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The 1/12° Global HYCOM Nowcast/Forecast System

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1.0 INTRODUCTION

Development of an advanced global ocean nowcasting/forecasting system has been of long-time US Navy interest. Such a system will provide the capability to depict (nowcast) and predict (forecast) the oceanic "weather", some components of which include the three dimensional (3-D) ocean temperature, salinity and current structure, the surface mixed layer and the location of mesoscale features such as eddies, meandering currents and fronts. The space scales of these eddies and meandering currents are typically about 100 km and currents speeds can easily exceed 1 m/s in the western boundary current regions of the Kuroshio, Gulf Stream and Somali Current. So, relatively high horizontal and vertical resolution numerical ocean models are needed to depict the 3-D ocean structure with accuracy superior to climatology and/or persistence (i.e. a forecast of no change). Knowledge of the oceanic mesoscale has many naval applications, including tactical planning, optimum track ship routing, search and rescue operations, long-range weather prediction, inputs to coastal models, and knowledge of high current shear zones.

A next generation ocean nowcast/forecast system based on the HYbrid Coordinate Ocean Model (HYCOM) has been under development at the Naval Research Laboratory (NRL) since 2000. HYCOM is unique in that it allows a truly general vertical coordinate and is designed to provide a major advance over the existing operational global ocean prediction systems, since it overcomes design limitations of the present systems as well as limitations in vertical and horizontal resolution. The assimilation component of the system uses the Navy Coupled Ocean Data Assimilation (NCODA).

2.0 System Components

2.1 Global HYCOM

HYCOM has a horizontal equatorial resolution of .08° or ~1/12° (~9 km). This makes HYCOM eddy resolving. Eddy-resolving models can more accurately simulate western boundary currents and the associated mesoscale variability and they better maintain more accurate and sharper ocean fronts. In particular, an eddy resolving ocean model allows upper-ocean – topographic coupling via flow instabilities, while an eddy-permitting model does not because fine resolution of the flow instabilities is required to obtain sufficient coupling (Hurlburt et al., 2008a). The coupling occurs when flow instabilities drive abyssal currents that in turn steer the pathways of upper ocean currents (e.g. Hurlburt and Hogan, 2008b in the Gulf Stream). This coupling is important for ocean model dynamical interpolation skill in data assimilation/nowcasting and in ocean forecasting, which is feasible on time scales up to about a month (Hurlburt et al., 2008c).

The HYCOM grid is on a Mercator projection from 78.64°S to 47°N and north of this it employs an Arctic dipole patch where the poles are shifted over land to avoid a singularity at the North Pole. This gives a mid-latitude (polar) horizontal resolution of approximately 7 km (3.5 km). Figure 1 shows the sea surface temperature on August 22, 2009 over the global domain.

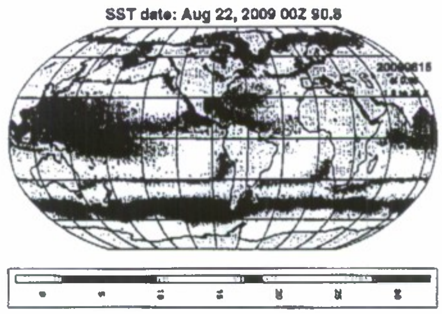

Figure 1. Real-time global HYCOM sea surface temperature on August 22 2009.

This version employs 32 hybrid vertical coordinate surfaces with potential density referenced to 2000 m and it includes the effects of thermobaricity (Chassignet et al., 2003). Vertical coordinates can be isopycnals (density tracking), often best in the deep stratified ocean, levels of equal pressure (nearly fixed depths), best used in the mixed layer and unstratified ocean and sigma-levels (terrain-following), often the best choice in shallow water. HYCOM combines all three approaches by choosing the optimal distribution at every time step. The model makes a dynamically smooth transition between coordinate types by using the layered continuity equation. The hybrid coordinate extends the geographic range of applicability of traditional isopycnic coordinate circulation models toward shallow coastal seas and unstratified parts of the world ocean. It maintains the significant advantages of an isopycnal model in stratified regions while allowing more vertical resolution near the surface and in shallow coastal areas, hence providing a better representation of the upper ocean physics. HYCOM is configured with options for a variety of mixed layer submodels (Halliwell, 2004) and this version uses the K-Profile Parameterization (KPP) of Large et al. (1994). A more complete description of HYCOM physics can be found in Bleck (2002).

