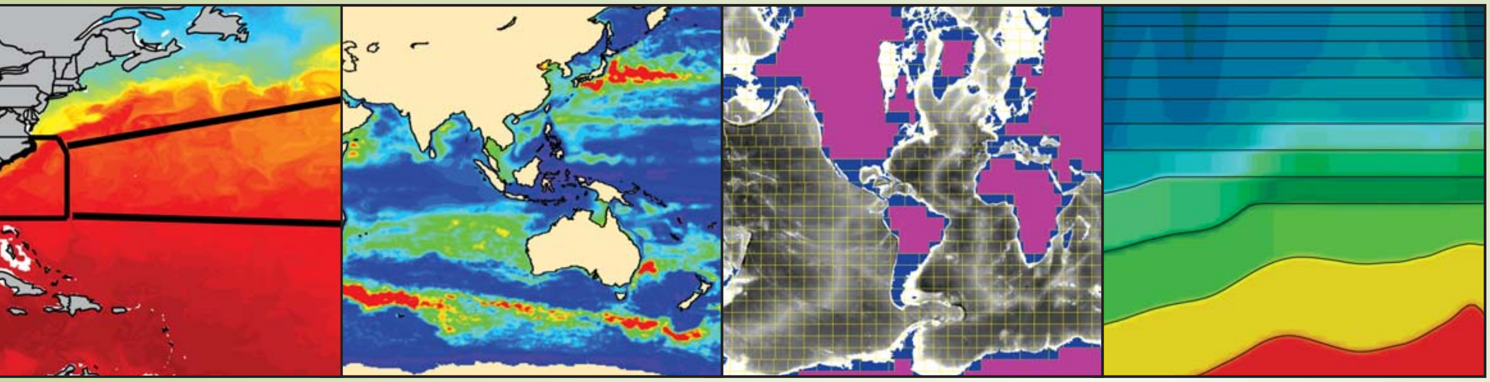


GENERALIZED VERTICAL COORDINATES

FOR EDDY-RESOLVING GLOBAL AND COASTAL OCEAN FORECASTS

BY ERIC P. CHASSIGNET, HARLEY E. HURLBURT, OLE MARTIN SMEDSTAD, GEORGE R. HALLIWELL, ALAN J. WALLCRAFT, E. JOSEPH METZGER, BRIAN O. BLANTON, CARLOS LOZANO, DESIRAJU B. RAO, PATRICK J. HOGAN, AND ASHWANTH SRINIVASAN

NUMERICAL MODELING STUDIES over the past several decades have demonstrated progress both in model architecture and in the use of rapidly advancing computational resources. Perhaps the most notable aspect of this progression has been the evolution from simulations on coarse-resolution horizontal and vertical grids that outline basins of simplified geometry and bathymetry and that are forced by idealized surface fluxes, to fine-resolution simulations that incorporate realistic coastline definition and bottom topography and that are forced by observational data on relatively short time scales (Hurlburt and Hogan, 2000; Smith et al., 2000; Chassignet and Garraffo, 2001; Maltrud and McClean, 2005).

The Global Ocean Data Assimilation Experiment (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.* Specific objectives of GODAE are to apply state-of-the-art ocean models and data assimilation methods to produce short-range open ocean forecasts, initial and boundary conditions to extend the predictability of coastal and regional subsystems, and to provide initial conditions for climate forecast models (International GODAE Steering Team, 2000). In the United States, a broad partnership of institutions[1] is addressing these objectives by building global and basin-scale ocean prediction systems using the versatile HYbrid Coordinate Ocean Model (HYCOM) (more information available at http://www.hycom.org).

The choice of the vertical coordinate system in an ocean model remains one of the most important aspects of its design. In practice, the representation and parameterization of the processes not resolved by the model grid are often directly linked to the vertical coordinate choice (Griffies et al., 2000). Oceanic general circulation models traditionally represent the vertical in a series of discrete intervals in either a depth, density, or terrain-following unit. Recent model comparison exercises performed in Europe (Willebrand et al., 2001) and in the United States (Chassignet et al., 2000) have, however, shown that the use of only one vertical coordinate representation cannot be optimal everywhere in the ocean. These and earlier comparison studies (Chassignet et al., 1996; Marsh et al., 1996, Roberts et al., 1996) show that all the models considered were able to simulate large-scale characteristics of the oceanic circulation reasonably well, but 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.

[1] University of Miami, Naval Research Laboratory (NRL), National Aeronautics and Space Administration/Goddard Institute for Space Studies (NASA/GISS), National Oceanic and Atmospheric Administration/National Centers for Environmental Prediction (NOAA/NCEP), National Oceanic and Atmospheric Administration/Atlantic Oceanographic Meteorological Laboratory (NOAA/AOML), National Oceanic and Atmospheric Administration/Pacific Marine Environmental Laboratory (NOAA/PMEL), Planning Systems, Inc. (PSI), Fleet Numerical Meteorology and Oceanography Center (FNMOC), Naval Oceanographic Office (NAVOCEANO), Service Hydrographique et Océanographique de la Marine (SHOM), Laboratoire des Ecoulements Géophysiques et Industriels (LEGI), Open Source Project for a Network Data Access Protocol (OPeNDAP), University of North Carolina, Rutgers, University of South Florida, Fugro GEOS, Roffer's Ocean Fishing and Forecasting Service (ROFFS), Orbimage, Shell, ExxonMobil.

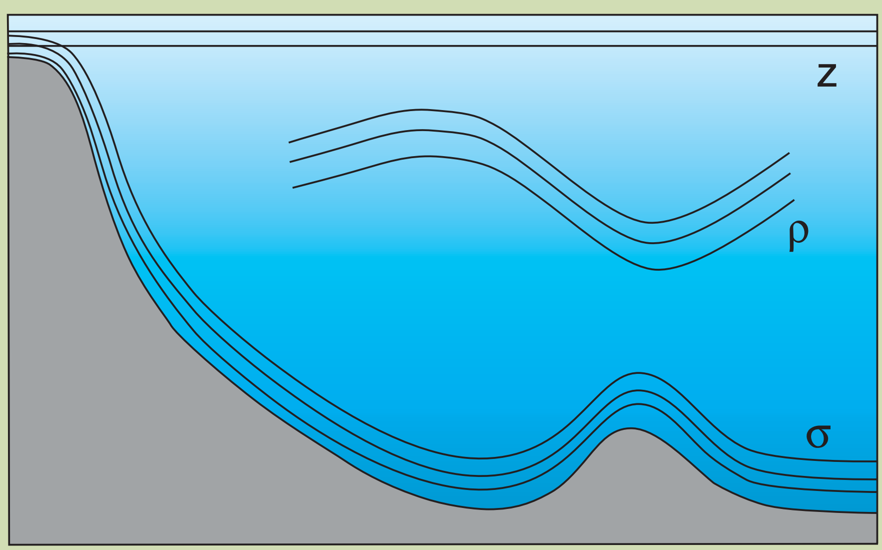
Because none of the three main vertical coordinates (depth, density, and terrain-following) (see Box 1 for details) provide universal optimality, it is natural to envision a hybrid approach that combines the best features of each vertical coordinate. Isopycnic (density-tracking) layers work best for modeling the deep stratified ocean, levels at constant fixed depth or pressure are best to use to provide high vertical resolution near the surface within the mixed layer, and terrain-following levels are often the best choice for modeling shallow coastal regions. In HYCOM, the optimal vertical coordinate distribution of the three vertical coordinate types is chosen at every time step. The hybrid vertical coordinate generator makes a dynamically smooth transition among the coordinate types using the continuity equation.

