Chapter 16

OCEAN PREDICTION WITH THE HYBRID COORDINATE OCEAN MODEL (HYCOM)

Eric P. Chassignet[1], Harley E. Hurlburt[2], Ole Martin Smedstad[3], George R. Halliwell[1], Patrick J. Hogan[2], Alan J. Wallcraft[2], and Rainer Bleck[4]

[1]RSMAS/MPO, University of Miami, Miami, Florida, USA; [2]Naval Research Laboratory, Stennis Space Center, Mississippi, USA; [3]Planning Systems Inc., Stennis Space Center, Mississippi,USA; [4]Los Alamos National Laboratory, Los Alamos, New Mexico, USA

Abstract: This chapter provides an overview of the effort centered on the HYbrid Coordinate Ocean Model (HYCOM) to develop an eddy-resolving, real-time global and basin-scale ocean prediction system in the context of the Global Ocean Data Assimilation Experiment (GODAE).

Keywords: HYCOM, GODAE, LAS, data assimilation, metrics.

1. Introduction

A broad partnership of institutions[1] is presently 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). The plan is to transition these systems 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 partnership is also the eddy-resolving global ocean prediction system development effort that is sponsored by the U.S. component of the Global Ocean Data Assimilation Experiment (GODAE). GODAE is a coordinated international effort envisioning *"a global system of observations, communications, modeling, and assimilation that will deliver regular, comprehensive information on the state of the oceans, in a way that will promote and engender wide utility and availability of this resource for maximum benefit to the community"*. Three

[1] U. of Miami, NRL, Los Alamos, NOAA/NCEP, NOAA/AOML, NOAA/PMEL, PSI, FNMOC, NAVOCEANO, SHOM, LEGI, OPeNDAP, U. of North Carolina, Rutgers, U. of South Florida, Fugro-GEOS, ROFFS, Orbimage, Shell, ExxonMobil

of the GODAE specific objectives are to apply state-of-the-art models and assimilation methods to produce short-range open ocean forecasts, boundary conditions to extend predictability of coastal and regional subsystems, and initial conditions for climate forecast models (GODAE Strategic Plan, 2000). 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 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).

Traditional ocean models use a single coordinate type to represent the vertical, but recent model comparison exercises performed in Europe (DYnamics of North Atlantic MOdels - DYNAMO) (Willebrand et al., 2001) and in the U.S. (Data Assimilation and Model Evaluation Experiment - DAMÉE) (Chassignet et al., 2000) have shown that no single vertical coordinate -- depth, density, or terrain-following sigma -- can by itself be optimal everywhere in the ocean. These and earlier comparison studies (Chassignet et al., 1996; Roberts et al., 1996, Marsh et al., 1996) have shown that the models considered are able to simulate the large-scale characteristics of the oceanic circulation reasonably well, but that the interior water mass distribution and associated thermohaline circulation are strongly influenced by localized processes that are not represented equally by each model's vertical discretization. The choice of the vertical coordinate system is one of the most important aspects of an ocean model's design and practical issues of representation and parameterization are often directly linked to the vertical coordinate choice (Griffies et al., 2000). Currently, there are three main vertical coordinates in use, none of which provides universal utility. Hence, many developers have been motivated to pursue research into hybrid approaches. Isopycnal (density tracking) layers are best in the deep stratified ocean, z-levels (constant fixed depths) are best used to provide high vertical resolution near the surface within the mixed layer, and σ-levels (terrain-following) are often the best choice in shallow coastal regions. HYCOM combines all three approaches and the optimal distribution is chosen at every time step. The model makes a dynamically smooth transition between the coordinate types via the layered continuity equation.

This chapter describes the various components of the HYCOM data assimilative system and is organized as follows: an overview of the main HYCOM characteristics is presented in section 2, the performance of the present near real time Atlantic forecasting system is discussed in section 3 and section 4 provides an outlook.