The ocean model uses the Fleet Numerical Meteorology and Oceanography Center (FNMOC) 3-hourly 0.5° Navy Operational Global Atmospheric Prediction System (NOGAPS) forcing. Typically atmospheric forcing forecast fields extend out to 120 hours. On those instances when atmospheric forecasts are shorter than 120 hours, an extension is created based on climatological products. The last available NOGAPS forecast field is then gradually blended toward climatology to provide forcing over the entire forecast period.

Global HYCOM includes a built-in energy loan, thermodynamic ice model. In this non-rheological system, ice grows or melts as a function of SST and heat fluxes. In addition, the Special Sensor Microwave Imager (SSMI) ice concentration analysis from NCODA is directly inserted into the model. The energy loan model is in the process of being replaced by the Los Alamos Community Ice Code (CICE, Bitz and Lipscomb, 1999) model. CICE and HYCOM will be coupled via the Earth System Modeling Framework (ESMF, Hill et al., 2004).

2.2 NCODA

NCODA is a fully three-dimensional multivariate optimum interpolation (MVOI) scheme (Cummings, 2005). The three-dimensional ocean analysis variables include temperature, salinity, geopotential and the vector velocity components 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. It can be run in stand-alone mode but here is cycled with HYCOM to provide updated initial conditions for the next model forecast in a sequential incremental update cycle. Corrections to the HYCOM forecast are based on all observations that have become available since the last analysis. These include surface observations from satellites, including altimeter SSH anomalies, SST, and sea ice concentration, plus *in-situ* SST observations from ships and buoys as well as T & S profile data from XBTs, CTDs and Argo floats. All observations must be quality controlled and this is done via NCODA_QC which is operational at the Naval Oceanographic Office (NAVOCEANO). By combining these various observational data types via data assimilation and using the dynamical interpolation skill of the model, the 3-D ocean environment can be more accurately nowcast and forecast. Cummings (2005) provides a detailed description of the two NCODA approaches for projecting surface observations downward to perform the 3-D ocean analysis: Cooper and Haines (CH) (1996) or synthetic profiles from the Modular Ocean Data Analysis System (MODAS, Fox et al., 2002). Synthetic profiles are only created where the satellite based SSH anomalies with respect to the previous day's ocean analysis exceed the altimeter measurement error threshold (~4 cm). Error analyses between non-assimilated T & S profile observations and simulated profiles using the MODAS approach yielded much smaller bias and RMSE than the CH approach. Thus MODAS synthetics were chosen for the downward projection methodology.

2.3 The HYCOM/NCODA run stream

A depiction of the HYCOM/NCODA real-time run stream is shown in Figure 2. The first NCODA ocean analysis is performed at $\tau = -126$ hours with the analysis window for altimeter data spanning ±36 hours. The other observations are used with the data spanning ±12 hours, except for profile observations for which the data span -12 days to +12 hours. (The first hindcast goes back 5+ days from the nowcast because of late arriving satellite altimeter data. An examination of the timeliness of the historical altimeter data determined an additional data gain of 18% between four and five days; orbits also improve with the age of the data.) After the NCODA analysis, HYCOM is run for 24 model hours with the NCODA analysis incrementally updating the ocean model over the first six hours, thus at 00Z HYCOM has fully ingested the observational data. The NCODA analysis and HYCOM hindcast cycle repeats itself daily up to the nowcast time and HYCOM continues to run in forecast mode out to 120 hours. In the hindcast results discussed below, the forecast period was extended to 14 days.

