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15. SUBJECT TERMS
ocean prediction; data assimilation; HYCOM; ocean modeling; GODAE; boundary conditions

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The HYCOM (HYbrid Coordinate Ocean Model) data assimilative system

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Abstract

This article 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 hindcast, nowcast, and prediction system in the context of the Global Ocean Data Assimilation Experiment (GODAE). The main characteristics of HYCOM are first presented, followed by a description and assessment of the present near real-time Atlantic forecasting system. Regional/coastal applications are also discussed since an important attribute of the data assimilative HYCOM simulations is the capability to provide boundary conditions to regional and coastal models. The final section describes the steps taken toward the establishment of the fully global eddy-resolving HYCOM data assimilative system and discusses some of the difficulties associated with advanced data assimilation given the size of the problem.

Keywords: Ocean prediction; Data assimilation; HYCOM; Ocean modeling; GODAE; Boundary conditions

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 hindcast, nowcast, and 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 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 data assimilative 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*

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[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.

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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 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, International GODAE Steering Team, 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).

Numerical modeling studies over the past several decades have demonstrated advances in both model architecture and the availability of computational resources for the scientific community. Perhaps the most noticeable aspect of this progression has been the evolution from simulations on coarse-resolution horizontal/vertical grids outlining basins of simplified geometry and bathymetry and forced by idealized stresses, to fine-resolution simulations incorporating realistic coastal definition and bottom topography, forced by observational data on relatively short time scales (Hurlburt and Hogan, 2000; Smith et al., 2000; Chassignet and Garraffo, 2001). Traditional Ocean General Circulation Models (OGCMs) 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 σ-levels–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 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 continuity equation using the hybrid vertical coordinate generator.

The layout of the paper is as follows. First, in Section 2, an overview of the HYCOM characteristics is presented with model performance illustrated using non-data assimilative basin-scale and regional nested simulations. The near real-time North Atlantic Ocean data assimilative system in then introduced in Section 3 and its hindcast capabilities evaluated. In Section 4, issues associated with regional/coastal applications are introduced and discussed. Future development plans are presented in Section 5.

2. The ocean model

HYCOM is designed to provide a significant improvement over existing operational OGCMs, since it overcomes design limitations of present systems as well as limitations in vertical discretization. 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 used in this study retains many of the characteristics of its predecessor, the isopycnic coordinate model MICOM (Miami Isopycnic Coordinate Model) (Bleck et al., 1992; Bleck and Chassignet, 1994), 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. Hybrid coordinates can mean different things to different people: it can be a linear combination of two or more conventional coordinates (Song and Haidvogel, 1994; Ezer and Mellor, 2004; Barron et al., in press) or truly generalized, i.e. aims to mimic different types of coordinates in different parts of a model (Bleck, 2002; Burchard and Beckers, 2004; Adcroft and Hallberg, 2006; Song and

Hou, 2006). HYCOM uses the same equations as MICOM, except that they have been modified to account for nonzero horizontal density gradient within all layers, not just the top layer as in MICOM. HYCOM remains a Lagrangian layer model in the sense that the MICOM solution procedure is unmodified, except that remapping of the vertical coordinate is performed via a hybrid coordinate generator at the end of each baroclinic time step (Bleck, 2002; Halliwell, 2004). HYCOM is thus classified as a Lagrangian Vertical Direction (LVD) model where the continuity (thickness tendency) equation is solved prognostically throughout the domain, with the Arbitrary Lagrangian-Eulerian (ALE) technique used to remap the vertical coordinate and maintain different coordinate types within the domain (Adcroft and Hallberg, 2006). This differs from Eulerian Vertical Direction (EVD) models with fixed z- and σ-coordinates that use the continuity equation to diagnose vertical velocity.

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 (see Section 2.1 for details). The capability of assigning additional coordinate surfaces to the oceanic mixed layer in HYCOM allows the option of implementing sophisticated vertical mixing turbulence closure schemes. The latest release of HYCOM has five primary vertical mixing algorithms, of which three are vertical diffusion models and two are slab models (see Section 2.2 for details). The choice of the vertical mixing parameterization is also of importance in areas of strong entrainment, such as overflows (see Section 2.3 for details).

2.1. Hybrid coordinate generator and its transition to coastal regions

The implementation of the generalized vertical 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 makes a dynamically smooth transition to σ coordinates in shallow coastal regions and to fixed pressure-level coordinates (hereafter referred to as p) in the surface mixed layer and/or unstratified seas (Fig. 1). In doing so, the model combines the advantages of the different coordinate types 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 as described in the appendix.

After the model equations are solved, the hybrid coordinate generator then relocates vertical interfaces to restore isopycnic conditions in the ocean interior to the greatest extent possible while enforcing the minimum thickness requirements specified by (1) in the appendix. If a layer is less dense than 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 over which the interface must be relocated so that volume-weighted density of the original plus new water in the layer equals the reference density. The minimum permitted thickness of each layer at each model grid point is then calculated using (1) in the appendix. The final minimum thickness is then calculated using a "cushion" function (Bleck, 2002) that produces a smooth transition from the isopycnic to the p and σ domains. The minimum thickness constraint is not enforced at the bottom in the open ocean, permitting the model layers to collapse to zero thickness there, as in MICOM. Repeated execution of this algorithm at every time step maintains layer density very close to its reference value as long as a minimum thickness does not have to be maintained and diabatic processes are weak. To insure that a permanent p-coordinate domain exists near the surface year round at all model grid points, the reference densities of the uppermost layers are assigned values smaller than any density values found in the model domain.

Fig. 1 illustrates the transition that occurs between p/σ and isopycnic (ρ) coordinates in the fall and spring in the upper 400 m and over the shelf in the East China and Yellow Seas. In the fall, the water column is stratified and can be largely 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 isopycnic coordinates is illustrated

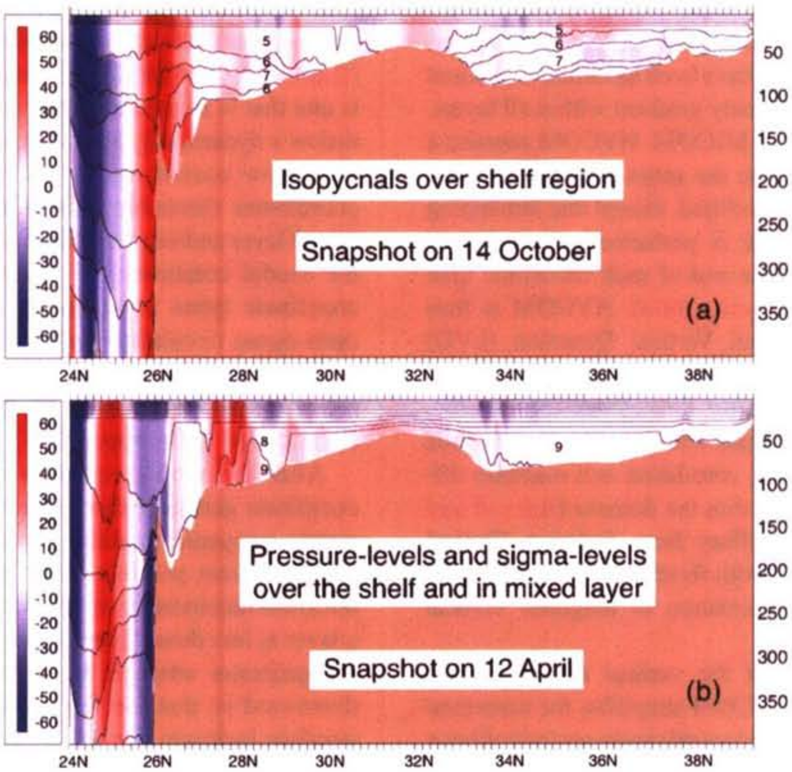

Fig. 1. Upper 400 m north–south velocity cross-section along 124.5°E in a 1/25° East China and Yellow Seas HYCOM embedded in a 1/6° North Pacific configuration forced with climatological monthly winds: (a) in the fall, the water column is stratified over the shelf and can be represented with isopycnals (ρ); (b) in the spring, the water column is homogenized over the shelf and the vertical coordinate becomes a mixture of pressure (p) levels and terrain-following (σ) levels. The isopycnic layers are numbered over the shelf, the higher the number, the denser the layer.