2. The ocean model

HYCOM is designed to provide a significant improvement over the existing global operational ocean products, since it overcomes design limitations of present systems as well as limitations in vertical resolution. The ultimate goal is a more streamlined system with improved performance and an extended range of applicability (*e.g.*, the present U.S. NAVY systems are seriously limited in shallow water and in handling the transition from deep to shallow water). The generalized coordinate (hybrid) ocean model HYCOM retains many of the characteristics of its predecessor, the isopycnic coordinate model MICOM (Miami Isopycnic Coordinate Model), while allowing coordinate surfaces to locally deviate from isopycnals wherever the latter may fold, outcrop, or generally provide inadequate vertical resolution in portions of the model domain. The freedom to adjust the vertical spacing of the coordinate surfaces in HYCOM simplifies the numerical implementation of several physical processes (mixed layer detrainment, convective adjustment, sea ice modeling, …) without robbing the model of the basic and numerically efficient resolution of the vertical that is characteristic of isopycnic models throughout most of the ocean's volume.

The implementation of the generalized coordinate in HYCOM follows the theoretical foundation set forth in Bleck and Boudra (1981) and Bleck and Benjamin (1993): i.e., each coordinate surface is assigned a reference isopycnal. The model continually checks whether or not grid points lie on their reference isopycnals and, if not, attempts to move them vertically toward the reference position. However, the grid points are not allowed to migrate when this would lead to excessive crowding of coordinate surfaces. Thus, vertical grid points can be geometrically constrained to remain at a fixed depth while being allowed to join and follow their reference isopycnals in adjacent areas (Bleck, 2002). The default configuration in HYCOM is one that is isopycnal in the open stratified ocean, but smoothly reverts to a terrain-following (σ) coordinate in shallow coastal regions and to fixed pressure-level coordinates (hereafter referred to as p) in the surface mixed layer and/or unstratified seas (Figure 1). In doing so, the model combines the advantages of the different types of coordinates in optimally simulating coastal and open-ocean circulation features. It is left to the user to define the coordinate separation constraints that control regional transitions among the three coordinate choices. Figure 1 illustrates the transition that occurs between p/σ and isopycnic (ρ) coordinates in the fall and spring in the upper 400 meters and over the shelf in the East China and Yellow Seas. In the fall, the water column is stratified and can be represented with isopycnals; in the spring, the water column is homogenized over the shelf and is represented by a mixture of p and σ coordinates. A particular advantage of ρ coordinates is illustrated by the density front formed by the Kuroshio above the peak of the sharp (lip) topography at the shelfbreak in Fig. 1a. Since the lip topography is only a few grid points wide, this topography and the associated front is best represented in ρ coordinates.

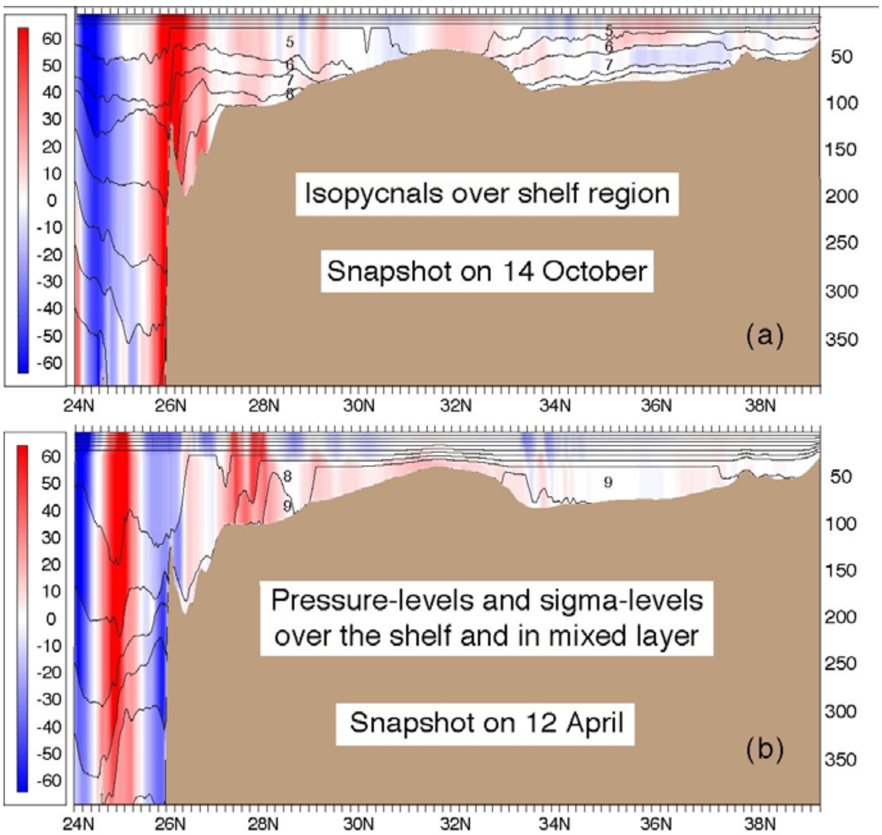

Figure 1. Upper 400 meters north-south velocity cross-section along 124.5°E in the East China and Yellow Seas: (a) Fall; (b) Spring.