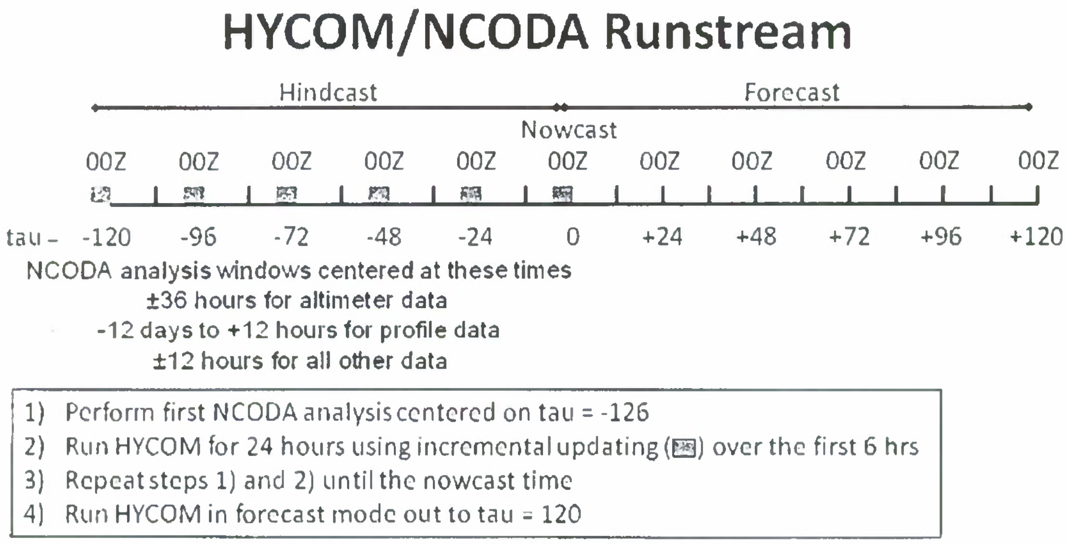

Figure 2: The HYCOM/NCODA runstream. Approximate run times using 619 Cray XT5 processors: a) six NCODA analyses – 1.4 hours/analysis = 8.4 hours, b) five HYCOM hindcast days using a 240 second timestep – 0.5 hours/model day = 2.5 hours, c) five HYCOM forecast days using a 240 second timestep – 0.5 hours/model day = 2.5 hours, for a total of d) 13.4 walltime hours.

3.0 Validation

A hindcast experiment is used in the validation of the HYCOM/NCODA system. The hindcast was initialized on 1 May 2007 from a non-assimilative HYCOM experiment. The hindcast used the same forcing as the real-time system, 3-hourly 0.5° NOGAPS forcing. The validation error analyses were performed over the year-long period 1 June 2007 – 31 May 2008. In order to examine model error as a function of forecast length, a series of forecasts were integrated and all were initialized from the hindcast described above. On the 1st, 8th, 15th and 22nd of each month, 14-day HYCOM forecasts were run for a total of 48 forecast integrations. In these 14 day forecast experiments forecast quality forcing was generally used out through 120 hours which then reverted to climatological forcing.

3.1 Coastal/island sea level error analysis

An error analysis has been performed against simulated vs. observed daily sea level obtained from the Joint Archive for Sea Level Center at the University of Hawaii Sea Level Center (Caldwell and Merrifield, 1992). The location of the 147 stations used in the analysis includes both open ocean island stations and coastal stations. The observations have been de-tided and atmospheric pressure loading effects have been removed similar to the methodology described in Barron et al. (2004). The sea level change can be a deterministic response to the atmospheric forcing or nondeterministic and associated with mesoscale flow instabilities. Since relatively fine horizontal resolution atmospheric forcing is used and the system employs data assimilation, the simulated sea level should be accurately represented. Shown in Figure 3a is the location of the sea level stations as well as histograms of correlation (3b) and RMSE (3c) for the year-long hindcast. The median correlation is 0.80 and median RMSE is 5.8 cm. The percentage of points with correlation higher than or equal to the bar centered on .8 is 68% and the percentage of points with RMSE lower than or equal to the bar centered on 6 cm is 68%.

