesh (courtesy R. Kolar and K. Dresback, U. Oklahoma)

IMPACT/APPLICATIONS

HYCOM with data assimilation is on track for use in an operational eddy-resolving, fully-global ocean prediction system. It will provide boundary conditions to finer resolution coastal/regional models that may use HYCOM or a different model. HYCOM is designed to make optimal use of three types of vertical coordinate, isopycnal, σ and pressure (~z-level). Isopycnals are the natural coordinate in stratified deep water, terrain-following (σ) coordinates in shallow water and z-levels within the mixed layer. The layered continuity equation allows a smooth dynamical space and time varying transition between the coordinate types. HYCOM permits isopycnals intersecting sloping topography by allowing zero thickness layers and it should allow accurate transition between deep and shallow water, historically a very difficult problem for ocean models. It also allows high vertical resolution where it is most needed, over the shelf and in the mixed layer. The isopycnal coordinate reduces the need for high vertical resolution in deep water. The project is represented by E. Chassignet (Florida State), J. Cummings (NRL) and H. Hurlburt (NRL) on the International GODAE Steering Team, a multinational effort designed to help justify a permanent global ocean observing system by demonstrating useful real-time global ocean products.

TRANSITIONS

None.

RELATED PROJECTS

This is a highly collaborative NOPP project with 24 partnering groups as listed above. Additionally, the project is receiving grants of super computer time from the DoD High Performance Computing Modernization Office and collaborates closely with the NOPP project led by G. Halliwell entitled "HYCOM Coastal Ocean Hindcasts and Prediction: Impact of Nesting in HYCOM GODAE Assimilative Hindcasts".

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