The algorithm that maintains the hybrid vertical coordinates is T/S conservative and monotonicity-preserving (i.e., no new T/S extrema during re-gridding). It is referred to as the "grid generator" (Bleck, 2002) and is the final algorithm executed during each model time step. The grid generator relocates vertical interfaces to restore isopycnic conditions in the ocean interior to the greatest extent possible while enforcing the minimum thickness requirements. The minimum thickness is enforced by a "cushion" function (Bleck, 2002) that produces a smooth transition from the isopycnic to the p-domain. The grid generator first attempts to restore the density of a given layer to its isopycnic reference density if necessary. If a layer is less dense that its isopycnic reference density, the generator attempts to move the bottom interface downward so that the flux of denser water across this interface increases density. If the layer is denser than its isopycnic reference density, the generator attempts to move the upper interface upward to decrease density. In both cases, the generator first calculates the vertical distance that the interface must be relocated so that volume-weighted density of the original plus new water in the layer equals the reference density. Repeated execution of this algorithm at every time step does maintain layer density very close to its reference value as long as a minimum thickness does not have to be maintained. To insure that a permanent p-coordinate domain exists near the surface year round at all model grid points, the uppermost layers are initialized with reference densities smaller than values found anywhere in the model domain. The minimum thickness constraint is not enforced at the bottom in the open ocean, permitting model layers to collapse to zero thickness there as in MICOM.

The capability of assigning additional coordinate surfaces to the HYCOM mixed layer allows the option of implementing sophisticated vertical mixing turbulence closure schemes [see Halliwell (2004) for a review]. The full set of vertical mixing options contained in the latest version of HYCOM (http://hycom.rsmas.miami.edu) includes five primary vertical mixing submodels, of which three are vertically “continuous” models and two are predominantly or totally bulk models. The three continuous models, which govern vertical mixing throughout the water column, are: K-Profile Parameterization of Large et al. (1994) (KPP), the level 2.5 turbulence closure of Mellor and Yamada (1982) (MY), and the Goddard Institute for Space Studies (GISS) level 2 turbulence closure of Canuto et al. (2001, 2002). The other two are the quasi-bulk dynamical instability submodel of Price et al. (1986) (PWP) and the bulk Kraus-Turner (1967) submodel (KT).

The following procedure is used to implement the three continuous vertical mixing submodels. Velocity components are interpolated to the *p* grid points from their native *u* and *v* points. The one-dimensional submodels are then run at each *p* point to calculate profiles of viscosity coefficients along with T and S diffusion coefficients on model interfaces. The one-dimensional vertical diffusion equation is then solved at each *p* point to mix T, S, and tracer variables, which involves the formulation and solution of a tri-diagonal matrix system using the algorithm provided with the KPP submodel (Large *et al.,* 1994). To mix momentum components, viscosity profiles stored on interfaces at *p* grid points are horizontally interpolated to interfaces at *u* and *v* grid points. Then the vertical diffusion equation is solved on both sets of points. For more details on the implementation of the various mixing schemes, the reader is referred to Halliwell (2004).

3. The North Atlantic prototype ocean prediction system

While HYCOM is a highly 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). While these are too sparse to characterize the horizontal variability, they provide valuable information about the vertical stratification. 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. By combining all of these observations through data assimilation into an ocean model it is possible to produce a dynamically consistent depiction of the ocean. It is important that the ocean model component of the forecast system has skill in predicting the ocean features of interest. Then the model can act as an efficient dynamical interpolator of the observations.