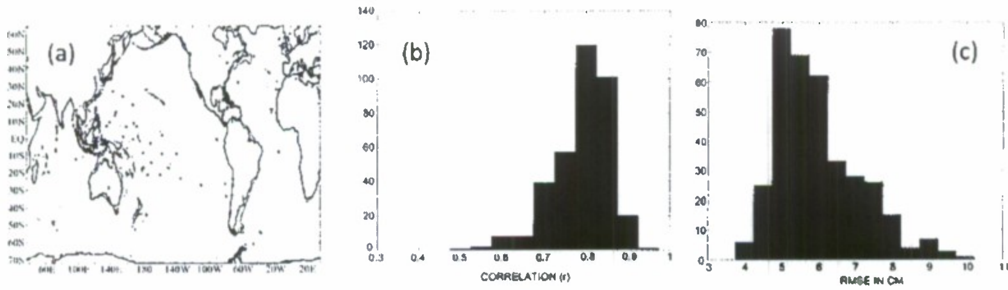

Figure 3: (a) Locations of the 147 coastal and island sea level stations used in this analysis. Simulated sea level was sampled at the model gridpoint closest to the observation location. Histograms of correlation (b) and RMSE (c) for simulated vs. observed sea level at the analysis time during the hindcast period 1 June 2007 – 31 May 2008 at the 147 stations. Median correlation is 0.8 and median RMSE is 5.8 cm. The statistics are computed basin-wide at each time point of the hindcast. The y-axis indicates the numbers of days in that bin, .05 for correlation and 0.5 for RMSE, and they sum to 366 days.

3.2 Temperature vs. depth error analysis

A temperature and salinity versus depth error analysis was performed using profile data from the Global Ocean Data Assimilation Experiment (GODAE) server. The database was separated into assimilated and yet-to-be unassimilated profiles. As expected, the system performs much better at assimilated profile locations and these results will not be discussed here. For a given unassimilated observation, the model is sampled at the nearest gridpoint and interpolated in the vertical to the observation depths. The analysis is broken into boreal seasons defined as summer (June-July-August [JJA]), fall (September-October-November [SON]), winter (December-January-February [DJF]) and spring (March-April-May [MAM]). The annual [ANL] statistics are also calculated. The statistical metrics are mean error (ME) and root mean square error (RMSE). Additional information on these statistical measures can be found in Murphy (1995). ME is the seasonal/annual bias and RMSE the absolute error between the model and data.

A comparison of the hindcast against unassimilated profiles is shown in Figure 4. The statistics shown here are from the region covering all three ocean basins between 70°S and 50°N. The model has a cold bias below ~50m with a maximum ME between 100-200m (-0.2°C). RMSE reaches a maximum value of about 1.3°C between 50-200 m. As can be seen from Figure 4 the seasonal variations are small.

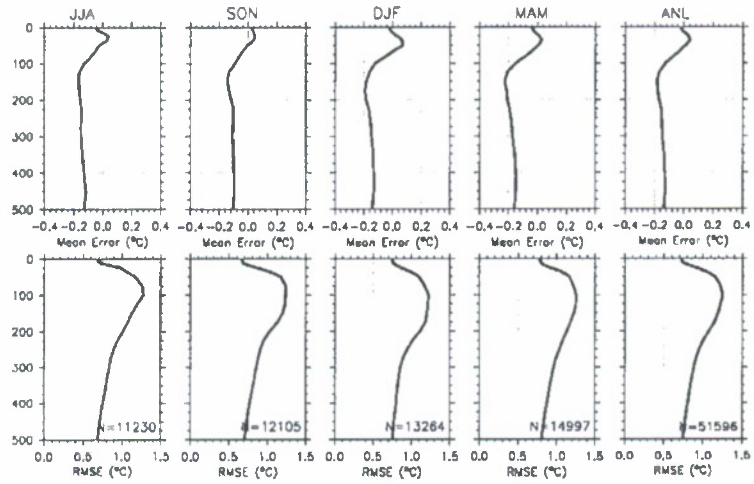

Figure 4: Temperature (°C) vs. depth error analysis in the upper 500 m against unassimilated profiles of the region 70°S to 50°N for the four seasons – summer (JJA), fall (SON), winter (DJF) and Spring (MAM) and annual (ANL). The top and bottom rows are mean error and RMSE, respectively. The number of unassimilated profiles used in each season is indicated in the bottom row. This is the number of near-surface observations used and this value decreases with depth since not all profiles exist down to 500 m depth.

A comparison of the 48 14 day forecasts against unassimilated profiles is shown in Figure 5. Again the analysis is done for the region 70°S to 50°N. The ME is largest in the upper 200 m of the water column. RMSE reaches a maximum between 50-200 m. Both the model and the climatology show a cold bias in the upper 500m. The results from the forecasts are clearly better than climatology. The RMSE increases by 0.02°C per day.