HYBRID VERTICAL COORDINATES

Hybrid vertical coordinates can mean different things to different people: they can be a linear combination of two or more conventional coordinates (Song and Haidvogel, 1994; Ezer and Mellor, 2004; Barron et al., 2006) or they can be truly generalized (i.e., aiming to mimic different types of coordinates in different regions of a model domain) (Bleck, 2002; Burchard and Beckers, 2004; Adcroft and Hallberg, 2006; Song and Hou, 2006). The generalized vertical coordinates in HYCOM deviate from isopycnals (constant density surfaces) wherever the latter may fold, outcrop, or generally provide inadequate vertical resolution in portions of the model domain. HYCOM is at its core a Lagrangian layer model, except for the remapping of the vertical coordinate by the hybrid coordinate generator after all equations are solved (Bleck, 2002; Chassignet et al., 2003; Halliwell, 2004) and for the fact that there is a nonzero horizontal density gradient within all layers. HYCOM is thus classified as a Lagrangian Vertical Direction (LVD) model in which the continuity (thickness tendency) equation is solved forward in time throughout the domain, while an Arbitrary Lagrangian-Eulerian (ALE) technique is used to re-map the vertical coordinate and maintain different coordinate types within the domain. This differs from Eulerian Vertical Direction (EVD) models with fixed vertical coordinates that use the continuity equation to diagnose vertical velocity (Adcroft and Hallberg, 2006). The ability to adjust the vertical spacing of the coordinate surfaces in HYCOM simplifies the numeri-

BOX 1: OCEAN REGIMES AND VERTICAL COORDINATES

Schematic of an ocean basin illustrating the three regimes of the ocean germane to the considerations of an appropriate vertical coordinate. The surface mixed layer is naturally represented using fixed-depth z (or pressure p) coordinates, the interior is naturally represented using isopycnic ρ (density tracking) coordinates; and the bottom boundary is naturally represented using terrain-following σ coordinates (after Griffies et al., 2000).



cal implementation of several physical processes (e.g., mixed-layer detrainment, convective adjustment, sea-ice modeling) without harming 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 (Bleck and Chassignet, 1994; Chassignet et al., 1996).

The default configuration of HYCOM is isopycnic in the open stratified ocean, but makes a dynamically smooth transition to terrain-following coordinates in shallow coastal regions and to fixed pressure-level coordinates in the surface mixed layer and/or unstratified seas (Figure 1). In doing so, the model takes advantage of the different coordinate types in optimally simulating coastal and open-ocean circulation features. A user-chosen option allows specification of the vertical coordinate separation that controls the transition among the three coordinate systems. The assignment of additional coordinate surfaces to the oceanic mixed layer also allows the straightforward implementation of multiple vertical mixing turbulence closure schemes (Halliwell, 2004). The choice of the vertical mixing parameterization is also of importance in areas of strong entrainment, such as overflows (Xu et al., submitted).

Figure 1 illustrates the transition among pressure, terrain-following, and isopycnic coordinates in 1/25° West Florida Shelf simulations nested within a 1/12° North Atlantic configuration, and it demonstrates the flexibility with which vertical coordinates can be chosen and the capability of adding additional vertical resolution. The original vertical discretization used in the 1/12° North Atlantic configuration is compared to two others with six layers added at the top—one with pressure-level coordinates and the other with terrain-following coordinates over the shelf—because in many coastal applications it is desirable to provide higher resolution from surface to bottom to adequately resolve the vertical structure of water properties and of the bottom boundary layer in shallow water. Halliwell et al. (in preparation) document the advantages and disadvantages of the choices shown in Figure 1.

COMPUTATIONAL ASPECTS

Before one can numerically solve (i.e., discretize) the model's equations, one must decide on a global projection and on how to treat the singularity associated with the North Pole (the South Pole, being over land, is not an issue). There are several projections that allow the Arctic to be included in a global ocean model. The HYCOM global configuration uses an Arctic dipole patch matched to a standard Mercator grid at 47°N (Figure 2). Because our target horizontal resolution is 1/12° at the equator (i.e., 9 km), the location of the dipoles at 47°N gives us a good resolution at mid latitude (i.e., 7 km) as well as in the Arctic Ocean (i.e., 3.5 km at the North Pole) where the Rossby radius of deformation is smaller. An advantage of this pole-shifting projection, as opposed to most others, is that all the grid points below 47°N remain on regular grid spacing (i.e., x-y grid ratio of 1). The corresponding numerical array size is 4500 by 3298 with 32 vertical hybrid layers. The complete system will include the Los Alamos Sea Ice Model (CICE) (Hunke and Lipscomb, 2004) on the same grid.

Eric P. Chassignet *(echassignet@rsmas.miami.edu) is Professor, Rosenstiel School of Marine and Atmospheric Science, Division of Meteorology and Oceanography, University of Miami, Miami, FL, USA.* **Harley E. Hurlburt** *is Senior Scientist, Naval Research Laboratory, Ocean Dynamics and Prediction Branch, Stennis Space Center, MS, USA.* **Ole Martin Smedstad** *is Principal Scientist, Planning Systems Inc., Stennis Space Center, MS, USA.* **George R. Halliwell** *is Research Associate Professor, Rosenstiel School of Marine and Atmospheric Science, Division of Meteorology and Oceanography, University of Miami, Miami, FL, USA.* **Alan J. Wallcraft** *is Computer Scientist, Naval Research Laboratory, Ocean Dynamics and Prediction Branch, Stennis Space Center, MS, USA.* **E. Joseph Metzger** *is Meteorologist, Naval Research Laboratory, Ocean Dynamics and Prediction Branch, Stennis Space Center, MS, USA.* **Brian O. Blanton** *is Research Assistant Professor, University of North Carolina, Ocean Processes Numerical Modeling Laboratory, Chapel Hill, NC, USA.* **Carlos Lozano** *is Physical Scientist, Environmental Modeling Center, National Centers for Environmental Prediction, National Oceanic and Atmospheric Administration, Camp Springs, MD, USA.* **Desiraju B. Rao** *is Branch Chief, Environmental Modeling Center, National Centers for Environmental Prediction, Marine Modeling and Analysis Branch, National Oceanic and Atmospheric Administration, Camp Springs, MD, USA.* **Patrick J. Hogan** *is Oceanographer, Naval Research Laboratory, Ocean Dynamics and Prediction Branch, Stennis Space Center, MS, USA.* **Ashwanth Srinivasan** *is Assistant Scientist, Rosenstiel School of Marine and Atmospheric Science, Division of Meteorology and Oceanography, University of Miami, Miami, FL, USA.*

