U.S. GODAE: Global Ocean Prediction with the HYbrid Coordinate Ocean Model

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LONG-TERM GOALS

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.

OBJECTIVES

Collaborative 5-year (FY04-08) National Ocean Partnership Program (NOPP) project to develop a next generation eddy-resolving, fully global ocean prediction system using HYCOM with .08° equatorial resolution. This system will be transitioned to NAVOCEANO for operational use in 2007 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 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

This is a highly collaborative NOPP project with 24 partnering groups listed in the proposal. These partners are universities (with Eric Chassignet at the University of Miami as the overall lead PI), government (Navy and NOAA), industry and international. Additional partnering efforts are listed under related projects. The description of the approach focuses primarily on aspects performed at NRL-Stennis, many in close collaboration with project partners and partnering projects.

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 MICOM, 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). An FY00-04 NOPP project, "HYCOM consortium for data assimilative ocean modeling", has been the primary vehicle for HYCOM development, a close collaboration between Los Alamos (Rainer Bleck), NRL (Alan Wallcraft) and the University of Miami (George Halliwell), where the person in parenthesis is the lead performer in each group. Alan Wallcraft 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 at NRL-Stennis 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 with E. Chassignet's group (U. Miami) and O.M. Smedstad (PSI), including evaluation of results. In addition, Bill Schmitz will join 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™) 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). NRL is represented on the U.S. and International GODAE Steering Teams by J. Cummings (U.S. co-chairman) and H. Hurlburt.

WORK COMPLETED

Initial funding was received in May 2004. A kick-off meeting for the HYCOM NOPP GODAE project was held at NOAA/NCEP in Aug. 2003 and a 2nd meeting at U. Miami in Feb. 2004. Both the .24° and the .08° fully global HYCOM configurations are part of the DoD HPC Modernization Office standard benchmark suite used in procuring new high performance computers. The benchmark cases contain all the files needed to run HYCOM and are fully realistic configurations with the standard amount of I/O, but the 1/12° run is for < 1 model day for economy. The new 2944 processor IBM p655+ system at NAVOCEANO and 2048 processor Intel cluster at the Army Research Laboratory both perform well on the HYCOM benchmarks.

There has been a strong collaborative effort between J. Cummings (NRL), O.M. Smedstad (PSI) and HS Kang (NOAA/AOML) to adapt J. Cummings MVOI/NCODA system for use in HYCOM with a generalized vertical coordinate. C. Thacker (NOAA/AOML) has done much work on optimal mapping of T & S profiles to isopycnal coordinates under the FY00-04 HYCOM NOPP project. A version of the MVOI/NCODA system is now being tested in a nested .08° Gulf of Mexico subdomain of the .08° HYCOM Atlantic prediction system and a preliminary one-year assimilation experiment has been performed with SSH, SST and BT profiles as input data and Cooper-Haines used for downward projection. A HYCOM forecast is used as the first guess for the MVOI analysis. Results are being compared to those from the existing near real-time .08° HYCOM Atlantic system that assimilates model independent SSH and SST analyses from MODAS. The SEEK filter data assimilation is working in 1/3° Atlantic HYCOM and is nearly ready for use in .08° Atlantic HYCOM. At 1/3° a major goal was to duplicate the results obtained by LEGI (France) using inputs available at NRL, including a later version of HYCOM, altimeter track data, AVHRR SST data, sea surface salinity from the NAVOCEANO GDEM3 climatology, and a new mean SSH (Niiler, 2003), a choice based on mean SSH comparisons by Lunde et al. (2004) performed under the FY00-04 HYCOM NOPP project. Application to .08° Atlantic HYCOM has required improved management of the different tasks of the assimilation system, with careful attention to the data transfer between the data servers and the IBM supercomputer at NAVOCEANO. This is nearly complete, but no results so far. The EnKF code was acquired (through excellent ongoing collaboration) from L. Bertino, G. Evensen, and K. Lisaeter in Norway. We have made minor modifications to the code to allow: i) increased portability and ii) improvements to be made in the model or data assimilation code without affecting the other. We have completed the generation of the initial ensemble and the ensemble forecasting with the maximum independence from changes in HYCOM. The main EnKF code is rewritten and is being debugged. Initial experiments will assimilate MODAS SSH and SST using a .08° Gulf of Mexico HYCOM.