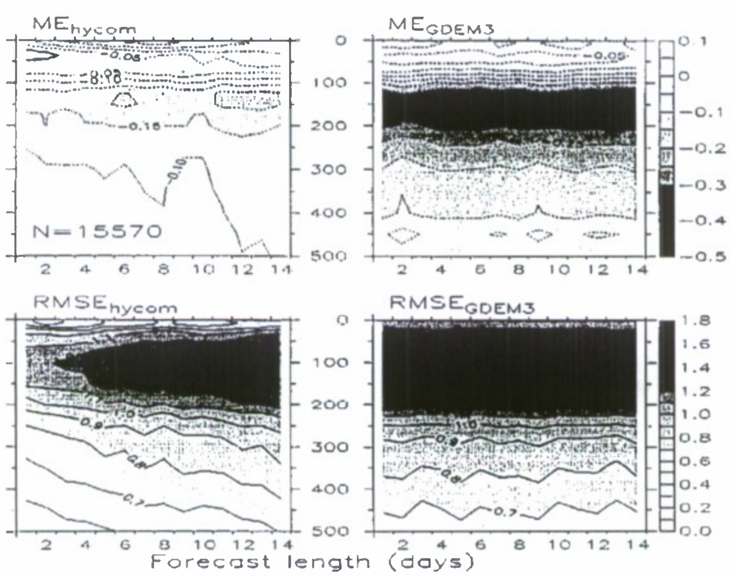

Figure 5. The global HYCOM temperature forecast skill for the 14 day forecast is shown as a function of depth. The left column shows the mean error and RMSE for HYCOM, while the right column shows the corresponding values using the Generalized Digital Environment Model (GDEM3, Carnes, 2009) climatology.

3.3 Real-time results

Figures 6 shows results from the real time run for sea surface height in the Kuroshio and Gulf Stream regions. Overlain on the model height fields are independent frontal analyses of satellite sea surface temperature observations performed at the NAVOCEANO. The frontal path in the model matches the observed front locations very well.

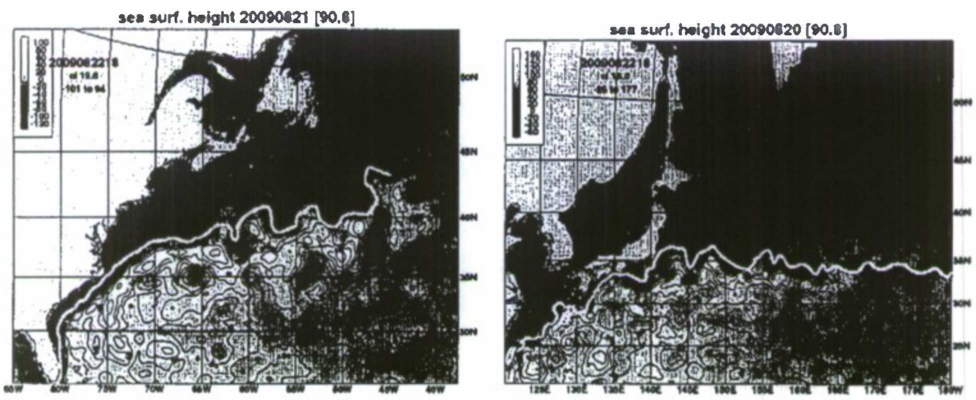

Figure 6. The global HYCOM sea surface height in the Gulf Stream region is shown on the left and the Kuroshio region on the right. The black and white line is the independent frontal analysis of satellite SST observations performed at NAVOCEANO. A black line represents data that are more than 4 days old.

4.0 Summary

Global HYCOM is routinely validated against a variety of observations, including T and S profiles, SST, SSH and sea level. The results presented here are a small subset of the validation of the system that can be found in Metzger et al. (2008). Results from the real time global system can be viewed on the HYCOM web page http://www.hycom.org. The model output (both from the real time run and the hindcast) can also be accessed through this web page. The future plans for the HYCOM system is to increase the horizontal resolution to 1/25° and include tidal forcing. The NCODA system is being upgraded as well to a 3D variational analysis system with a new covariance formulation. In the 3DVar, the covariances are non-separable (length scales vary with location and depth), adaptive, flow dependent structures that evolve with time based on the forecast model background state.

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