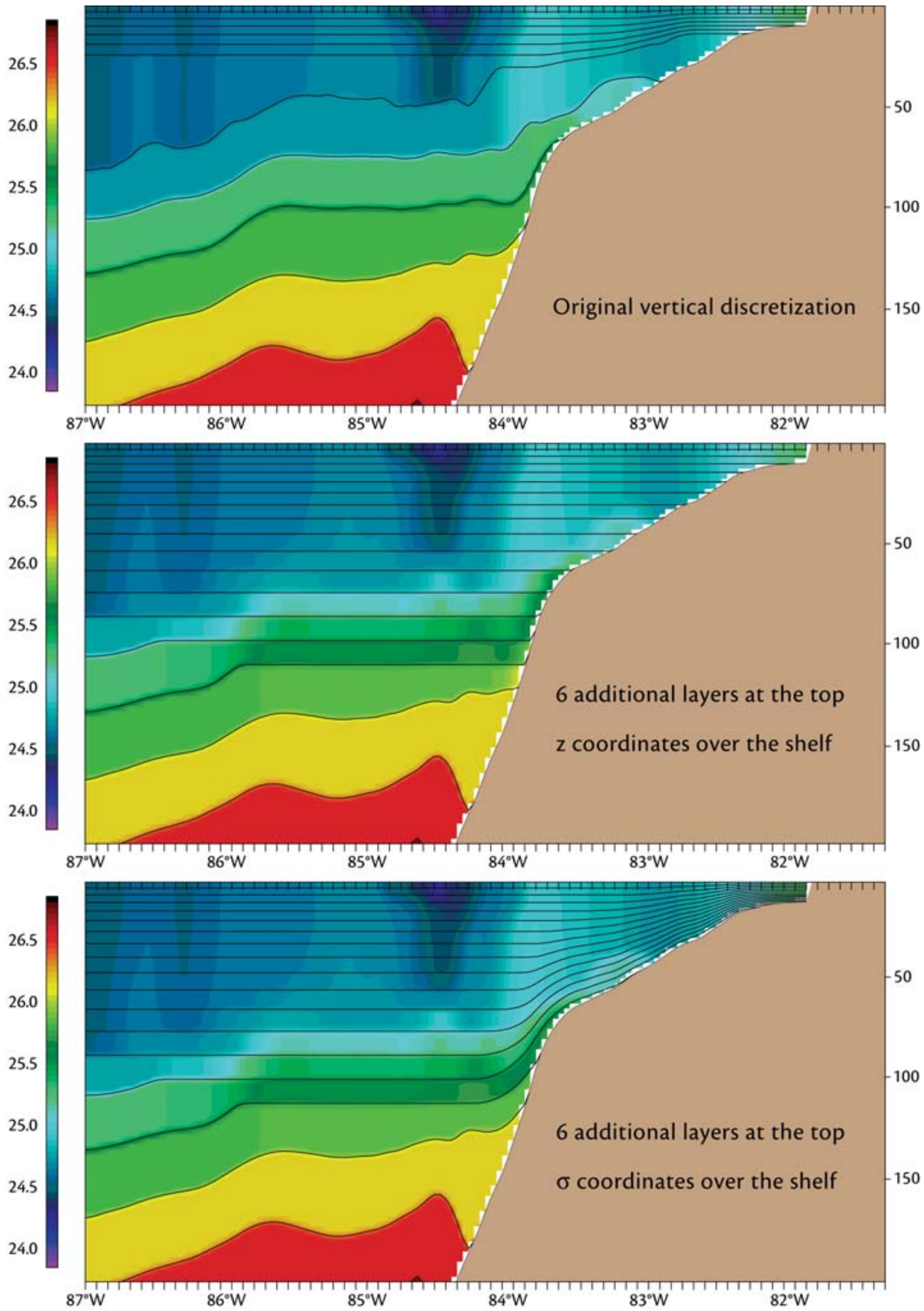


Figure 1. Cross sections of layer density and model interfaces across the West Florida Shelf in a 1/25° West Florida Shelf subdomain covering the Gulf of Mexico east of 87°W and north of 23°N and embedded in a 1/12° Atlantic basin HYCOM simulation (Halliwell et al., in preparation). This figure illustrates the transition among pressure, terrain-following, and isopycnic coordinates in 1/25° West Florida Shelf simulations nested within a 1/12° North Atlantic configuration, and it demonstrates the flexibility with which vertical coordinates can be chosen and the capability of adding additional vertical resolution.

The ocean and ice models will run simultaneously, but on separate sets of processors (a much smaller number for CICE), communicating via an Earth System Modeling Framework (ESMF)-based coupler (Hill et al., 2004).

HYCOM's basic parallelization strategy is two-dimensional domain decomposition (i.e., the entire model domain is divided up into smaller sub-domains, or tiles, and each processor "owns" one tile). A halo region is added around each tile to allow communication operations (e.g., updating the halo) to be completely separated from computational kernels, greatly increasing the maintainability and expandability of the code base. Rather than the conventional one- or two-grid points-wide halo, HYCOM has a six-grid-point-wide halo, which is "consumed" over several operations to reduce halo communication overhead. For global and basin-scale applications, it is important to avoid calculations over land. HYCOM fully "shrink wraps" calculations on each tile and discards tiles that are completely over land (Bleck et al., 1995). HYCOM goes farther than most structured grid ocean models in land avoidance by allowing more than one neighboring tile to the north and south. Figure 2 shows the current tiling for the 1/12° global domain with equal sized tiles that (a) allows rows to be offset from each other if this gives fewer tiles over the ocean and (b) allows two tiles to be merged into one larger tile if less than 50% of their combined area is ocean. The Mediterranean region of Figure 2 illustrates both these optimizations.

In the example presented in Figure 3, the global model is initialized from an oceanic climatology of temperature and salinity. The model is forced by prescribed climatological atmospheric wind, thermal, and precipitation fields while evaporation is computed using the modeled sea surface temperature (SST). There is also a weak relaxation to climatological surface salinity. These simulations use a simple thermodynamic sea-ice model (CICE is running stand-alone on the global Arctic patch grid, but we are awaiting ESMF-based coupling between HYCOM and CICE before running a coupled case). Even without ice dynamics, the seasonal cycle of ice coverage is good overall (not illustrated). One reason for the good agreement is that the atmospheric forcing is based on an accurate ice extent, which provides a strong tendency for the ocean/sea-ice system to form ice appropriately. Figure 3 compares the sea surface height (SSH) variability from the climatologically forced 1/12° global HYCOM to the Oct. 1992–Nov. 1998 SSH variability based on *Topex-Poseidon*, *ERS-1*, and *ERS-2* altimeter data (derived by Collecte Localisation Satellite (CLS), France). Overall, the modeled regions of high variability are in reasonably good agreement with the observations, especially in the Antarctic Circumpolar Current region. The equatorial Pacific is an exception because the altimeter data include interannual variability not present in the model (e.g., the large variability associated with the 1997–1998 El Niño).