Performance of HYCOM in the North and Equatorial Atlantic has been documented by Chassignet et al. (2003) within the framework of the Community Modeling Experiment (CME). The near real time 1/12^o (~7 km mid-latitude resolution) HYCOM Atlantic Ocean prediction system (http://hycom.rsmas.miami.edu/ocean_prediction.html) spans from 28^{o}S to 70^{o}N, including the Mediterranean Sea and has been running since July 2002. The vertical resolution consists of 26 hybrid layers, with the top layer typically at its minimum thickness of 3 m (*i.e.,* in fixed coordinate mode to provide near surface values). In coastal waters, there are up to 15 sigma-levels, and the coastline is at the 10 m isobath. The northern and southern boundaries are treated as closed, but are outfitted with 3 ^{o} buffer zones in which temperature, salinity, and pressure are linearly relaxed toward their seasonally varying climatological values. Three-hourly wind and daily thermal forcing (interpolated to three hours) are presently provided by the FNMOC Navy Operational Global Atmospheric Prediction System (NOGAPS) (Rosmond et al., 2002), available from NAVOCEANO and the U.S. GODAE data server in Monterey. The HYCOM prediction system uses surface wind stress, air temperature, and specific humidity (from dewpoint temperature and sea level pressure) in addition to shortwave and longwave radiation. Surface heat flux is calculated using NOGAPS fields and the Kara et al. (2002) bulk parameterization of latent and sensible heat flux, which uses model SST.

Mostly because of its simplicity, robustness, and low computational costs, operational ocean prediction systems around the world (NLOM, MERCATOR, FOAM, etc.) are presently using Optimal Interpolation (OI) based data assimilation techniques. For the current 1/12° Atlantic HYCOM ocean forecasting system, we have adopted a similar approach by selecting an OI technique with Cooper and Haines (1996) for downward projection of SSH from altimetry [see Chassignet et al. (2005) for details]. Real time satellite altimeter data (Geosat-Follow-On (GFO), ENVISAT, and Jason-1) are provided via the Altimeter Data Fusion Center (ADFC) at NAVOCEANO to generate the two-dimensional Modular Ocean Data Assimilation System (MODAS) SSH (1/4°) analysis (Fox et al., 2002) that is assimilated daily. The MODAS analysis is an OI technique which is using a complex covariance function that includes spatially varying length and time scales as well as propagation terms derived from many years of altimetry (Jacobs et al., 2001). The model sea surface temperature is relaxed to the daily MODAS 1/8° SST analysis which uses daily Multi-Channel Sea Surface Temperature (MCSST) data derived from the 5-channel Advanced Very High Resolution Radiometers (AVHRR) – globally at 8.8 km resolution and at 2 km in selected regions. The system runs once a week every Wednesday and consists of a 10-day hindcast and a 14-day forecast.

At the present time, evaluation of the model outputs relies on systematic verification of key parameters and computation of statistical indexes by reference to both climatological and real time data, and, in a delayed mode, to quality controlled observations. The accuracy of data assimilative model products is theoretically a non-decreasing function of the amount of data that is assimilated. A degradation caused by assimilation generally indicates inaccurate assumptions in the assimilation scheme. While models can be forced to agree with observations (*e.g.*, by replacing equivalent model fields with data), improvements with respect to independent observations are not trivial. An assessment of model improvement (or lack of degradation) with respect to unassimilated, independent measurements is therefore an effective means of assessing the performance of an assimilation system. Variances of these model-data differences serve as common measures of the estimation accuracy. For the evaluation of flow accuracy and water mass characteristics, we follow the guidelines put forward by the international GODAE metrics group as well as the validation tests commonly used at the operational centers before official transition to operational use. In the remainder of this section, we outline some of these metrics and provide examples for the HYCOM Atlantic forecasting system.

Large-scale circulation features: These tests evaluate whether the global and basin-scale models correctly place the large-scale features of ocean circulation, such as gyres, strong fronts, and currents. It is indeed necessary to know the oceanic mean SSH over the time period of the altimeter observations before one can assimilate the SSH anomalies determined from satellite altimeter data. Furthermore, at the scales of interest (tens of kilometres), it is also necessary to have the mean of major ocean currents and associated SSH fronts sharply defined. This is not feasible from coarse hydrographic climatologies (~1º horizontal resolution) and from present geoid measurements since the geoid is not yet known accurately on the mesoscale. The approach taken by the HYCOM-based system is to use a model mean generated by a previous 1/12º North Atlantic simulation performed with MICOM (Chassignet and Garraffo, 2001).