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 isopycnic coordinates. In other applications in the coastal ocean, it may be more desirable to provide high resolution from surface to bottom to adequately resolve the vertical structure of water properties and of the bottom boundary layer. Since vertical coordinate choices for open ocean HYCOM runs typically maximize the fraction of the water column that is isopycnic, it is often necessary to add more layers in the vertical to coastal HYCOM simulations nested within larger-scale HYCOM runs. The nested West Florida Shelf simulations analyzed by Halliwell (in preparation) use this technique, which is illustrated in the cross-sections in Fig. 2. The original vertical discretization is compared to two others with six layers added at the top: one with p coordinates and the other with σ coordinates over the shelf. This illustrates the flexibility with which vertical coordinates can be chosen using the minimum layer thickness algorithm in the appendix. Halliwell (in preparation) documents the advantages of using high-resolution σ coordinates compared to the other two choices shown in Fig. 2.

Maintaining hybrid vertical coordinates can be thought of as upwind finite volume advection. The original grid generator (Bleck, 2002) used the simplest possible scheme of this type, the 1st order donor-cell upwind scheme. A major advantage of this scheme is that moving a layer interface does not affect the layer profile in the down-wind (detraining) layer, which greatly simplifies remapping to isopycnal layers. However, the scheme is diffusive when layers are remapped (there is no diffusion when layer interfaces remain at their original location). Isopycnal layers require minimal remapping in response to weak interior diapycnal diffusivity, but fixed coordinate layers often require significant remapping, especially in regions with significant upwelling or downwelling. Therefore, to minimize diffusion associated with the remapping, the grid generator now uses the piecewise linear method with a monotonized central-difference (MC) limiter (van Leer, 1997) for layers that are in fixed coordinates while still using donor-cell upwind for layers that are non-fixed (and hence tending to isopycnal coordinates). The piecewise linear method replaces the "constant within each layer" profile of donor-cell with a linear profile that equals the layer average at the center of the layer. The slope must be limited to maintain

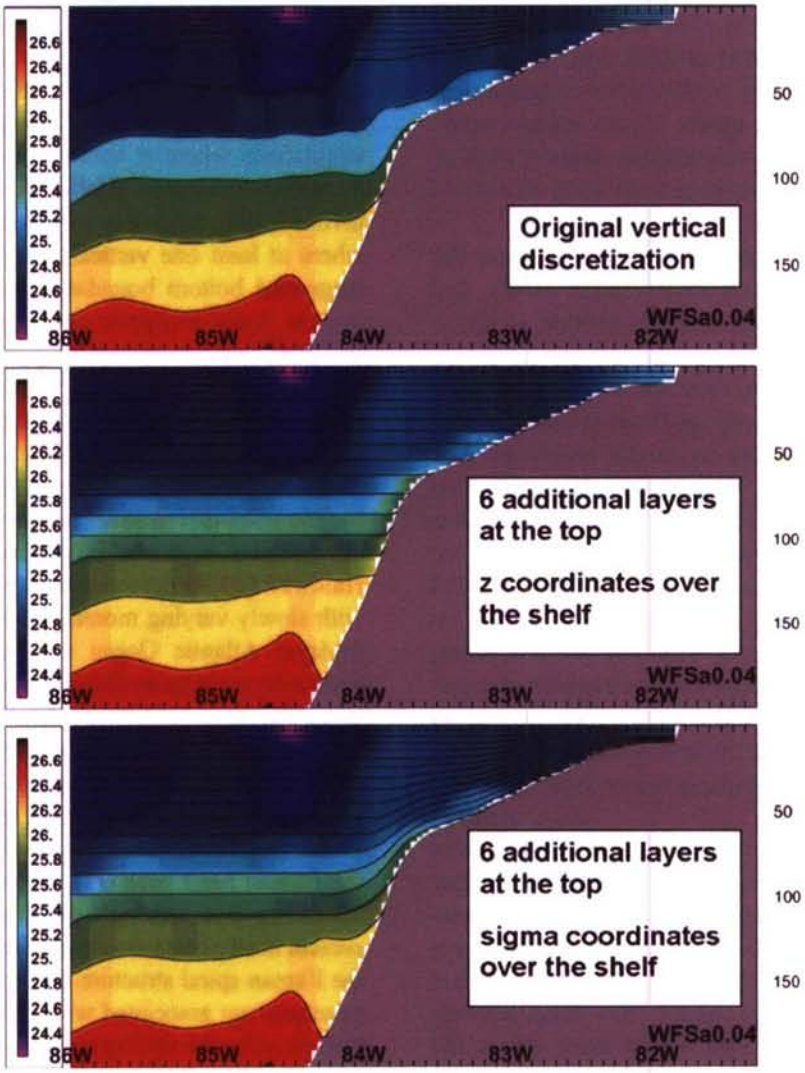

Fig. 2. Cross-sections of layer density and model interfaces across the West Florida Shelf illustrating the capability to add new layers at the top for a nested coastal simulation and the capability to specify different coordinate types over the shelf. The 1/25° West Florida Shelf subdomain covers the Gulf of Mexico east of 87°W and north of 23°N and is embedded in a 1/25° Intra-Americas Sea, itself nested within a climatologically-forced 1/12° Atlantic basin HYCOM simulation (Halliwell, in preparation).

monotonicity; there are many possible limiters but the MC limiter is one of the more widely used (Leveque, 2002).

2.2. Mixed layer options

As noted earlier, 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 "continuous" vertical diffusion models and two are predominantly or totally bulk models. The three vertical diffusion models, which govern vertical mixing throughout the water column, are the 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 and Turner (1967) submodel (KT). Since these latter two mixed layer models do not provide mixing from surface to bottom, HYCOM contains two diapycnal mixing models, one explicit and one implicit, to provide this mixing in the interior ocean. All mixing schemes within HYCOM are kept up to date. The MY model is the version implemented in the Princeton Ocean Model

(POM), specifically POM98. The latest recommended coefficients are implemented in KPP, and we have an ongoing collaboration with NASA/GISS to implement the latest changes in their model. Future plans include implementing and testing new mixing models, such as the generic length scale equation turbulence closure of Umlauf and Burchard (2003).

The following procedure is used to implement the three vertical diffusion submodels (KPP, GISS, and MY). 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, 1997). 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. These three mixing models all diagnose mixed layer thickness using the method of Kara et al. (2000, 2003), which is implemented as follows: the user first specifies a minimum temperature jump for estimating mixed layer thickness, which is converted to an equivalent density jump using the equation of state. The mixed layer base is then assumed to reside at the depth where density differs from layer 1 density by the value of this jump. Moving down from layer 1, the first model layer where the density exceeds layer 1 density by more than the value of this jump is identified. Given the central depth and density of this layer along with the central depth and density of the layer above, linear interpolation is used to estimate the thickness.