OCEAN PREDICTION

Although HYCOM is a relatively sophisticated model that includes a large suite of physical processes and incorporates numerical techniques that are optimal for dynamically different regions of the ocean, data assimilation is still essential for ocean prediction because (a) many ocean phenomena are due to nonlinear processes (i.e., flow instabilities) and thus are not a deterministic response to atmospheric forcing, (b) errors exist in the atmospheric forcing, and (c) ocean models are imperfect, including limitations in numerical algorithms and in resolution.

Substantial information about the ocean surface's space-time variability is obtained remotely from instruments

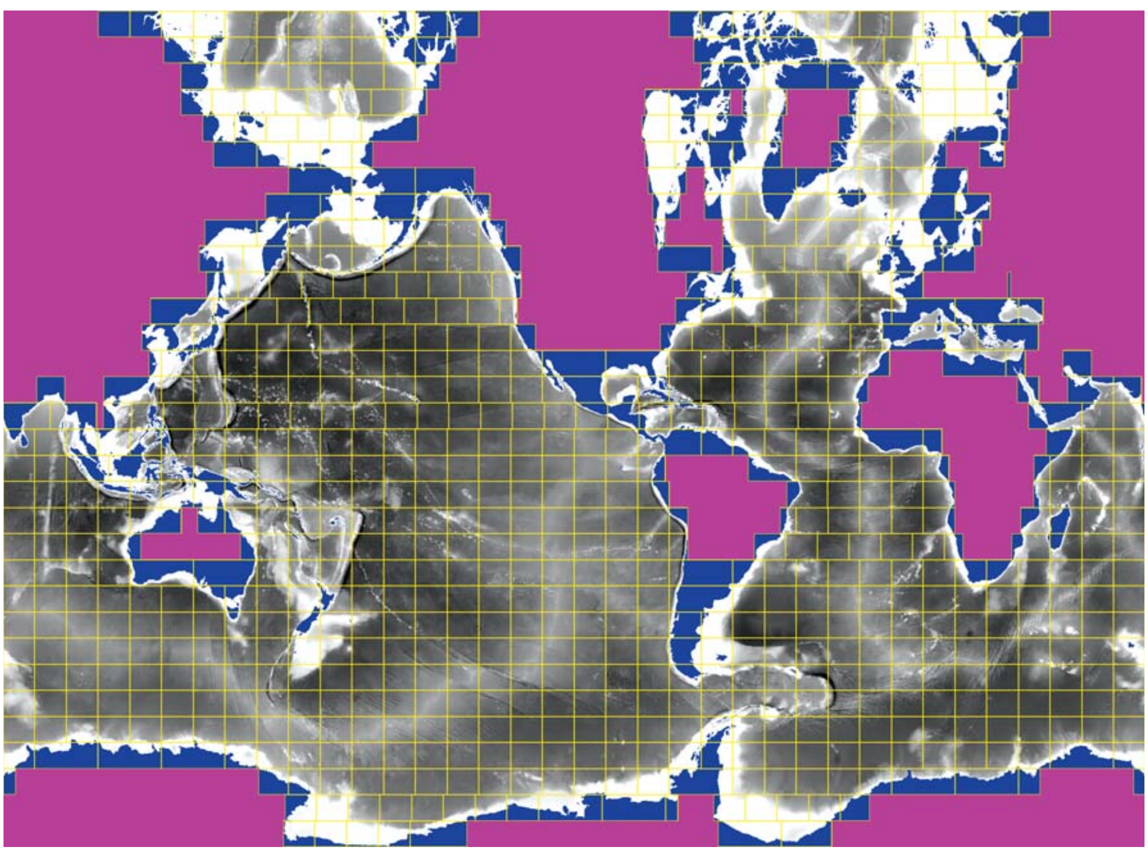


Figure 2. Current tiling for the 1/12° global domain with equal-sized tiles that (a) allows rows to be offset from each other if this gives fewer tiles over the ocean and (b) allows two tiles to be merged into one larger tile if less than 50 percent of their combined area is ocean. The Mediterranean region especially illustrates both these optimizations; out of the original 1152 (36 by 32) approximately equal-sized tiles, 371 tiles are entirely land and are discarded, leaving 781. The Arctic "wraps" between the left and right halves of the top edge.