Eddy kinetic energy/SSH variability: These tests evaluate whether the models have a realistic level and distribution of energy (mean and variability) at depths where observations are available.

Sea Surface Height (analysis, forecast): Provide an assessment of the models' ability to represent observed sea surface heights.

Sea Surface Temperature (analysis, forecast): These tests evaluate whether the models are producing acceptable nowcasts and forecasts of sea surface temperature. The near real-time system is routinely compared to buoy observations of SST.

Vertical profiles, time series of profiles and vertical cross sections (analysis, forecast): Since the present forecasting system assimilates only surface quantities (SSH, SST), quantitative comparisons of model temperature and salinity to unassimilated profile data from XBTs, CTDs, and ARGO floats, and moored buoys can be used to assess the model's performance in the ocean interior. In Figure 2, model temperature sections are compared to XBT measurements obtained from the Marine Environmental Data Service (MEDS) dataset. A quantitative assessment using the RMS difference between the model and data profiles is shown in Figure 3. With assimilation of surface data only, the Atlantic HYCOM forecasting system has, overall, larger RMS error than climatology or MODAS-3D. MODAS-3D (Fox et al., 2002) uses the statistics of the historical hydrographic data base to downward project the same MODAS SSH anomaly and SST analyses assimilated by HYCOM, indicating superior performance for a data-based method of downward projection than the Cooper and Haines (1996) technique used in HYCOM, at least in this application.

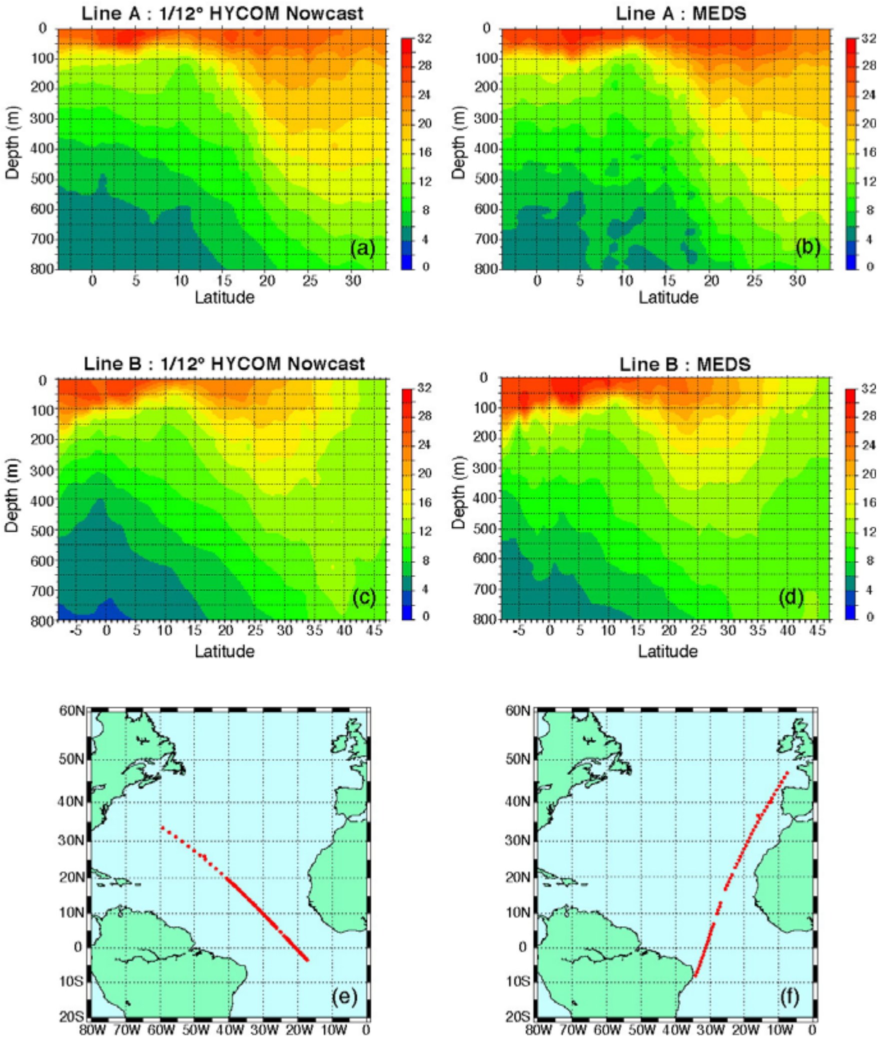

Figure 2. (a) Temperature section along line A from the 1/12°near real-time Atlantic system, (b) corresponding section from the MEDS data, (c) temperature section along line B from the 1/12°near real-time Atlantic system, (d) corresponding section from the MEDS data.