The original KPP submodel did not contain a bottom boundary layer parameterization, but one was added by Halliwell (in preparation) to perform coastal simulations over the West Florida Shelf. It is essentially the same parameterization used for the surface layer, but turned "upside-down". The procedure implemented in HYCOM essentially follows the procedure implemented in the Regional Ocean Model System (ROMS) (Durski et al., 2004) with the exception that radiative fluxes are nonzero at the bottom wherever significant radiation can penetrate to that depth. In this situation, the radiation reaching the bottom is assumed to heat the bottom layer of the model and also provide a destabilizing buoyancy flux that generates turbulence in the bottom boundary layer. This bottom buoyancy flux is significant only in very shallow nearshore regions. Since isopycnic bottom layers are usually much thicker that the bottom boundary layer (BBL) in the deep ocean, use of the BBL parameterization is optional and usually invoked in coastal ocean simulations where σ coordinates provide good surface to bottom resolution (Halliwell, in preparation). When invoked, BBL mixing is only implemented at grid points where at least one vertical coordinate exists within the diagnosed bottom boundary layer thickness above the bottom. Since isopycnic coordinates migrate to resolve the density front on top of dense overflows, tests are underway to determine if the KPP BBL parameterization improves the representation of these flows (Section 2.3).

The three vertical diffusion mixing submodels are capable of resolving both geostrophic shear and ageostrophic wind-driven shear in the upper ocean, which was not possible with the bulk mixed layer of MICOM. Halliwell (2004) demonstrated this by forcing HYCOM with slowly varying monthly climatological forcing in a 30-layer Atlantic Ocean simulation designed so that several layers were available to resolve the surface Ekman layer. The expected Ekman spiral is verified at two model grid points: CRBN in the Caribbean Sea and NAC in the North Atlantic Current (Fig. 3), with the former representing the Trade Wind belt and the latter representing the Westerly Wind belt. Vector velocity relative to velocity at the Ekman layer base (Fig. 3) resemble Ekman spirals, indicating that although geostrophic velocity shear is present in all of the velocity profiles, it is too small to mask the Ekman spiral structure. Differences among the spiral structures are associated with different viscosity profiles calculated by the mixing models (not shown). The central depths of the reference layers can be used as a proxy for Ekman layer thickness for comparison among the cases plotted in Fig. 3, the theoretical Ekman layer thickness being an e-folding scale. At point CRBN, the MY Ekman layer is thicker than the KPP and GISS Ekman layers (67 m versus 41 m reference layer depth) because the MY model produces larger viscosity coefficients. The NAC Ekman layers are equally thick (78 m reference layer depth) for all mixing models and thicker than all of the CRBN Ekman layers. Although the increasing Coriolis parameter acts to reduce Ekman layer thickness toward higher latitudes, the larger viscosity present at point NAC more than compensates for this influence.

To illustrate the performance of two vertical mixing choices in continental shelf simulations, zonal sections of temperature and vertical viscosity coefficient across the West Florida Shelf at 27.55°N are presented for two HYCOM experiments: one using KPP mixing that includes the new bottom boundary layer parameterization and one using MY mixing (Fig. 4). Sections are shown for

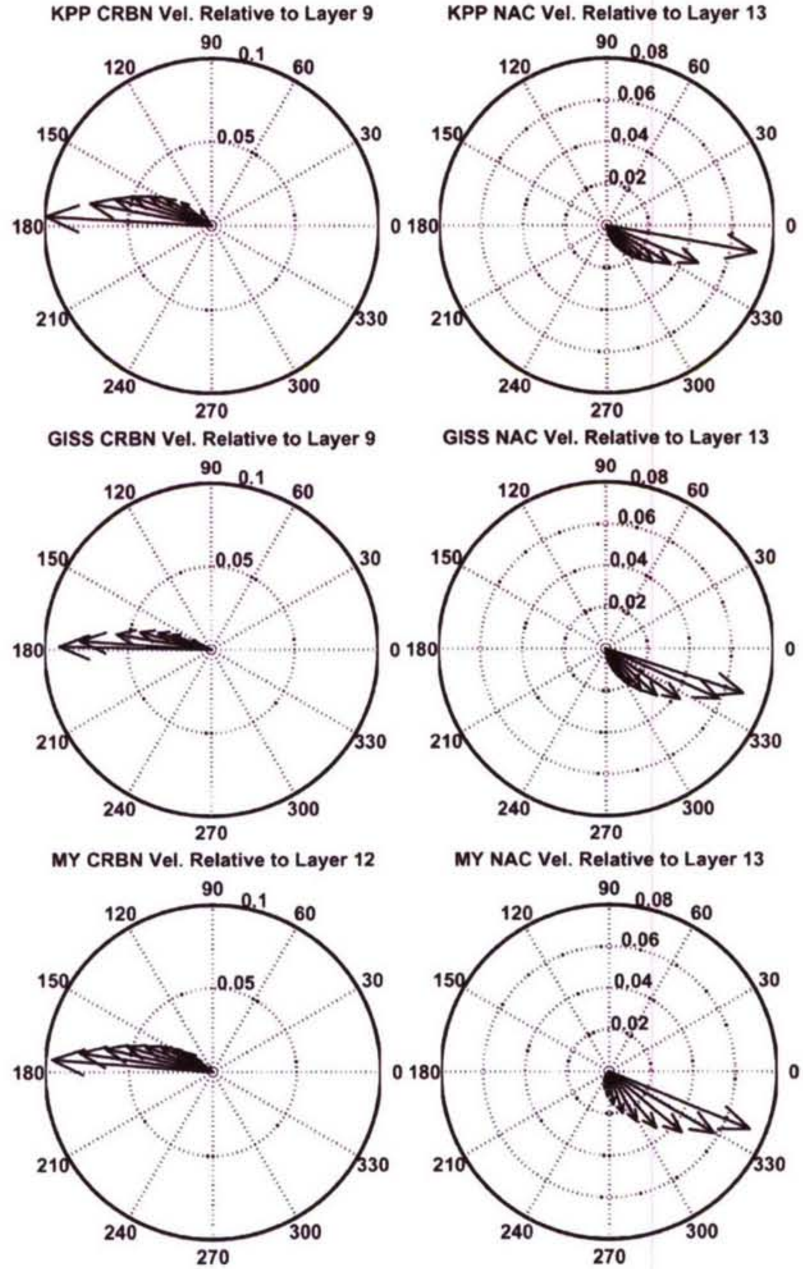

Fig. 3. Winter (mid-February) velocity vectors (m/s) at two model grid points: CRBN (left) and NAC (right) for coarse resolution North Atlantic HYCOM simulations (Halliwell, 2004) using KPP (top), GISS (middle) and MY (bottom) mixing. Vectors are shown for model layers located above a reference layer given in the label for each panel and chosen by inspection to reside at the base of the Ekman layer. The reference layer velocity has been subtracted from all vectors in each panel.

March 22, 2002 when there was a strong upwelling event in the presence of moderate stratification. The magnitude and distribution of vertical viscosity coefficients is broadly similar between the KPP and MY cases, with distinct surface and bottom boundary layers present over the middle and outer shelf. Quantitative differences exist, with weaker turbulence in the bottom boundary layer present in the MY case compared to the KPP case. Stronger nearbottom stratification in the MY case is associated with the weaker turbulence. Offshore, stronger turbulence is produced in the surface boundary layer by MY compared to KPP. This conclusion that the KPP and MY produce qualitatively similar, but quantitatively different turbulence patterns has also been reached in idealized shelf simulations using POM (Wijesekera et al., 2003) and ROMS (Durski et al., 2004).