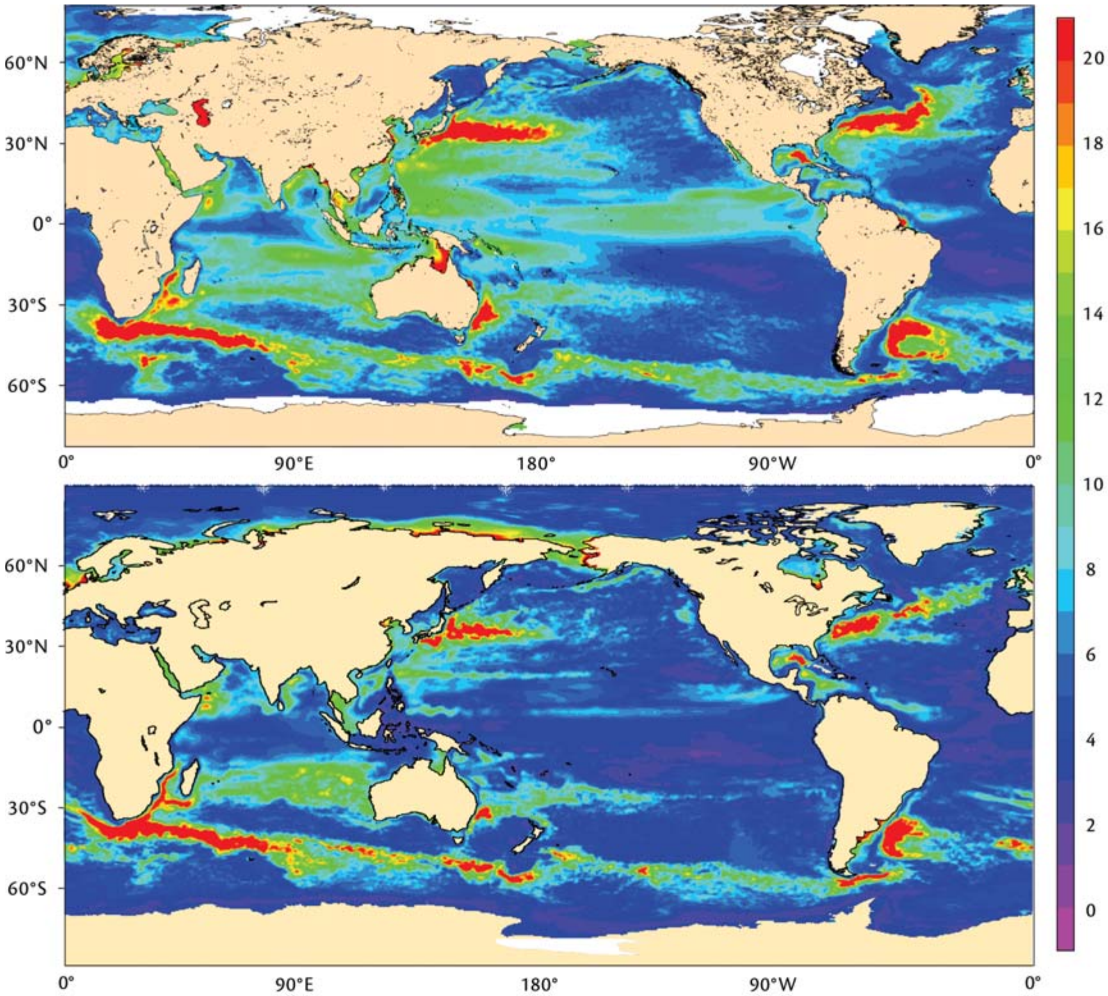


Figure 3. Comparison between the (observed) Oct. 1992–May 2005 sea surface height (SSH) variability based on *Topex-Poseidon*, *ERS-1*, and *ERS-2* altimeter data (top) (derived by Collecte Localisation Satellite [CLS], France) and three years of (modeled) sea surface height (SSH) variability from the climatologically forced 1/12° global HYCOM (bottom). Overall, the modeled regions of high variability are in good agreement with the observations, especially in the Antarctic Circumpolar Current region. The equatorial Pacific is an exception because the altimeter data include interannual variability not present in the model, for example, the large variability associated with the 1997–1998 El Niño.

aboard satellites, but these observations are insufficient for specifying the subsurface variability. Vertical profiles from expendable bathythermographs (XBT), conductivity-temperature-depth (CTD) profilers, and profiling floats (e.g., Argo, which measures temperature and salinity in the upper 2000 m of the ocean) provide another substantial source of data. 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 present 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, however, extremely important that the freely evolving ocean model (i.e., non-data-assimilative model) has skill in hindcasting and in predicting ocean features of interest. For a detailed overview of the HYCOM data assimilative system, the reader is referred to Chassignet et al. (in press).

The present Navy near-real-time 1/12° North Atlantic HYCOM ocean forecasting system is the first step toward the fully global 1/12° HYCOM prediction system. The North Atlantic system assimilates daily, real-time satellite altimeter data (*Geosat-Follow-On* [GFO], *Environmental Satellite* [*ENVISAT*] *1*, and *Jason-1*). These data are provided via the Altimeter Data Fusion Center (ADFC) at the Navel Oceanographic Office (NAVOCEANO) to generate the two-dimensional Modular Ocean Data Assimilation System (MODAS) SSH analysis (Fox et al., 2002). The MODAS analysis is an optimal interpolation technique that uses complex covariance functions, including spatially varying length and time scales as well as propagation terms derived from many years of altimetry (Jacobs et al., 2001). The model SST is relaxed to the daily MODAS SST analysis that 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.

To properly assimilate the SSH anomalies determined from satellite altimeter data, the oceanic mean SSH over the altimeter observation period must be determined. In this mean, it is essential that the mean current systems and associated SSH fronts be accurately represented (position, amplitude, and sharpness). Unfortunately, Earth's geoid is not presently known with sufficient accuracy for this purpose, and coarse hydrographic climatologies (~1° horizontal resolution) cannot provide the spatial resolution necessary. HYCOM, therefore, uses a mean SSH from a previous fully eddy-resolving ocean model simulation that was found to have fronts in the correct position and is consistent with hydrographic climatologies (Chassignet and Garraffo, 2001). Several satellite missions are either underway or planned to determine a more accurate geoid, but until the accuracy reaches a few centimeters on horizontal scales of about 30 km, the present approach will be necessary.

The North Atlantic system runs weekly every Wednesday and produces a 10-day hindcast and a 14-day forecast. The Navy Operational Global Atmospheric Prediction System (NOGAPS) (Rosmond et al., 2002) provides the atmospheric forcing, but in the 14-day forecasts, the forcing linearly reverts toward climatology after five days. During the forecast period, the SST is relaxed toward climatologically corrected persistence of the nowcast SST with a relaxation time scale of one-fourth the forecast length (i.e., one day for a four-day forecast). The impact of these choices is discussed by Smedstad et al. (2003) and Shriver et al. (in press). For an evaluation of the North Atlantic system, the reader is referred to Chassignet et al. (2005, in press).

The near real-time North Atlantic basin model outputs are made available to the ocean science community within 24 hours via the HYCOM Consortium data server (more information available at http://www.hycom.org/dataserver) using a familiar set of tools such as OPeNDAP, Live Access Server (LAS), and file transfer protocol (FTP). These tools have been modified to perform with hybrid vertical coordinates to provide HYCOM subsets to coastal or regional nowcast/forecast partners as initial and boundary conditions. The LAS has been implemented with an intuitive user interface to enhance the usability of ocean prediction system outputs and to perform diagnostics.

BOUNDARY CONDITIONS FOR REGIONAL MODELS

The chosen horizontal and vertical resolution for the above HYCOM prediction system only marginally resolves the coastal ocean (7 km at mid latitudes, with up to 15 terrain-following σ coordinates over the shelf), but provides an excellent starting point for even higher-resolution coastal ocean prediction systems. The model resolution should increase to 1/25° (3–4 km at mid-latitudes) by the end of the decade. An important attribute of the data assimilative HYCOM simulations is, therefore, its capability to provide boundary conditions to regional and coastal models.

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 must be able to handle dissimilar vertical grids. Coupling HYCOM to HYCOM is now routine via one-way nesting (Zamudio et al., in preparation). Outer model fields are periodically interpolated to the horizontal mesh of the nested model (specified by the user, but typically daily) and stored in an archive file. The number of coordinates can be increased to augment the vertical resolution of the nested model and to ensure that there is sufficient vertical resolution to resolve the bottom boundary layer. The nested model is initialized from the first archive file; the entire set of archives provides boundary conditions during the nested run, ensuring consistency between initial and boundary conditions. Coupling HYCOM to other finite difference models, such as the Navy Coastal Ocean Model (NCOM) or the Regional Ocean Model System (ROMS), has already been demonstrated, and coupling of HYCOM to unstructured grid/finite element models is in progress.

We now describe the use of near-real-time HYCOM nowcasts and forecasts as boundary and initial-condition providers to a nested coastal simulation in the South Atlantic Bight (SAB) region of the eastern U.S. coast. The 1/12° North Atlantic HYCOM does not necessarily include all forcing and physics relevant at the coastal region scale (e.g., lack of tidal forcing in the present simulation). The nesting of higher-resolution models within the basin-scale HYCOM therefore allows limited-area regional forcings (terrestrial buoyancy inputs, tides), physics (wetting and drying), and coastal geometry (tidal inlets, estuaries) to add value to the larger-scale HYCOM ocean-state estimates.

The quasi-operational regional-scale modeling system developed at the University of North Carolina (UNC)-SAB (National Ocean Partnership Program [NOPP]-funded South Atlantic Bight Limited Area Model [SABLAM], SouthEast U.S. Atlantic Coastal Ocean Observing System [SEACOOS]) (Blanton, 2003) uses the finite element coastal ocean model QUODDY (Lynch et al., 1996). Terrestrial buoyancy inputs to the continental shelf, strong tides, and a vigorous western boundary current contribute to the complexity of this region. To simulate the density-dependent dynamics, the UNC-SAB modeling system is nested within the HYCOM GODAE near-real-time system. Boundary and initialization data for the SAB regional-scale model are obtained from the HYCOM GODAE Live Access Server and are mapped to the finite element regional model domain. For each forecast, the system spins up the regional tides for five model days, with the density field held fixed. The atmospheric (buoyancy and momentum) and river fluxes are turned on. The timing is synchronized such that the fluxes are active for one day at the time the HYCOM fields are valid.