<u>Current cross sections</u>: These tests evaluate model velocity cross-sections through qualitative and quantitative comparisons of biases when data are available. When observations are available, transport time series provide an excellent measure of the model's ability to represent daily to seasonal variability (see example shown in Figure 4 for the Florida Straits).

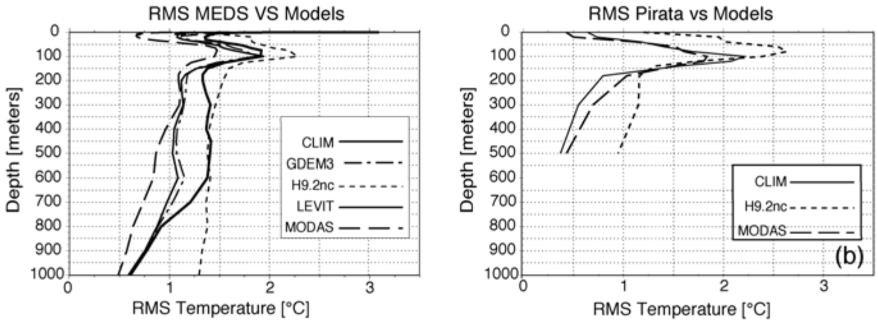

Figure 3. (a) Statistics for the month of February between the 1/12° HYCOM system and available Marine Environmental Data Service (MEDS) profile observations. The RMS difference between the MEDS data, MODAS3D (MODAS), and different climatologies (MODAS (CLIM), Levitus (LEVIT), and the Generalized Digital Environmental Model (GDEM3)) is also shown. (b) Statistics for the month of May between the 1/12° HYCOM system and available PIRATA profile observations. The RMS between the PIRATA data, MODAS3D, and MODAS climatology (CLIM) is also shown.

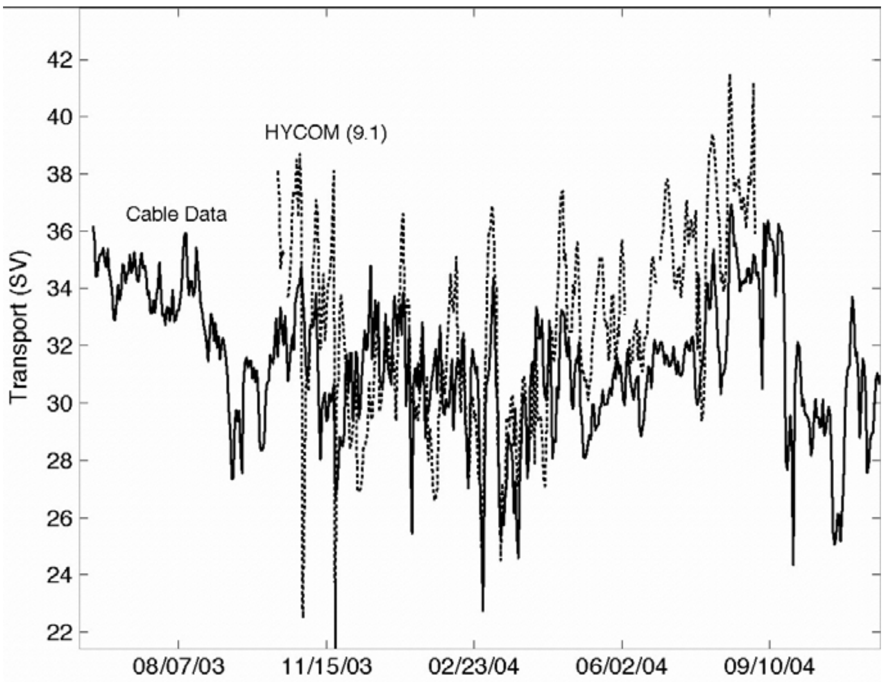

Figure 4. The transport in the Florida Current at 27°N from the 1/12° Atlantic near real-time system are shown with dotted lines. Observations from the cable data are shown in solid black.