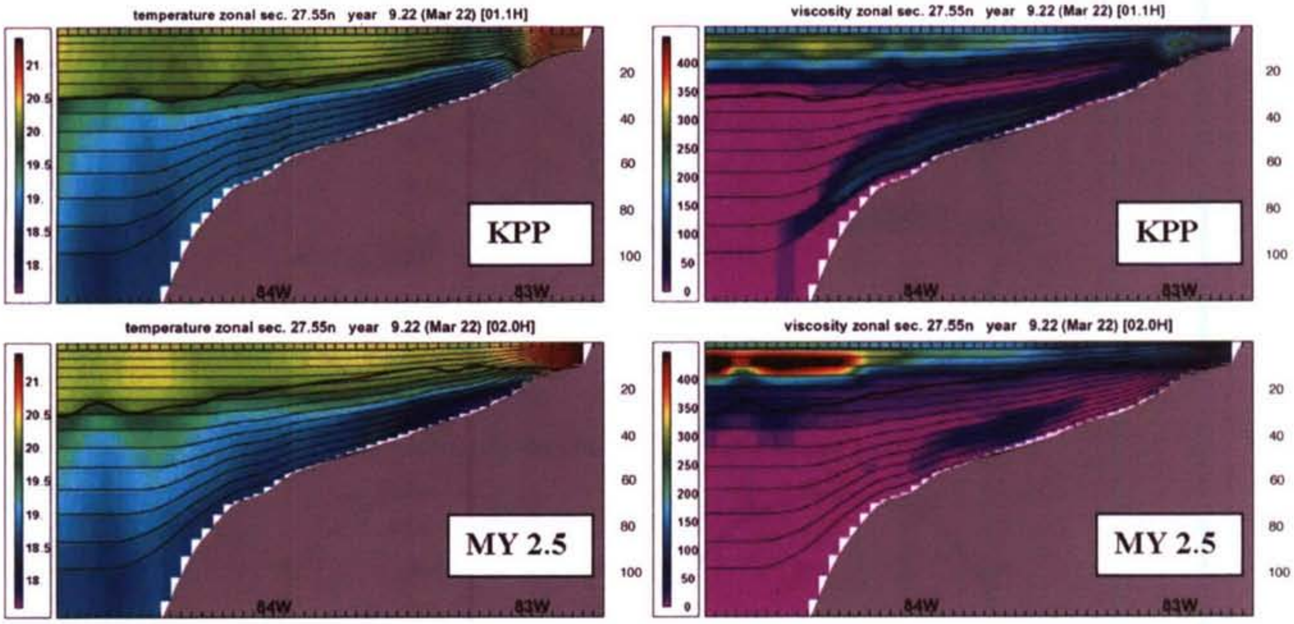

Fig. 4. Temperature (left) and vertical viscosity coefficient (right) in a section across the West Florida Shelf from two simulations: one using KPP mixing with the new bottom boundary layer parameterization (top) and one using MY mixing (bottom).

2.3. Overflows

A proper representation of overflow waters has always been challenging for OGCMs. The primary reason for this difficulty is that most current model configurations utilize horizontal resolutions that cannot explicitly resolve the complex geometry associated with most overflows. A further challenge in the modeling of overflows is that different model formulations have different levels of success in representing them (Griffies et al., 2000). Of particular importance is the model's vertical discretization (DYNAMO; Willebrand et al., 2001). On one hand, terrain-following (σ) coordinates provide the ability to concentrate resolution near the bottom boundaries, and hence can resolve overflow processes quite well (Jungclaus and Mellor, 2000), provided that the vertical and horizontal resolution is sufficiently fine. However, the pressure-gradient errors associated with σ coordinates become large when the topography is steep. Without an explicit representation of the BBL, z- (or p-) coordinate models tend to exhibit unphysically strong entrainment as gravity currents descend, unless both the vertical resolution is fine enough to resolve the BBL thickness (of order tens of meters) and the horizontal resolution can resolve the BBL thickness divided by the slope (of order kilometers) (Winton et al., 1998); resolutions much higher than currently computationally affordable. Isopycnic coordinate models (or hybrid coordinate models that are essentially isopycnic at depth such as HYCOM), on the other hand, have vertical resolution that naturally migrates to the density front atop a gravity current and do not require a deviation from the underlying model framework to capture the structure of the gravity current (Hallberg, 2000). In isopycnic coordinates, there is no numerically induced diapycnal mixing and it is necessary to explicitly parameterize the amount of mixing occurring during entrainment. For example, Fig. 5 shows the colder fresher water forming over the shelf in the Nordic Seas. It spills over the Denmark Strait entraining more saline Irminger Sea water in a 1/12° North Atlantic HYCOM. The default parameterization used for the ocean interior in that simulation is based on the original KPP without BBL parameterization. Comparison to high-order non-hydrostatic spectral element simulations and to the laboratory experiment of Turner (1986) however shows that the interior KPP parameterization (primarily shear instability mixing tuned for the ocean interior) underestimates the amount of mixing that is needed for entrainment, but that the KPP bottom boundary layer parameters can be calibrated to agree with the high-order simulations (Chang et al., 2005), although it is not known if a unique calibration can be found. This is illustrated in Fig. 6 which shows the Mediterranean outflow representation in a 1/12° regional configuration of HYCOM using the original KPP parameterization and one modified to increase mixing in high isopycnal slope regions (courtesy of X. Xu). With the modified parameterization, the Mediterranean outflow finds a neutral depth comparable to that observed (which is too deep with the original KPP). More work, however, is needed to fully develop a physically-

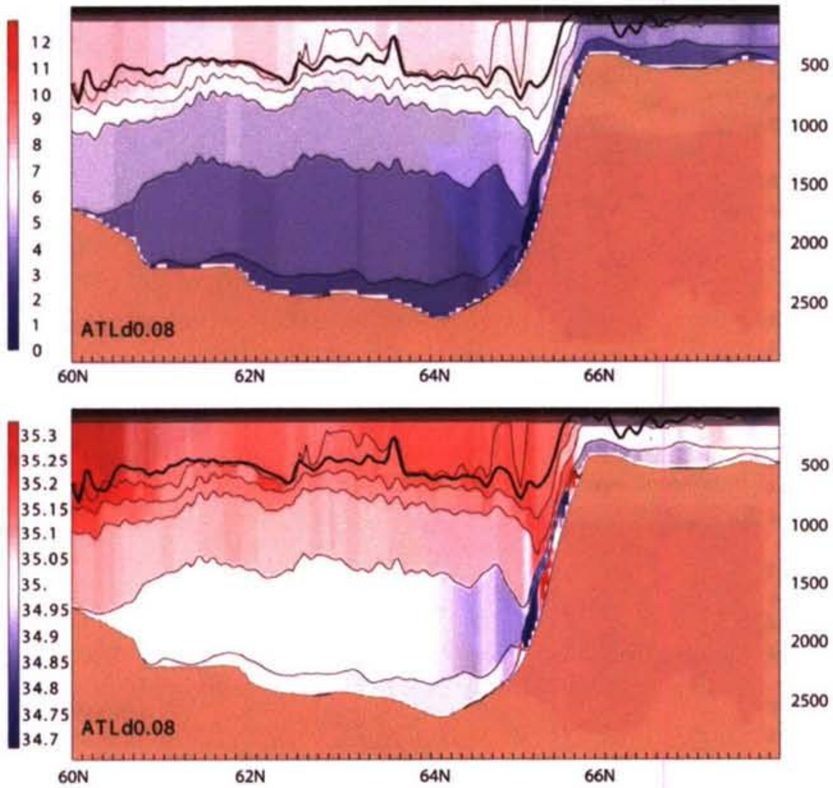

Fig. 5. Example of entrainment in the Denmark Straits overflow along 31°W in a climatologically-forced 1/12° North Atlantic HYCOM: colder fresher water forms over the shelf in the Nordic Seas and spills over the Denmark Strait and entrains more saline Irminger Sea water (top panel: temperature; bottom panel: salinity).

based parameterization that can be used in all regions of high vertical shear.