An example of this nested system is shown in Figure 4. The HYCOM nowcast for November 28, 2005 is used to initialize the regional model domain, onto which the tides and high-resolution atmospheric fluxes are applied. The resulting solution is used to initialize and drive the limited-area, estuary-resolving finite element implementation. The effects of both the Gulf Stream, as provided by the HYCOM initial and boundary conditions, and the local tides are seen in the limited-area model (Figure 4, right). Strong along-shelf and poleward flow is seen at the shelfbreak. The poleward, offshelf-directed flow on the shelf is due

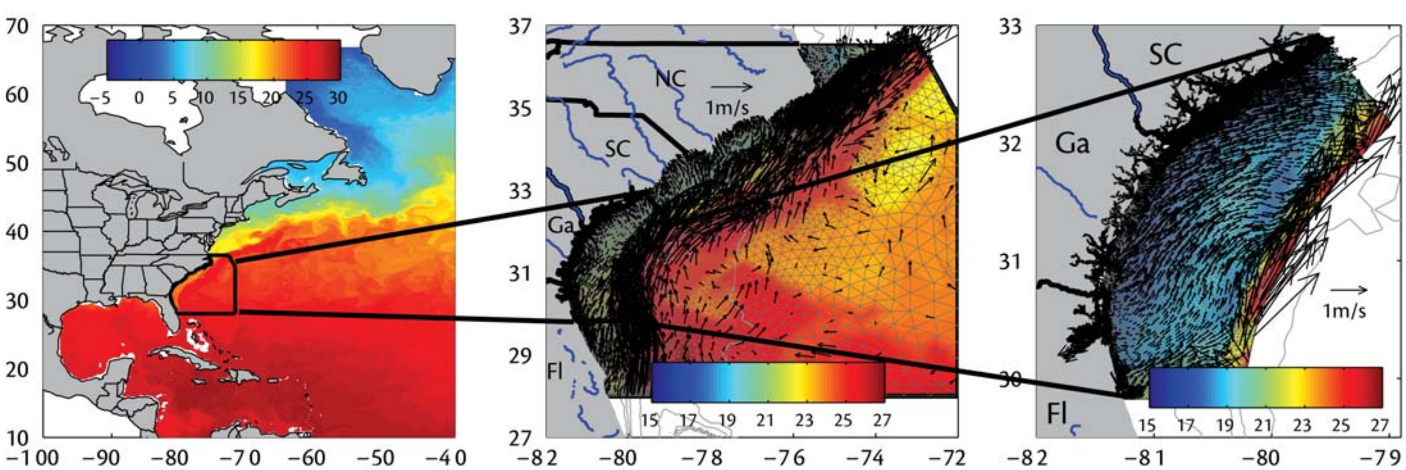


Figure 4. (Left) 1/12° North Atlantic HYCOM-GODAE sea surface temperature (SST) nowcast for November 28, 2005. The three-dimensional solution for this date is used to initialize the University of North Carolina-South Atlantic Bight (UNC-SAB) finite element modeling system (middle, every 5th model vector). The surface temperature and velocity are shown, after addition of the regional tides and atmospheric fluxes. The limited-area finite element implementation (right, every 3rd model vector) includes the estuary and tidal inlets along the Georgia/South Carolina coast and extends to the shelf-break. This snapshot also shows surface temperature and velocity and is for three days after initialization. The color scales between the HYCOM and nested plots are not the same.

to the tides.

Evaluation of the near real-time HYCOM outputs relative to available observations in the SAB consists of comparisons to National Ocean Service water levels along the coast and mid-shelf temperature from an established continental shelf observational network (SABSOON) (Seim, 2000). Variability in observed coastal water levels is due to tides, wind-stress-driven and other lower-frequency fluctuations (deep-ocean contributions to shelf-wide sea level). In the SAB, tides account for at least 90% of the total water level variability. Figure 5a shows *subtidal* coastal water levels for two stations in the SAB. Lower-frequency, seasonal-scale variations are well captured by HYCOM. Weather-band fluctuations are also reasonably well represented. Observations of *in situ* water fields (salinity, temperature) are comparatively less available in the SAB. The SABSOON observational network, situated on the Georgia continental shelf, has been making routine and real-time observations of water properties for three years. Figure 5b shows observed SABSOON R2 near-surface temperature and HYCOM mixed-layer temperature. The HYCOM mixed layer covers most of the water column vertical grid in this region. The root mean square (RMS) error between the signals (where both are available) is 1.4° C. Strong, prolonged cooling of the SAB continental shelf during summer 2003 is seen in the HYCOM temperature (Figure 5b), and is attributable to a variety of coincident environmental conditions (for a review see Aretxabaleta et al. [submitted]). The HYCOM best-prior-estimates from summer 2003 are being used, with the regional modeling system, to examine the physical nature of this extreme cooling event.

OUTLOOK

The long-term goal of the HYCOM consortium is an eddy-resolving, fully global ocean prediction system with data assimilation to be transitioned to the U.S. Naval Oceanographic Office at 1/12° equatorial (~7 km mid-latitude) resolution in 2007 and 1/25° resolution by 2011. Development of the global system is underway and includes the ocean model, ice model, tides, and data assimilation. Data assimilation is traditionally formulated as a least-squares estimation problem. In spite of a fairly simple theoretical framework, application to nonlinear numerical models of the ocean circulation is far from trivial (Brasseur, 2006). The difficulty is in finding algorithms that provide an acceptable solution in terms of computer resources. The size of the problem makes it indeed very difficult to use sophisticated assimilation

