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

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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 will 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 project 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 **U. of Miami** (E. Chassignet, G. Halliwell, M. Iskandarani, T. Chin, A. Mariano, Z. Garraffo, A. Srinivasan, P. Minnett, R. Evans, W. Schmitz), **NRL/STENNIS** (H. Hurlburt, A. Wallcraft, J. Metzger, B. Kara, J. Cummings, G. Jacobs, H. Ngodock, L. Parent, C.A. Blain, P. Hogan, J. Kindle), **NAVOCEANO** (E. Johnson, J. Harding), **FNMOC** (M. Clancy), **NRL/MONTEREY** (R. Hodur, M. Flatau, X. Hong, J. Pullen), **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, B. Lunde), **LANL** (R. Bleck), **CSIRO** (D. Bi **), SHOM** (R. Baraille), **LEGI** (P. Brasseur), **OPeNDAP** (P. Cornillon), **U. of N. Carolina** (C. Werner), **Rutgers** (J. Wilkin, D. Haidvogel), **U. of S. Florida** (R. Weisberg), **Fugro-GEOS/Ocean Numerics** (D. Szabo, G. Evensen), **Horizon Marine Inc.** (J. Feeney, S. Anderson), **ROFFS** (M. Roffer), **Orbimage** (L. Stathoplos), **Shell Oil Company** (M. Vogel), **ExxonMobil** (O. Esenkov).

OBJECTIVES

The main ojective is to use the HYbrid Coordinate Ocean Model (HYCOM) with data assimilation in an eddy-resolving, fully global ocean prediction system with transition to the Naval Oceanographic Office (NAVOCEANO) at .08° equatorial (~7 km mid-latitude) resolution in 2007 and .04° resolution by 2011. The model will include shallow water to a minimum depth of 5 m and provide boundary conditions to finer resolution coastal and regional models that may use HYCOM or a different model. In addition, HYCOM will be coupled to atmospheric, ice and bio-chemical models, with transition to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) for the coupled ocean-atmosphere prediction. Basin-scale configurations will also form the backbone of the NOAA/NCEP/MMAB Ocean Forecast System. All the systems will be transitioned with assimilation of sea surface height (SSH) from satellite altimeters, sea surface temperature (SST) and temperature (T)/salinity (S) profiles, including profiles from ARGO floats. In addition, 30-day forecasts are planned once a week. The global system will include two-way coupling to an ice model and a version with two-way coupling to an atmospheric model for transition to FNMOC. The project will ensure that an accurate and generalized ocean model nesting capability is in place to support regional and littoral applications when global HYCOM becomes operational. This will include the capability to provide boundary conditions to nested models with fixed depth z-level coordinates, terrain following coordinates, generalized coordinates (HYCOM), and unstructured grids. To facilitate this goal, HYCOM will be developed into a full-featured coastal ocean model in collaboration with a partnering project. The project will participate in the multinational Global Ocean Data Assimilation Experiment (GODAE) and international GODAE-related ocean prediction system intercomparison projects.

APPROACH AND WORK PLAN

1. Ocean model design: HYCOM is a generalized (hybrid isopycnal/σ/z) coordinate ocean model. It is isopycnal in the stratified ocean, but reverts to a terrain-following (σ) coordinate in shallow coastal regions, and to z-level coordinates in the surface mixed layer. The vertical coordinate is dynamic in space and time via the layered continuity equation, which allows a dynamical transition between the coordinate types. Like its predecessor, the Miami Isopycnic Coordinate Ocean Model, HYCOM allows isopycnals intersecting sloping topography by allowing zero thickness layers. HYCOM was developed from MICOM using the theoretical foundation for implementing a hybrid coordinate system set forth in Bleck and Boudra (1981), Bleck and Benjamin (1993), Bleck (2002) and Halliwell (2004). Alan Wallcraft (NRL) is in charge of developing and maintaining the standard version of the model, one that is scalable/portable and can run on the latest computer architectures. HYCOM is maintained as a single source code with the maximum feasible backward compatibility.