3. The prototype Atlantic Ocean data assimilative 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 hindcasting and predicting the ocean features of interest. Then the model can act as an efficient dynamical interpolator of the observations. The 1/16° near global Navy Layered Ocean Model (NLOM) is an example of how an ocean model can be a successful dynamical interpolator of surface information in the assimilation of satellite altimetry observations (Smedstad et al., 2003). Shriver et al. (2006-this issue) show that the 1/32° version of NLOM is an even better dynamical interpolator.

Performance of HYCOM in the North and Equatorial Atlantic has been documented by Chassignet et al.

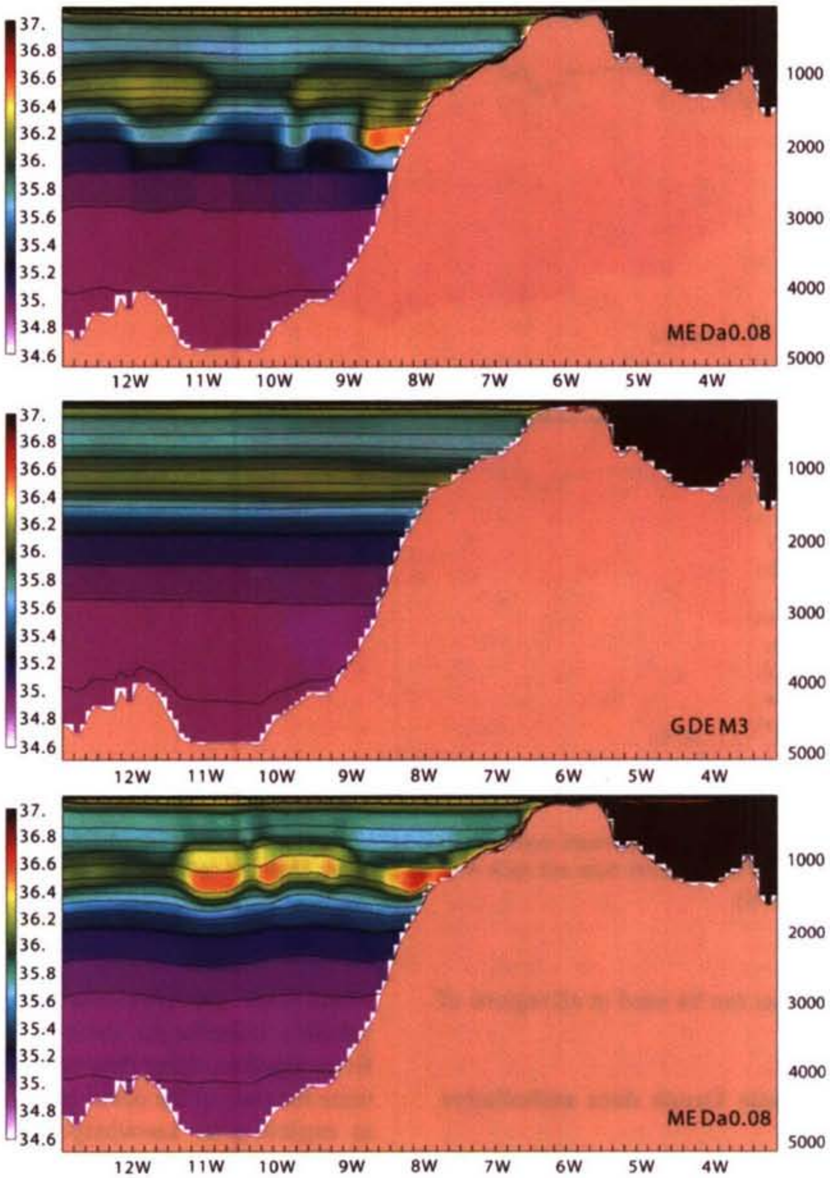

Fig. 6. Mediterranean overflow at 36°N in a 1/12° regional configuration (which includes most of the Gulf of Cadiz, part of the Eastern North Atlantic, and a small part of the Mediterranean Sea): left panels, original KPP; middle panels climatology; right panels, modified KPP. Top panels, temperature; bottom panels, salinity (courtesy of X. Xu).

(2003) within the framework of the Community Modeling Experiment (CME). The near real-time 1/12° (~7 km mid-latitude resolution) HYCOM Atlantic Ocean data assimilative system (http://hycom.rsmas.miami.edu/ocean_prediction.html) spans from 28°S to 70°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 σ-levels and the coastline is at the 10 m isobath. The northern and southern boundaries are treated as closed, but are outfitted with 3° 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 3 h) are presently provided by the FNMOC Navy Operational Global Atmospheric Prediction System (NOGAPS), available from NAVOCEANO and the U.S. GODAE data server in Monterey. The HYCOM data assimilative system uses surface wind stress, air temperature, and specific humidity (from dew point temperature and sea level pressure) in addition to shortwave and longwave radiation. Surface heat flux is

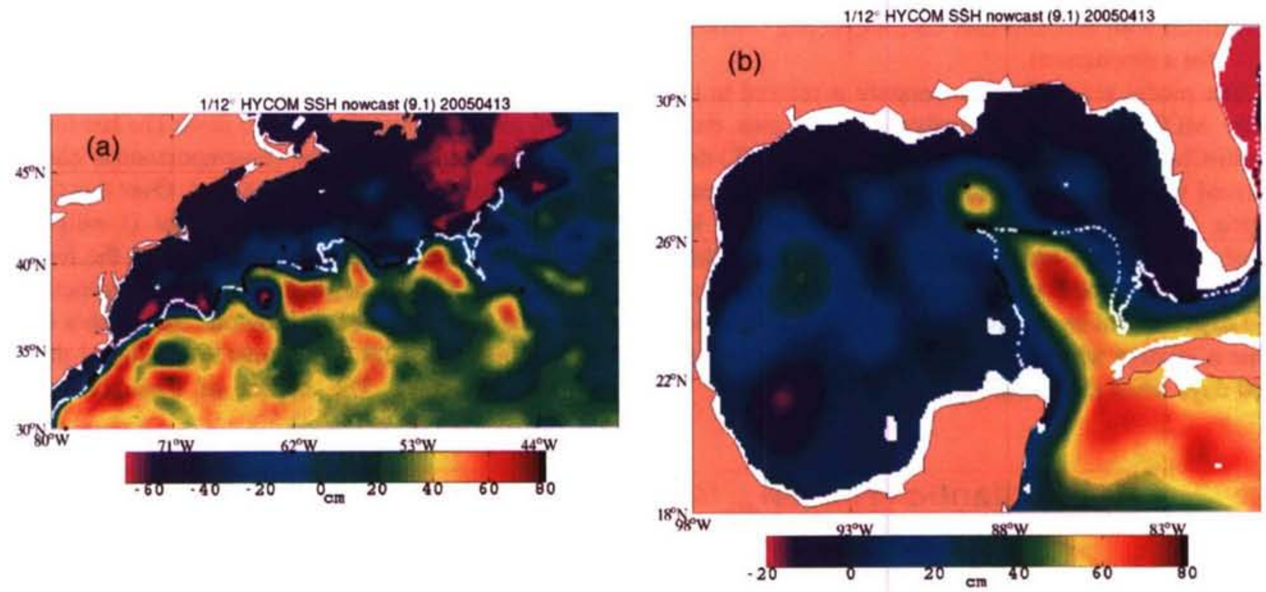

Fig. 7. (a) The sea surface height from the 1/12° Atlantic HYCOM in the Gulf Stream region on April 13, 2005. (b) The sea surface height from the 1/12° Atlantic HYCOM in the Gulf of Mexico region on April 13, 2005. Overlain is an independent frontal analysis of high resolution MCSST observations performed at NAVOCEANO. The frontal position is marked in black if the observations are more than 4 days old. There is a very good agreement between the model frontal location and the one determined from the MCSST frontal analysis.

calculated via a bulk parameterization from the NOGAPS fields and model SST. The model was spun-up for 3 years starting from the end of a previous 1/12° North Atlantic simulation performed with the MICOM (Chassignet and Garraffo, 2001).