A robust capability to nest HYCOM in HYCOM has been developed mostly under partnering projects, an NRL Common High Performance Computing Software Support Initiative (CHSSI) project in FY03 and the CO-NESTS project in FY04. The vertical and horizontal interpolation in the nesting is designed to conserve properties. Using boundary conditions from basin-scale HYCOMs, nested HYCOMs have been run in the Gulf of Mexico, East Asian Seas, Norwegian coastal region, California Current system, and Gulf of California (GoC). A .08° Atlantic HYCOM was used to force nested .08° Gulf of Mexico HYCOM using (1) hybrid coordinates and (2) fixed σ–z coordinates to emulate NCOM. The GoC has been used to investigate the propagation of a coastally trapped wave (CTW) across nested boundaries, and the sensitivity of boundary condition accuracy to updating frequency, e-folding relaxation time across the buffer zone, and buffer zone width (paper in preparation). In particular, nested GoC HYCOMs at .08°, .04° and .027° resolution were nested in .08° Pacific HYCOM. They were used to study a CTW pulse, generated by Hurricane Juliette in September 2001, as it propagated along the west Mexican coast. Model sensitivity to atmospheric forcing product was also investigated by forcing the nested models with both NOGAPS and regional Central America COAMPS.

RESULTS

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.

All simulations (.08° Pacific and .08°, .04° and .027° GoC) accurately reproduced the phase of the CTW generated by Hurricane Juliette, when compared to tide gauge data. When forced by 1° NOGAPS, the amplitude of the signal was lower than observed and not significantly different in the four model configurations. However, forcing the nested models with the .2° Central America COAMPS improved the amplitude of the CTW signal in relation to the observations, although it was still a bit low. For the most part, COAMPS produced a better representation of Hurricane Juliette and the oceanic signal produced by HYCOM more closely matched the coastal tide guage data. The accuracy of the nesting results is illustrated in Figure 1.

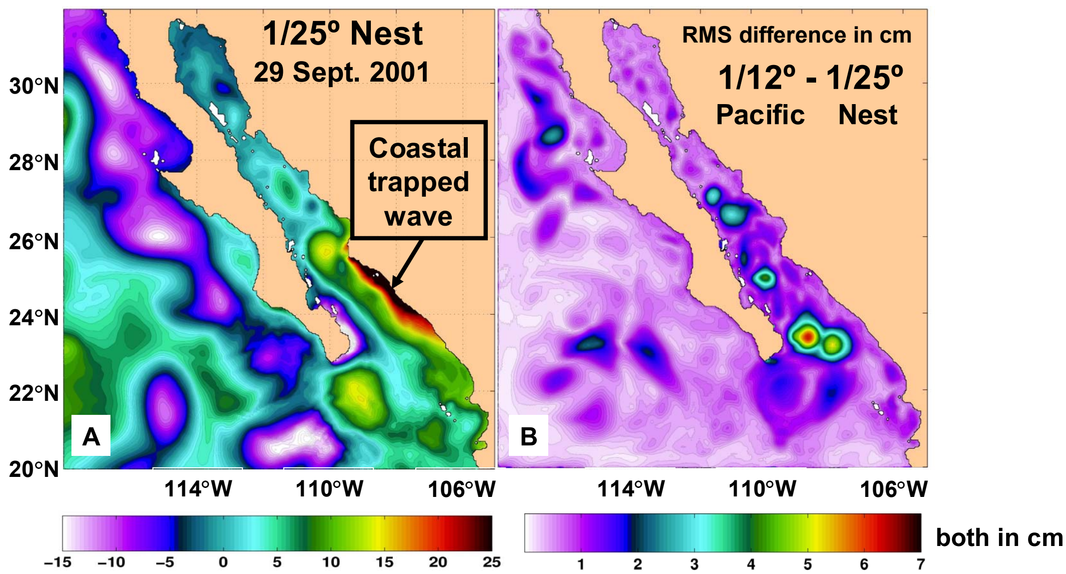

Figure 1. (A) SSH snapshot covering the whole domain of the nested .04° GoC HYCOM, the GoC plus the Pacific adjacent to Baja California. It depicts the CTW generated by Hurricane Juliette as high SSH adjacent to the eastern GoC coast. (B) The rms SSH difference (over Sept-Oct 2001) between the nested .04° GoC HYCOM and the .08° Pacific HYCOM that provided the boundary conditions. The rms difference is low (< 1 cm) except near non-deterministic eddy features which tend to be stronger in the higher resolution model.

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.

TRANSITIONS

None.