2. Data assimilation techniques: The effort is focusing on (1) multi-variate optimum interpolation (MVOI) (Daley, 1991), (2) the Singular Evolutive Extended Kalman (SEEK) filter (Pham et al., 1998), and (3) the ensemble Kalman filter (EnKF) (Evensen, 1997). MVOI is used in the NRL Coupled Ocean Data Assimilation (NCODA) system of J. Cummings (NRL) which is being adapted for use in HYCOM in collaboration with O.M. Smedstad (Planning Systems, Inc.), C. Thacker and HS. Kang at NOAA/AOML, and C. Lozano at NOAA/NCEP/MMAB. For all the techniques, the primary data types are SSH from satellite altimetry, SST and subsurface T & S profiles. 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 SEEK filter is based on the Kalman filter plus a reduction of the background error covariance matrix. This one is initialized with a low-rank matrix determined from an EOF analysis, an analysis of output from the most realistic HYCOM simulation with interannual atmospheric forcing available. The reduced-order decreases the computational burden of a Kalman filter in a dramatic way. This approach has been used extensively as part of two European projects, Diadem and Topaz. Thanks to the collaboration with LEGI (France), we use the same software to implement this assimilation method in .08° Atlantic HYCOM. The EnKF is also based on the Kalman filter equations, where the background covariance matrix is approximated by Monte-Carlo methods using the model dynamics. The ensemble is generated by adding random perturbations to initial or boundary conditions and/or external forcings. The ensemble is then forecast using the model dynamics. At the analysis time, the covariance matrix is built and inserted into the Kalman filter update equation. Although the EnKF is too expensive computationally for global high resolution models, it can be used in subregions of a global domain and smaller nested models.

3. Ocean model and prediction system configurations: A fully global configuration of HYCOM will be the primary model domain used in this project. It consists of an Arctic dipole patch matched to a standard Mercator grid at 47°N. The target resolution is .08°cosθ in latitude (θ) south of 47°N by .08° in longitude or ~7 km resolution for each model variable at mid-latitudes and 3.5 km at the North Pole. The array size is 4500 x 3298 with 28 or more hybrid layers in the vertical. This will be run using a large FY05-07 DoD High Performance Computing (HPC) Challenge grant of computer time starting early in 2005. It will first be run with atmospheric forcing only. Data assimilation will be added in FY06. A .24° configuration of the global model will also be used. Before FY06, data assimilative model runs will use existing basin-scale configurations, .08° Atlantic HYCOM (28°S-70°N including the Mediterranean Sea) and .08° Pacific HYCOM (north of 20°S). This work will be performed in close collaboration between NRL, E. Chassignet's group (U. Miami) and O.M. Smedstad (PSI), including evaluation of results. In addition, W. Schmitz has joined the evaluation effort. A wide range of data sets are available for the evaluation (Chassignet et al., 2000; Hurlburt and Hogan, 2000) and these papers discuss many climatological model-data comparisons. In addition, we have long time series of transports through the Florida Straits, sea level at tide gauges, altimetric SSH, SST, subsurface T profiles from BTs and moored buoys, and T & S profiles from ARGO floats, some data obtained routinely and some from research field programs.

4. Boundary conditions for littoral and regional models: Work on this topic will be highly collaborative with project partners and partnering projects. At NRL it will include a nesting capability for at least the following models: (1) HYCOM, (2) the Navy Coastal Ocean Model (NCOM) which allows mixed z-level and terrain following coordinates, (3) the ADvanced CIRCulation model for shelves, coasts and estuaries (ADCIRC), an unstructured grid model, and (4) the Regional Ocean Model System (ROMS), which has predetermined non-Lagrangian hybrid

coordinates in the vertical. NCOM is also the model component of the regional Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS^{TM}) developed at NRL-Monterey (Hodur, 1997), a project partner for nesting NCOM in HYCOM.

5. GODAE: The project will participate in GODAE and the related prediction system intercomparison projects, e.g. the European MERSEA. The purpose of GODAE is to help justify a permanent global ocean observing system by demonstrating useful real-time global ocean products. Consistent with this goal, real-time HYCOM prediction system output will be made available to the public within 24 hours via the U.S. GODAE and Miami Live Access Servers (LAS). HYCOM is represented on the U.S. and International GODAE Steering Teams by J. Cummings (U.S. co-chairman), H. Hurlburt, and E. Chassignet.

WORK COMPLETED

a) Global, basin-scale, and regional simulations
b) Implementation of data assimilation capabilities for HYCOM
c) Evaluation of the ability of the North Atlantic ocean prediction system to provide boundary conditions to coastal models
d) Model outputs available via a Live Access Server

RESULTS

The data assimilative 1/12° Atlantic version of HYCOM is a first step towards the fully global 1/12° HYCOM prediction system. The system assimilates the daily MODAS SSH anomaly analysis and SST of available real time satellite data. The atmospheric forcing of the near real time system comes from the Fleet Numerical Meteorology and Oceanography Center (FNMOC) Navy Operational Global Atmospheric Prediction System (NOGAPS). The system runs every Wednesday and consists of a 10-day hindcast and a 14-day forecast. The results are displayed on the HYCOM Consortium web page at http://hycom.rsmas.miami.edu. It includes comparisons to unassimilated observations, e.g. the independent frontal analysis of high resolution SST data performed by NAVOCEANO. The web page that is available to the project participants is also being updated on a weekly basis. This site is used in the evaluation of the model performance and to see the effect of future upgrades to the model and the assimilation scheme. Data from the system are now available in near real time. The HYCOM Consortium web page has a link (http://hycom.rsmas.miami.edu/dataserver) to a data server where the model fields are available for downloading in a variety of formats (e.g. netCDF, binary).