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 assimilation techniques. For our current 1/12° North 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. The basic principle behind Cooper and Haines (1996) is conservation of the subsurface potential vorticity during the assimilation time step. The implementation in HYCOM follows that of Hoang et al. (1997) for MICOM, i.e., (1) there is a reference isopycnal in the deep ocean below which the Montgomery potential is unmodified by the vertical projection of the SSH correction, (2) the subsurface potential vorticity is conserved by displacing homogenously the coordinate interfaces below the mixed layer and above the reference isopycnal, and (3) the geostrophic relation is used to calculate the velocity increments (except in the equatorial band where no velocity increments are computed).

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). Before one can assimilate the SSH anomalies determined from the satellite altimeter data, it is necessary to know the oceanic mean SSH over the time period of the altimeter observations. Unfortunately, the geoid is not presently known accurately on the mesoscale. Several satellite missions are either underway or planned to try to determine a more accurate geoid, but until the measurements become accurate to within a few centimeters on scales down to approximately 30 km, one has to define a mean oceanic SSH. At the scales of interest (tens of kilometers), it is necessary to have the mean of major ocean currents and associated SSH fronts sharply defined. This is not feasible from coarse hydrographic climatologies (~1° horizontal resolution) and the approach taken by the HYCOM data assimilative system has been to use a model-derived mean SSH. This requires a fully eddy-resolving ocean model which is consistent with hydrographic climatologies and with fronts in the correct position. The HYCOM-based system uses the model mean generated by a previous 1/12° North Atlantic simulation performed with MICOM (see Chassignet and Garraffo, 2001 for a discussion).

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 e-folding relaxation time is a function of the mixed layer depth (30 days × mixed layer depth/20 m) so that the relaxation time is 30 days when the mixed layer depth is 20 m and 300 days when the mixed layer depth is 200 m.

The system runs once a week every Wednesday and consists of a 10-day hindcast and a 14-day forecast. The atmospheric forcing for the 14-day forecasts gradually reverts toward climatology after 5 days. The last forecast record is weighted with the contemporaneous climatological values over a 10 day time span. Over that time, a linearly decreasing (increasing) weight (1-weight) is used for the forecast (climatology). During the forecast period, the SST is relaxed toward climatologically-corrected persistence of the nowcast SST with a relaxation time scale of 1/4 the forecast length (i.e., 1 day for a 4-day forecast). The impact of these choices is

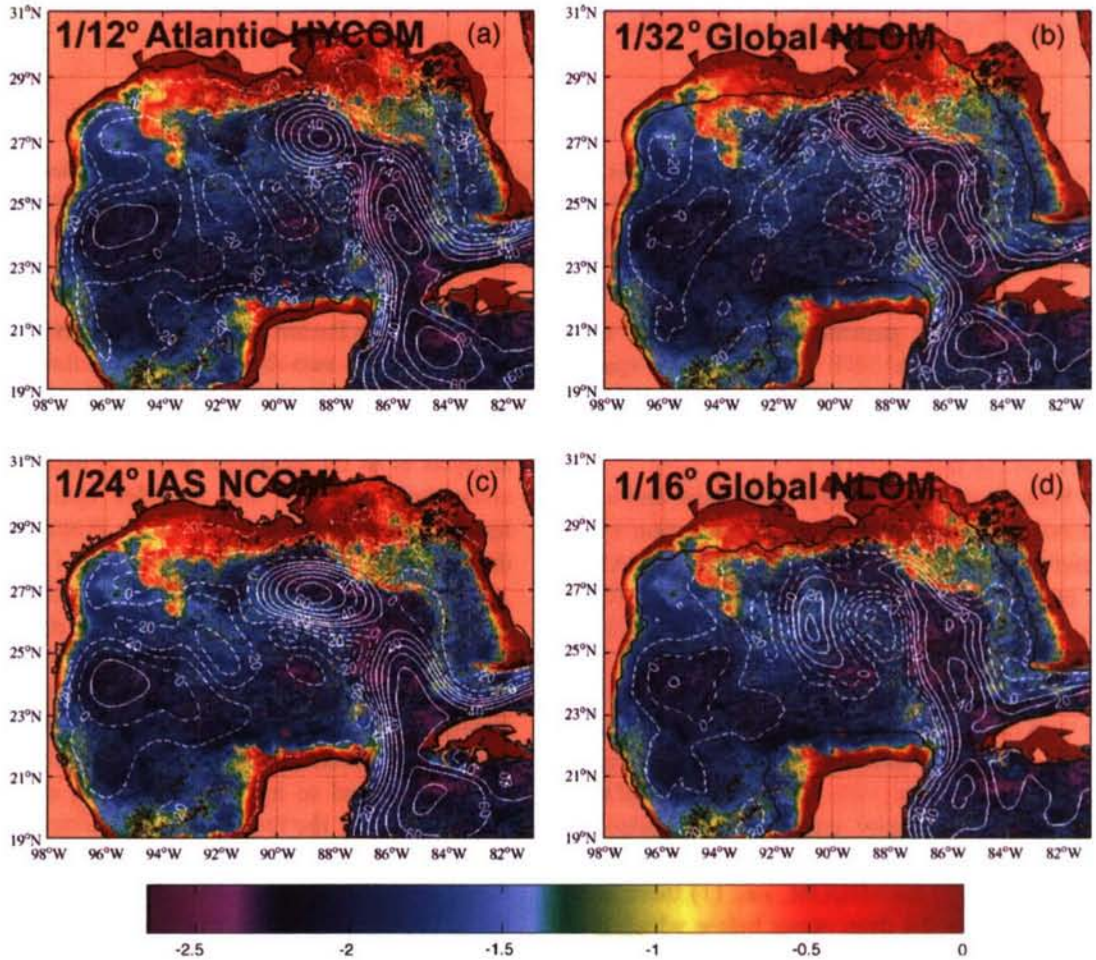

Fig. 8. The sea surface height (contour interval of 10 cm) in the Gulf of Mexico from four different real-time or near real-time systems overlain on the SeaWiFS chlorophyll concentrations on August 8, 2003. Red/yellow colors indicate areas with high concentration, while the darker blue color represents areas with low concentrations. With most of a previously detached ring reattached, the Loop Current is elongated and extends quite far to the west and to the north. Both HYCOM 1/12° and the global NLOM 1/32° do a good job at capturing the full northwestward extent of the Loop Current. There are some small differences in the representation of the recaptured Loop Current ring; the ring in HYCOM 1/12° is still showing closed SSH contours with a signature slightly farther north. Both HYCOM 1/12° and NLOM 1/32° fail to correctly place the eastward frontal position of the Loop Current, which is well delineated by high chlorophyll in the observations. In the global NLOM 1/16°, the ring did not remain attached and moved westward of 90°W. The Loop Current position is however reasonably well represented east of 88°W. In the 1/24° Navy Coastal Ocean Model (NCOM) configured for the Intra-Americas Sea (IAS), the Loop Current is in generally the right location, except that it does not penetrate far enough northward and the recaptured ring is too far south by half a degree.

discussed by Smedstad et al. (2003) and Shriver et al. (2006-this issue).