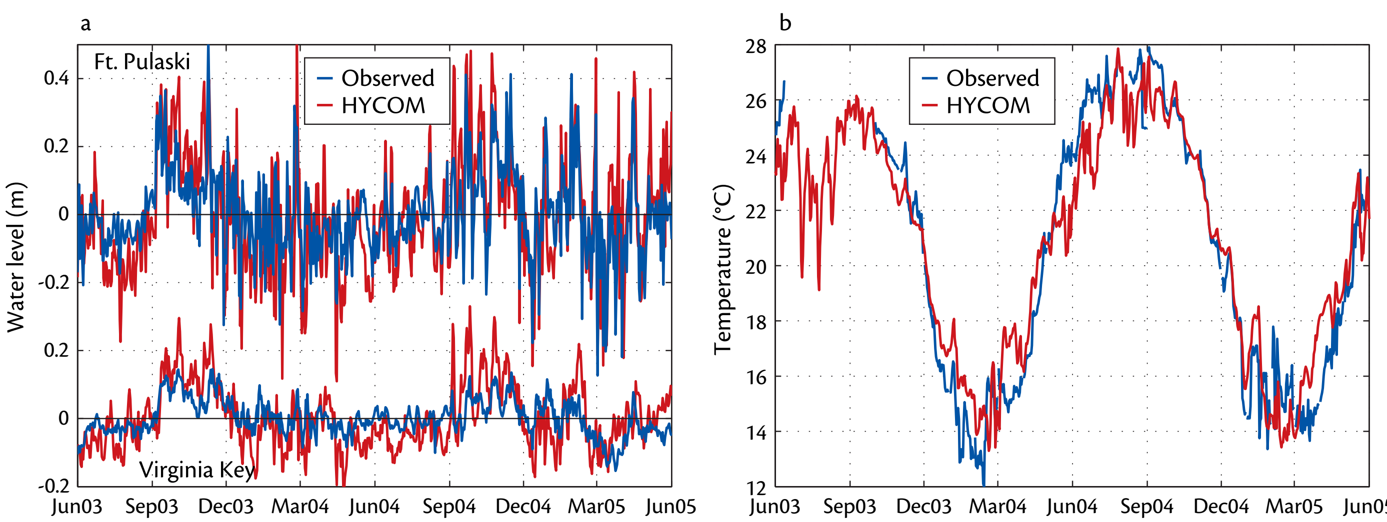


Figure 5. (a) Water level comparison for two stations in the SAB. Daily HYCOM best-estimate water levels (blue) and observed NOS water levels (red) are shown for Fort Pulaski, Georgia and Virginia Key, Florida. The two stations are arbitrarily offset for clarity. (b) Observed, near-surface temperature (blue) and HYCOM mixed-layer temperature (red) for the SABSOON mid-shelf station R2. The root mean square (RMS) error at this location is 1.4°C.

techniques because some of these methods can increase the cost of running the model by a factor of 100. The strategy we adopted is to start with a low-cost and simple data assimilation approach (e.g., Cooper and Haines [1996]), and then gradually increase the complexity. Several sophisticated data assimilation techniques are already in place to work with HYCOM and are being evaluated. These techniques are, in increasing level of sophistication, the Naval Research Laboratory (NRL)'s Coupled Ocean Data Assimilation (NCODA), the Singular Evolutive Extended Kalman (SEEK) filter, the Reduced Order Information Filter (ROIF), the Reduced Order Adaptive Filter (ROAF) (including adjoint), the Ensemble Kalman Filter (EnKF), and the 4D-VAR Representer method. Although these techniques work with HYCOM, it does not mean that they will be used operationally: the NCODA and SEEK techniques are presently being considered as the next generation data assimilation to be used in the near-real-time system. The remaining techniques, because of their cost, are being evaluated mostly within specific limited areas of high interest or coastal HYCOM configurations.

Another HYCOM North Atlantic configuration forms the backbone of the National Oceanic and Atmospheric Administration (NOAA)/National Centers for Environmental Prediction (NCEP)/North Atlantic Ocean Forecast System (NAOFS) (more information available at http://polar.ncep.noaa.gov/ofs/), which provides daily nowcasts and five-day forecasts. It primarily differs from the North Atlantic Navy system described earlier in three ways: (a) the choice of horizontal grid, (b) the use of NCEP-based wind and thermal forcing, and (c) the choice of data assimilation technique. The NOAA/NCEP group is using a configuration that, for the same number of grid points as in the regular Mercator projection used in the Navy system, has finer resolution in the western and northern portions of the basin and on shelves (3–7 km), in order to provide higher resolution along the U.S. coast rather than toward the east and southeast (7–13 km). The model domain configuration is from 20°S to 76°N, including marginal seas, except for the Mediterranean and Baltic Seas. Atmospheric momentum, heat, and water fluxes are derived from the three hourly NCEP-based fields. Tidal forcing and river outflows are prescribed. The observations used in the assimilation include remotely sensed and *in situ* SST, remotely sensed SSH anomalies, and subsurface data. The goals of the NOAA system are to provide (a) accurate estimates and forecasts of the coastal ocean, (b) initial and boundary conditions to NOAA's regional and coastal models, (c) coupled circulation-wave-storm-surge models, and (d) coupled atmosphere-ocean hurricane forecasts.

The generalized coordinate approach used in HYCOM minimizes the liabilities associated with a single coordinate system and provides the user with the flexibility to tailor the model to the specific application. Generalized hybrid vertical coordinate ocean models are currently used for an increasingly diverse suite of applications, from high-resolution nowcasting and short-term prediction of the regional ocean state, to global tidal simulations, El Niño-Southern Oscillation (ENSO) forecasting, multi-century climate simulations, and theoretical studies of the ocean's dynamics. U.S. ocean modelers have, therefore, engaged in a broader dialogue as to whether the various community modeling efforts could be channeled into an ocean modeling environment (see white paper on HOME [Hybrid Ocean Modeling Environment] available at ftp://hycom.rsmas.miami.edu/eric/HOME). A modeling environment is defined here as a uniform code comprising a diverse collection of interchangeable algorithms and supporting software from which particular models design can be selected (e.g., HYCOM). It would not only provide diversity of modeling approaches, but also would standardize coupling with other models (e.g., atmospheres or ocean sub-models) and various ways for user specification of parameters, grids, domains, initial conditions, forcings, and diagnostics.

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REFERENCES

Adcroft, A., and R. Hallberg. 2006. On methods for solving the oceanic equations of motion in generalized vertical coordinates. *Ocean Modelling* 11:224–233.

Aretxabaleta, A., J.R. Nelson, J.O. Blanton, H.E. Seim, F.E. Werner, J.M. Bane, and R. Weisberg. Submitted. Cold event in the South Atlantic Bight during summer of 2003: Anomalous hydrographic and atmospheric conditions. *Journal of Geophysical Research.*

Barron, C.N., P.J. Martin, A.B. Kara, R.C. Rhodes, and L.F. Smedstad. 2006. Formulation, implementation and examination of vertical coordinate choices in the Global Navy Coastal Ocean Model (NCOM). *Ocean Modelling* 11:347–375.

Blanton, B. 2003. *Towards Operational Modeling in the South Atlantic Bight*, Ph.D. Dissertation, University of North Carolina at Chapel Hill, 135 pp.

Bleck, R., and E.P. Chassignet. 1994. Simulating the oceanic circulation with isopycnic coordinate models. Pp. 17–39 in *The Oceans: Physical-Chemical Dynamics and Human Impact* , S.K. Majundar, E.W. Mill, G.S. Forbes, R.E. Schmalz, and A.A. Panah, eds. The Pennsylvania Academy of Science, Pittsburgh, PA.

Bleck, R., S. Dean, M. O'Keefe, and A. Sawdey. 1995. A comparison of data-parallel and message-passing versions of the Miami Isopycnic Coordinate Ocean Model (MICOM). *Parallel Computing* 21:1,695–1,720.

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

Brasseur, P. 2006. Ocean data assimilation using sequential methods based on the Kalman filter: From theory to practical implementations. Pp. 271–315 in *Ocean Weather Forecasting: An Integrated View of Oceanography,* E.P. Chassignet, and J. Verron, eds. Springer-Verlag, New York, NY.Burchard, H., and J.-M. Beckers. 2004. Non-uniform adaptive vertical grids in one-dimensional numerical ocean models. *Ocean Modelling* 6:51–81.