Comparison with drifting buoys: These tests will evaluate the models' ability to produce ocean currents that yield drifter and ARGO floats trajectories similar to observations.

Mixed Layer Depth (MLD) (analysis, forecast, simulation without ocean data assimilation): Model analyses, forecasts, and simulations will be compared to mixed layer depths from profile data (e.g. XBTs, ARGO floats, CTDs, and moored buoys) and to an MLD climatology.

Event comparisons: Independent data are used for qualitative and quantitative evaluation of prediction system skill in nowcasting and forecasting specific oceanic events and features. A classical example is the impact of hurricanes on the ocean circulation (Zamudio et al., 2002). Comparisons of surface height and temperature with ocean color imagery can at times provide clear and dramatic qualitative model assessment (Chassignet et al, 2005).

The near real-time North Atlantic basin model outputs are made available to the community at large within 24 hours via the Miami Live Access Server (LAS) (http://hycom.rsmas.miami.edu/las). Specifically, the LAS supports model-data and model-model comparisons; provides HYCOM subsets to coastal or regional nowcast/forecast partners as boundary conditions, and increases the usability of HYCOM results by "application providers".

4. Outlook

The long term goal is an eddy-resolving, fully global ocean prediction system with data assimilation based on HYCOM to be transitioned to the Naval Oceanographic Office at 1/12° equatorial (~7 km mid-latitude) resolution in 2007 and 1/25° resolution by 2011. This paper summarizes the present status of the HYCOM effort and illustrates its capabilities. The present systems are a first step towards the fully global 1/12° HYCOM prediction system. The size of the problem makes it very difficult to use sophisticated assimilation techniques. Some of these methods can increase the cost of running the model by a factor of 100. It is, however, important to evaluate the performance of these advanced data assimilation techniques. Several additional techniques for assimilating data into HYCOM are already in place or are in the process of being implemented. These techniques vary in sophistication and computational requirements and include: NRL Coupled Ocean Data Assimilation (NCODA), Singular Evolutive Extended Kalman (SEEK) filter, Reduced Order Information Filter (ROIF), Ensemble Kalman Filter (EnKF), Reduced Order Adaptive Filter (ROAF) (including adjoint), and the 4D-VAR Representer method.

NCODA is an oceanographic version of the multivariate optimum interpolation (MVOI) technique widely used in operational atmospheric forecasting systems. A description of the MVOI technique can be found in Daley, (1991). The ocean analysis variables in NCODA are temperature, salinity, geopotential (dynamic height), and velocity. The horizontal correlations are multivariate in geopotential and velocity, thereby permitting adjustments to the mass field to be correlated with adjustments to the flow field. NCODA assimilates all available operational sources of ocean observations. This includes along track satellite altimeter observations, MCSST and in situ observations of SST and SSS, subsurface temperature and salinity profiles from BT's and profiling floats, and sea ice concentration.

Both the SEEK filter (Pham et al, 1998) and ROIF (Chin et al., 1999) are sequential in nature, implying that only past observations can influence the current estimate of the ocean state and are especially well suited for large dimensional problems. The ROIF assumes a tangent linear approximation to the system dynamics, while the SEEK filter can use the non-linear model to propagate the error statistics forward in time (Ballabrera et al., 2001). Besides the NCODA, SEEK and ROIF methods, other techniques such as the EnKF and the ROAF are also being evaluated. Because of their cost, they are presently being evaluated mostly within coastal HYCOM configurations or in specific limited areas of high interest. The NCODA and SEEK techniques are being considered as the next generation data assimilation to be used in the near real-time system.

Development of the global HYCOM prediction system is presently taking place and includes model development, data assimilation, and ice model embedment. The model configuration is fully global with the Los Alamos CICE ice model embedded and will run at three resolutions: ~60 km, ~20 km and ~7 km at mid-latitudes with the NCODA data assimilation. As stated above, some of the more expensive data assimilation techniques, while impractical over a high resolution global domain, can be used in subregions of the global model domain where there is special interest or where they provide particular value added.

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