RELATED PROJECTS

This is a highly collaborative NOPP project with 24 partnering groups listed in the proposal. These partners are universities (with Eric Chassignet at the University of Miami as the overall lead PI), government (Navy and NOAA), industry and international. Partnering projects at NRL include 6.1 Dynamics of Low Latitude Western Boundary Currents, 6.2 NOPP HYCOM Consortium for Data Assimilative Ocean Modeling, 6.2 Coastal Ocean NESTing Studies (CO-NESTS), and 6.4 Altimeter Data Fusion Center (ADFC) Support. Additionally, the project received grants of HPC time from the DoD High Performance Computing Modernization Office, including a dedicated node on the SGI Origin 3900 at the Aeronautical Systems Center and an FY02-04 HPC challenge grant entitled “Basin-scale ocean prediction with the HYbrid Coordinate Ocean Model” on the IBM SP3 at the Naval Oceanographic Office. This project is represented on the International and U.S. GODAE Steering Teams by E. Chassignet (U. Miami), J. Cummings (NRL) and H. Hurlburt (NRL).

REFERENCES

Bleck, R., 2002. An oceanic general circulation model framed in hybrid isopycnic-cartesian coordinates. *Ocean Modelling*, **4**, 55-88.

Bleck, R. and S. Benjamin, 1993. Regional weather prediction with a model combining terrain-following and isentropic coordinates. Part I.: Model description. *Mon. Wea. Rev.*, **121**, 1770-1785.

Bleck, R. and D. Boudra, 1981. Initial testing of a numerical ocean circulation model using a hybrid (quasi-isopycnic) vertical coordinate. *J. Phys. Oceanogr.*, **11**, 755-770.

Chassignet, E.P., H. Arango, D. Dietrich, T. Ezer, M. Ghil, D.B. Haidvogel, C.-C. Ma, A. Mehra, A.M. Paiva, and Z. Sirkes, 2000. DAMEE-NAB: the base experiments. *Dyn. Atmos. Oceans.*, **32**, 155-184.

Cooper, M. and K. Haines, 1996. Altimetric assimilation with water property conservation. *J. Geophys. Res.*, **101 (C1)**, 1059-1077.

Daley, R., 1991: *Atmospheric Data Analysis*. Cambridge University Press, Cambridge, 457 pp.

Evensen, G., 1997. Advanced data assimilation for strongly nonlinear dynamics, *Mon. Wea. Rev.*, **125 (6)**, 1342-1354.

Fox, D.N., W.J. Teague, C.N. Barron, M.R. Carnes and C.M. Lee, 2002. The Modular Ocean Data Assimilation System (MODAS). *J. Atmos. Oceanic Tech.*, **19**, 240-252.

Halliwell, G., 2004. Evaluation of vertical coordinate and vertical mixing algorithms in the HYbrid Coordinate Ocean Model (HYCOM). *Ocean Modelling*, **7 (3-4)**, 285-322.

Hodur, R.M., 1997. The Naval Research Laboratory's coupled ocean/atmosphere mesoscale prediction system (COAMPS). *Mon. Wea. Rev.*, **125 (7)**, 1414-1430.

Hurlburt, H.E. and P.J. Hogan, 2000. Impact of 1/8° to 1/64° resolution on Gulf-Stream model-data comparisons in basin-scale subtropical Atlantic Ocean Models. *Dyn. Atmos. Oceans.*, **32**, 283-330.

Lunde, B.N., O.M. Smedstad, E.P. Chassignet, and H.E. Hurlburt, 2004. Comparing mean dynamic topographies with in-situ estimates. *J. Mar. Sys.* (in preparation)

Niiler, P. P., N.A. Maximenko, and J.C. McWilliams, 2003. Dynamically balanced absolute sea level of the global ocean derived from near-surface velocity observations, *Geophys. Res. Lett.*, **30(22)**, 2164, doi:10.1029/2003GL018628.

Pham, D.T., J. Verron and M.C. Roubaud, 1998. A singular extended filter for data assimilation in oceanography. *J. Mar. Sys.*, **16**, 323-340.

PUBLICATIONS

Chassignet, E.P., H.E. Hurlburt, O.M. Smedstad, C.N. Barron, D.S. Ko, R.C. Rhodes, J.F. Shriver, A.J. Wallcraft, and R.A. Arnone, 2004. Assessment of ocean prediction systems in the Gulf of Mexico using ocean color. AGU Monograph Series. (submitted)