Figures 1 and 2 show examples of the comparison between the prediction system and a set of independent observations. Figure 1a shows the vertical section of the mean velocity across the Yucatan Channel from the 1/12° Atlantic system over the time period of September 2003 through August 2004. Observations of velocities from Abascal et al. (2003) are shown in Figure 1b. The mean velocity/transport across 35°W between 5°S and 5°N from the model is shown in Figure 2a, while a corresponding plot of observations from Schott et al. (2003) is shown in Figure 2b. There is a good agreement between the model and the observations both when it comes to structure and amplitude.

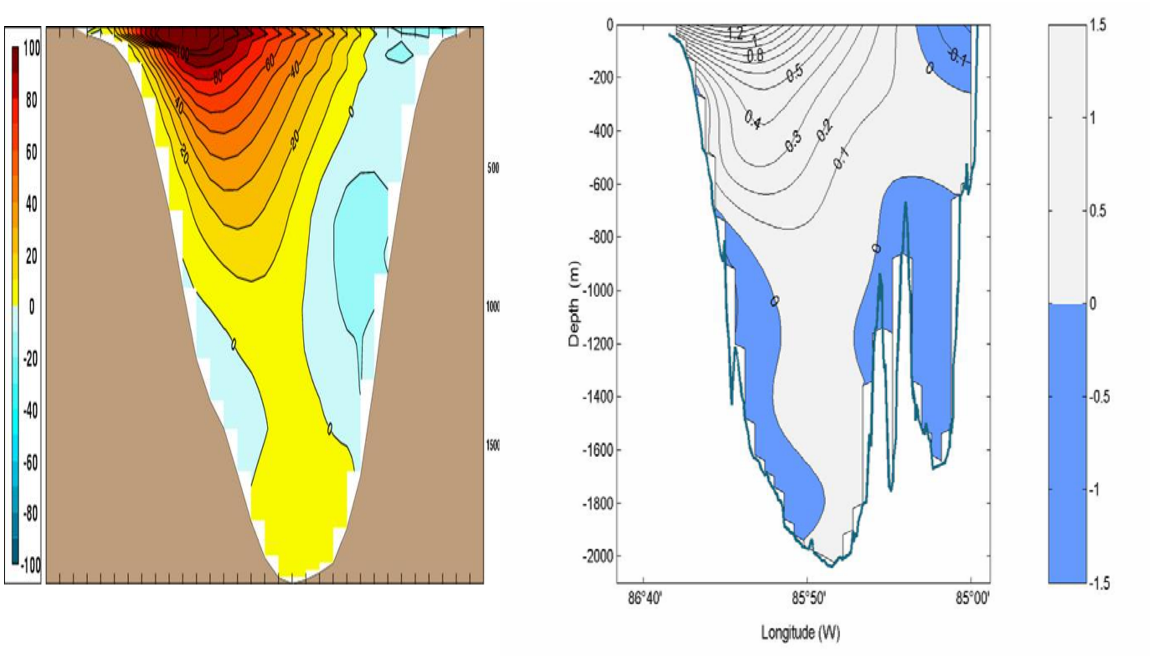
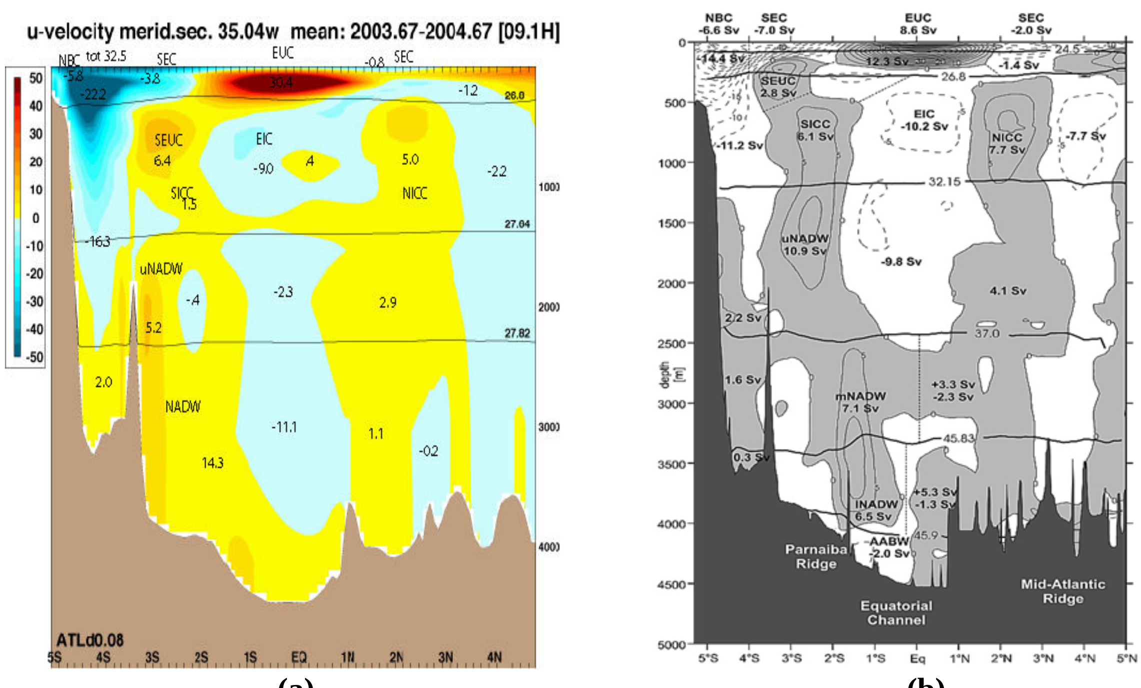