Chassignet, E.P., and Z.D. Garraffo. 2001. Viscosity parameterization and the Gulf Stream separation. In: *From Stirring to Mixing in a Stratified Ocean*. Pp. 37-41 in *Proceedings 'Aha Huliko'a Hawaiian Winter Workshop.* University of Hawaii, January 15–19., P. Müller and D. Henderson, eds.

Chassignet, E.P., L.T. Smith, R. Bleck, and F.O. Bryan. 1996. A model comparison: Numerical simulations of the North and Equatorial Atlantic Ocean circulation in depth and isopycnic coordinates. *Journal of Physical Oceanography* 26:1,849-1,867.

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. *Dynamics of Atmosphere and Oceans* 32:155–184.

Chassignet, E.P., L.T. Smith, G.R. Halliwell, and R. Bleck. 2003. North Atlantic simulations with the HYbrid Coordinate Ocean Model (HYCOM): Impact of the vertical coordinate choice, reference density, and thermobaricity. *Journal of Physical Oceanography* 33:2,504–2,526.

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. 2005. Assessment of ocean prediction systems in the Gulf of Mexico using ocean color. Pp. 87–100 in *Circulation in the Gulf of Mexico: Observations and models*, W. Sturges and A. Lugo-Fernadez, eds. AGU Monograph Series, 161. American Geophysical Union, Washington, D.C.

Chassignet, E.P., H.E. Hurlburt, O.M. Smedstad, G.R. Halliwell, P.J. Hogan, A.J. Wallcraft, R. Baraille, and R. Bleck. In press. The HYCOM (HYbrid Coordinate Ocean Model) data assimilative system. *Journal of Marine Systems*.

Cooper, M., and K. Haines. 1996. Altimetric assimilation with water property conservation. *Journal of Geophysical Research* 101:1,059–1,078.

Ezer, T., and G. Mellor. 2004. A generalized coordinate ocean model and a comparison of the bottom boundary layer dynamics in terrain-following and z-level grids. *Ocean Modelling* 6:379–403.

Fox, D.N., W.J. Teague, C.N. Barron, M.R. Carnes, and C.M. Lee. 2002. The Modular Ocean Data Analysis System (MODAS). *Journal of Atmospheric and Oceanic Technology* 19:240–252.

Griffies, S.M., C. Böning, F.O. Bryan, E.P. Chassignet, R. Gerdes, H. Hasumi, A. Hirst, A.-M. Treguier, and D. Webb. 2000. Developments in ocean climate modelling. *Ocean Modelling* 2:123–192.

Halliwell, Jr., G.R. 2004. Evaluation of vertical coordinate and vertical mixing algorithms in the HYbrid Coordinate Ocean Model (HYCOM). *Ocean Modelling* 7:285–322.

Halliwell, Jr., G.R., V. Kourafalou, R. Balotro, E.P. Chassignet, V. Garnier, P.J. Hogan, A.J. Wallcraft, H.E. Hurburt, and R.H. Weisberg. In preparation. Development and evaluation of HYCOM as a coastal ocean model.

Hill C., C. DeLuca, V. Balaji, M. Suarez, and A. da Silva. 2004. The Architecture of the Earth System Modeling Framework. *Computing in Science and Engineering* 6:18–28.

Hunke, E.C., and W.H. Lipscomb. 2004. CICE: The Los Alamos sea ice model documentation and software user's manual. [Online] Available at http://climate.lanl.gov/Models/CICE (accessed January 16, 2006).

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. *Dynamics of Atmosphere and Oceans* 32:283–329.

International GODAE Steering Team. 2000: GODAE Strategic Plan. N. Smith, ed. GODAE Project Office, Bureau of Meteorology, Melbourne, Australia.

Jacobs, G.A., C.N. Barron, and R.C. Rhodes. 2001. Mesoscale characteristics. *Journal of Geophysical Research*, 106(C9):19,581–19,595.

Lynch. D.R., J.T.C. Ip, C.E. Naimie, and F.E. Werner. 1996. Comprehensive coastal circulation model with application to the Gulf of Maine. *Continental Shelf Research* 16:875–906.

Maltrud, M.E., and J.L. McClean. 2005. An eddy-resolving global 1/10° ocean simulation. *Ocean Modelling* 8:31–54.

Marsh, R., M.J. Roberts, R.A. Wood, and A.L. New. 1996. An intercomparison of a Bryan-Cox type ocean model and an isopycnic ocean model. Part II: The subtropical gyre and heat balances. *Journal of Physical Oceanography* 26:1,528–1,551.

Roberts, M.J., R. Marsh, A.L. New, and R.A. Wood, 1996. An intercomparison of a Bryan-Cox type ocean model and an isopycnic ocean model. Part I: The subpolar gyre and high-latitude processes. *Journal of Physical Oceanography* 26:1,495–1,527.

Rosmond, T.E., J. Teixeira, M. Peng, T.F. Hogan, and R. Pauley. 2002. Navy Operational Global Atmospheric Prediction System (NOGAPS): Forcing for ocean models. *Oceanography* 15:99–108.

Seim, H. 2000. Implementation of the South Atlantic Bight Synoptic Offshore Observational Network. *Oceanography* 13:18–23.

Shriver, J.F., H.E. Hurlburt, O.M. Smedstad, A.J. Wallcraft, and R.C. Rhodes. In press. 1/32° real-time global ocean prediction and value-added over 1/16° resolution. *Journal of Marine Systems*.

Smedstad, O.M., H.E. Hurlburt, E.J. Metzger, R.C. Rhodes, J.F. Shriver, A.J. Wallcraft, and A.B. Kara. 2003. An operational eddy-resolving 1/16 global ocean nowcast/forecast system. *Journal of Marine Systems* 40–41:341–361.

Smith, R.D., M.E. Maltrud, F.O. Bryan, and M.W. Hecht. 2000. Numerical simulations of the North Atlantic Ocean at 1/10°. *Journal of Physical Oceanography* 30:1,532–1,561.

Song, Y., and D.B. Haidvogel. 1994. A semi-implicit ocean circulation model using topography-following coordinate. *Journal of Computational Physics* 115:228–244.

Song, Y.T., and T.Y. Hou. 2006. Parametric vertical coordinate formulation for multiscale, Boussinesq, and non-Boussinesq ocean modeling. *Ocean Modelling* 11:298-332.

Willebrand, J., B. Barnier, C. Böning, C. Dieterich, P.D. Killworth, C. Le Provost, Y. Jia, J.-M. Molines, and A.L. New. 2001. Circulation characteristics in three eddy-permitting models of the North Atlantic. *Progress in Oceanography* 48:123–161.

Xu, X., Y.S. Chang, H. Peters, T.M. Özgökmen, and E.P. Chassignet. Submitted. Parameterization of gravity current entrainment for ocean circulation models using a high-order 3D nonhydrostatic spectral element model. *Ocean Modelling*.

Zamudio, L., P.J. Hogan, and E.J. Metzger. In Preparation. Nesting the Gulf of California in Pacific HYCOM.