3.1. Evaluation

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 (Le Provost et al., 2002) as well as the validation tests commonly used at the operational centers before official transition to operational use.

Furthermore, within GODAE, the Atlantic Ocean has been chosen as a pilot project for an inter-comparison of different ocean data assimilative systems, including tests and evaluation of the inter-comparison process. The Atlantic was chosen because of the developmental status of the required components of an ocean forecasting system: already well instrumented, large number of available models, high user interest. The comparison exercise took place within the framework of MERSEA (Marine EnviRonment and Security for the European Area) funded by the European Union and consisted of comparing similar diagnostics and fields from corresponding realizations of several systems (MERCATOR, FOAM, MFS, TOPAZ, and HYCOM) (Crosnier and Le Provost, 2006-this issue). In the remainder of this section, we provide evaluation examples for the HYCOM Atlantic forecasting system that differ from the ones discussed by Crosnier and Le Provost (2006-this issue).

Examples of assessments of the models' ability to represent observed flow features can be seen in Figs. 7a, b and 8. These tests qualitatively evaluate model analyses against alternate, unassimilated observations of flow features in regions of interest. Fig. 7a and b show the model SSH hindcast on April 13, 2005 for the Gulf Stream region and the Gulf of Mexico region. Overlain on the SSH is an independent frontal analysis of SST data. Close examination of the figures on this date and others (see HYCOM web site for movies) shows overall a very good agreement between the model frontal structures and the independent SST observations. Comparisons of surface height and temperature with ocean color imagery can also at times provide clear and dramatic qualitative model assessment (Chassignet et al., 2006).

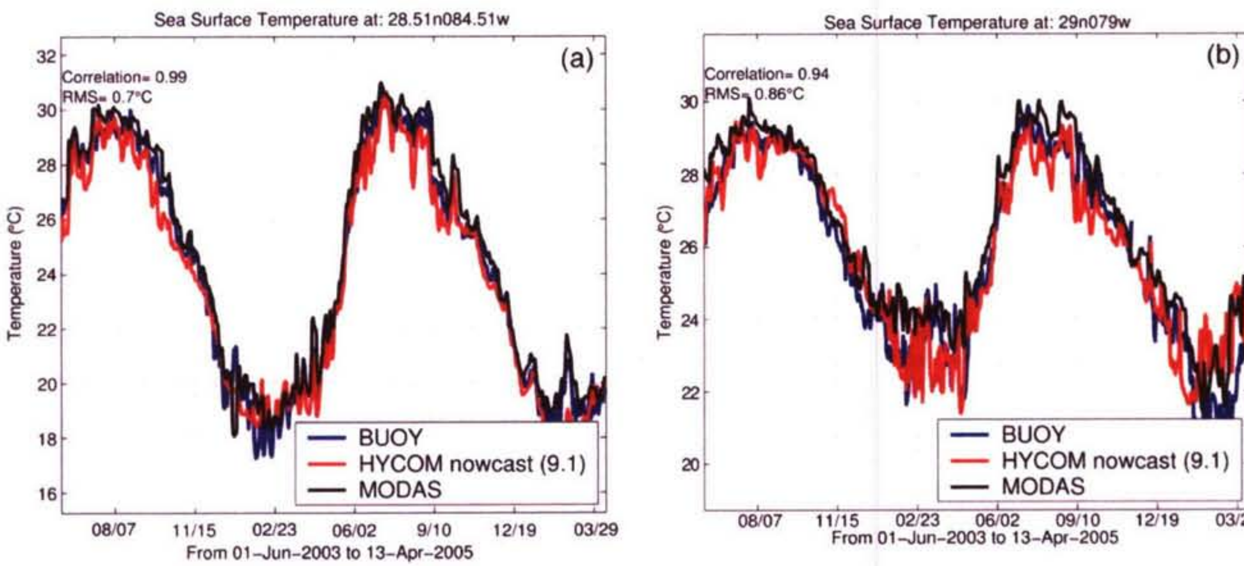

Fig. 9. Comparison between buoy observations of SST (blue), the 1/12° North Atlantic data assimilative system (red), and MODAS (black) at (a) 28.51°N, 84.51°W and (b) 29°N, 79°W.

Fig. 8 illustrates the value of SeaWiFS ocean color imagery in assessing the ability of four ocean prediction systems to map mesoscale variability in the Gulf of Mexico and in helping to diagnose specific strengths and weaknesses of the systems. Dark areas (chlorophyll poor) are found in the interior of the Loop Current and a semi-detached eddy, while light areas (chlorophyll rich) such as the Mississippi River plume outline the eastern edge of the eddy and the northern Loop Current. The results clearly illustrate nowcast accuracy differences in the positioning of the Loop Current and in representing the eddy by the four prediction systems (see Fig. 8 and Chassignet et al., 2006 for details).

In order to evaluate whether the models are producing acceptable nowcasts and forecasts of sea surface temperature, the near real-time system is also routinely compared to unassimilated buoy time series of SST. Fig. 9 shows two examples; the first (Fig. 9a) is a buoy in the northern part of the Gulf of Mexico, while the second one (Fig. 9b) is a buoy off the east coast of Florida in the Atlantic Ocean. Time evolutions of the model hindcast SST compare well to the independent buoy measurements and to the MODAS SST (the latter is not surprising since the MODAS SSTs are assimilated).

Since the North Atlantic system assimilates only surface quantities (SSH, SST), quantitative comparison of model temperature and salinity to unassimilated profile data from XBTs, CTDs, and ARGO floats, and moored buoys allow us to assess system performance in the ocean interior, including the skill in projecting surface data downward. Two good examples of profiles are shown in Fig. 10, one from an ARGO profile at 5.4°S and 6.9°W (Fig. 10a) and one from a PIRATA buoy at 10°N and 10°W (Fig. 10b). Model temperature sections can also be compared to XBT measurements as shown in Fig. 11 for the Marine Environmental Data Service (MEDS) data set. A quantitative assessment can then be performed by looking at the RMS difference between the model and data profiles. Fig. 12 shows that, with only surface data assimilation, the version of the