FIGURE 1. (a) Vertical section of the mean velocity across the Yucatan Channel from the 1/12° Atlantic system over the time period of September 2003 through August 2004. (b) Observations of velocities from Abascal et al. (2003).



(a) (b)

FIGURE 2. (a) A vertical section of the mean velocity across 35°W from 5°S to 5°N from the 1/12° Atlantic system. The mean is over the time period July 2003 through August 2004. (b) Observations of transports across 35°W (from Schott et al., 2003)

A .08° Gulf of Mexico HYCOM nested in .08° Atlantic HYCOM was used as the test bed for the first year-long experiment with the MVOI/NCODA data assimilation scheme. The experiment covered Aug 1999 – Sept 2000 and assimilated satellite altimeter track data, SST from AVHRR and in situ T profiles once a week using the model forcast as a 1st guess. The surface fields from the assimilation show good agreement with operational model-independent satellite IR frontal analyses performed at NAVOCEANO. The results are very similar to the existing near real-time .08° Atlantic HYCOM system where a daily analyzed SSH field was assimilated. The MVOI results were slightly better on most days when a frontal analysis was available. Comparing the subsurface fields, a few problems with the first experiment were observed and modifications are underway to correct them. To validate the SEEK filter data assimilation, the benchmark experiment used the 1/3° Atlantic HYCOM. It covered 1993-1994 and was forced by atmospheric fields from the European Centre for Medium-Range Weather Forecasts. Surface data (SSH, SST and SSS) were assimilated every 3 days and the rms misfit was estimated online. Compared to the 1/3° Atlantic HYCOM with atmospheric forcing but no ocean data assimilation, the Gulf Stream has a better pathway (without overshoot), the Loop Current is more realistic and the Azores Current is present with a good connection to the Gulf Stream. In comparison to unassimilated temperature profiles, the data assimilative model run showed an rms difference of ~2.7°C vs ~4.5°C in the model without the data assimilation in the challenging Gulf Stream region.

IMPACT/APPLICATIONS

HYCOM with data assimilation is planned for use in an eddy-resolving, fully global ocean prediction system. It will provide boundary conditions to finer resolution coastal 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 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 (U. Miami), J. Cummings (NRL) and H. Hurlburt (NRL) on the U.S. and International GODAE Steering Teams, a multinational effort designed to help justify a permanent global ocean observing system by demonstrating useful real-time global ocean products.

Web outreach is also a strong component of the HYCOM initiative. A significant issue in ocean modeling and data assimilation is making both the observational data and model output available to (a) the members of our consortium for HYCOM and data assimilation code development, (b) the wider oceanographic and scientific communities, including climate and ocean ecosystem researchers; and (c) the general public. The real-time model outputs are made available to the community at large within 24 hours via the Miami Live Access Server (LAS). Software development and integration of the server system is performed by the NOAA/PMEL group (S. Hankin) in collaboration with those in charge of the U.S. GODAE and Miami servers. Collaboration with the OPeNDAP (formerly named DODS) group (URI, P. Cornillon) will ensure that the remote data sets and model outputs are accessible in real time, despite their size.

National Security
Global real-time generation of optimal estimates of the time-varying ocean state in support of U.S. Navy needs on spatial scales typically of 10-1000 km (mesoscale) with forecasts up to 30 days.

Economic Development
Precise knowledge and prediction of ocean mesoscale features are used by the oil industry and fisheries for risk avoidance and optimal use of their resources.

Science Education and Communication
Web-access to an up-to-date description of the world ocean currents.

TRANSITIONS

None.

RELATED PROJECTS

HYCOM Consortium for Data Assimilative Ocean Modeling

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