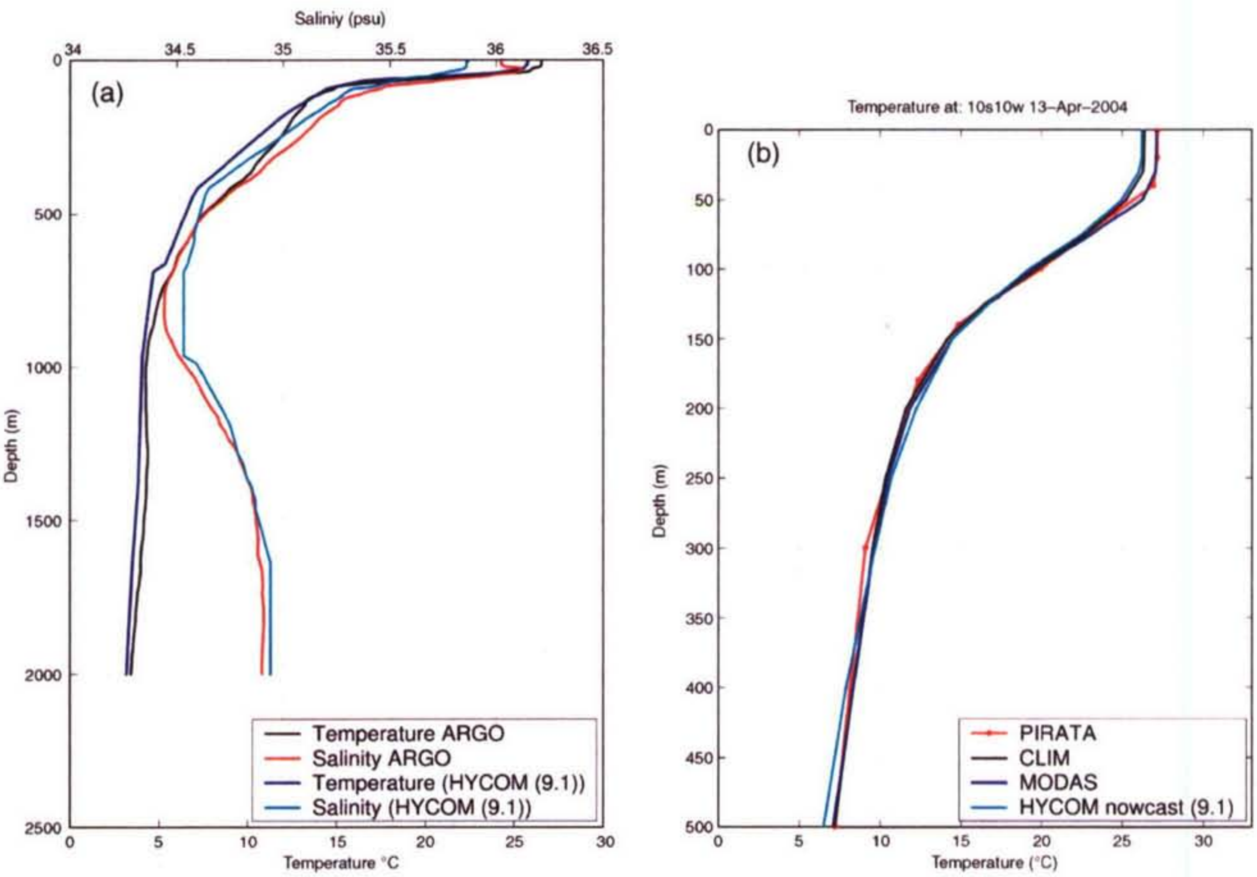

Fig. 10. (a) Temperature and salinity profiles from ARGO at 5.4°S and 6.9°W compared to the 1/12° near real-time Atlantic system on January 15, 2004. The ARGO temperature profile is in black, the salinity profile in red. The corresponding model profiles are in blue (temperature) and cyan (salinity). (b) Temperature profiles from PIRATA at 10°N and 10°W on April 13, 2004. The PIRATA profile is in red, the corresponding model profile in cyan, the climatological profile in black and the MODAS-3D profile in blue.

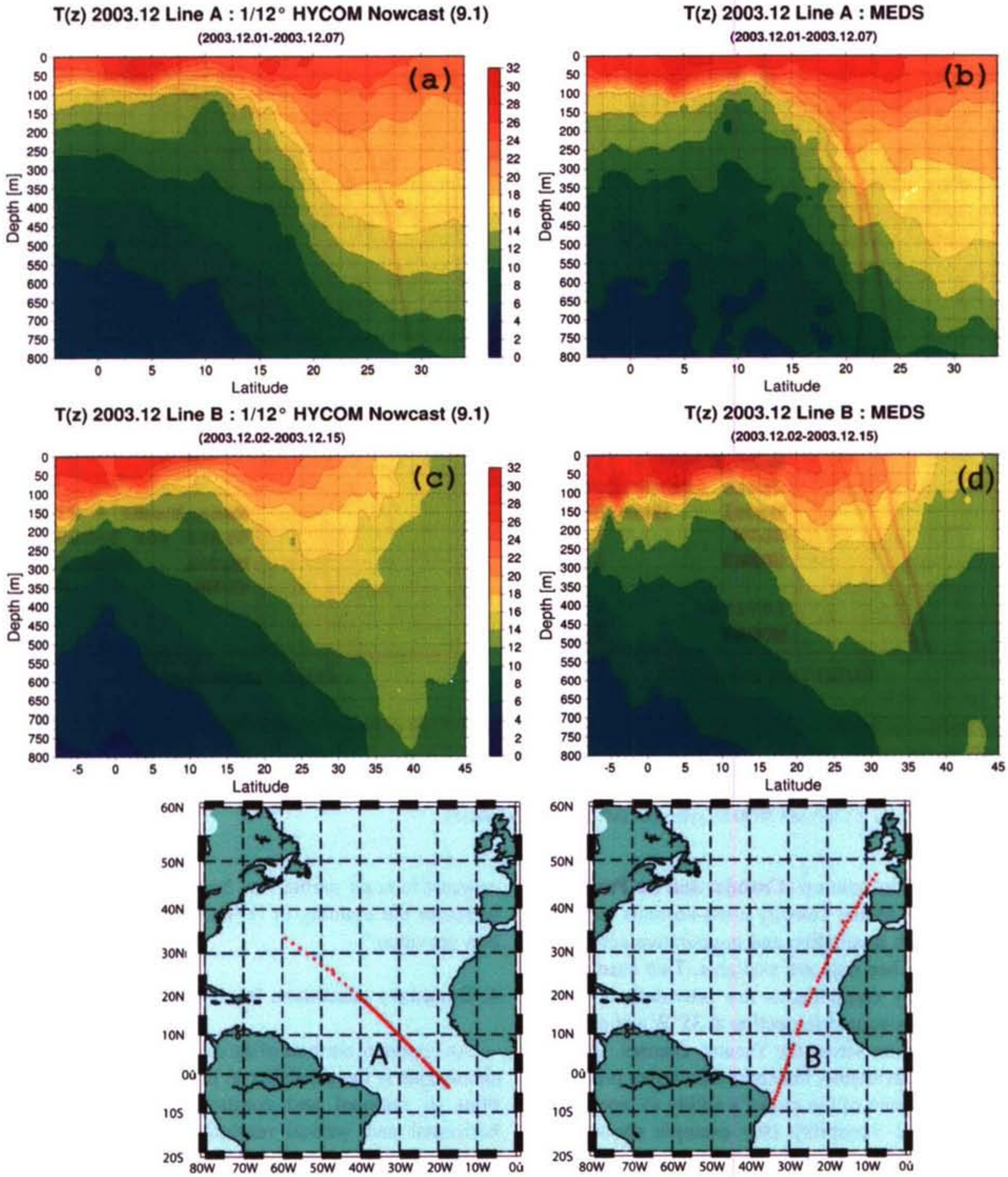

Fig. 11. (a) Temperature section along line A from the 1/12° near real-time Atlantic system, (b) corresponding section from the MEDS data, (c) temperature section along line B from the 1/12° near real-time Atlantic system, (d) corresponding section from the MEDS data.

Atlantic HYCOM prediction system presented here has overall a greater nowcast RMS error than climatology or MODAS-3D. MODAS-3D (Fox et al., 2002) uses the statistics of the historical hydrographic database 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. This is also indicative of the drift in T and S that

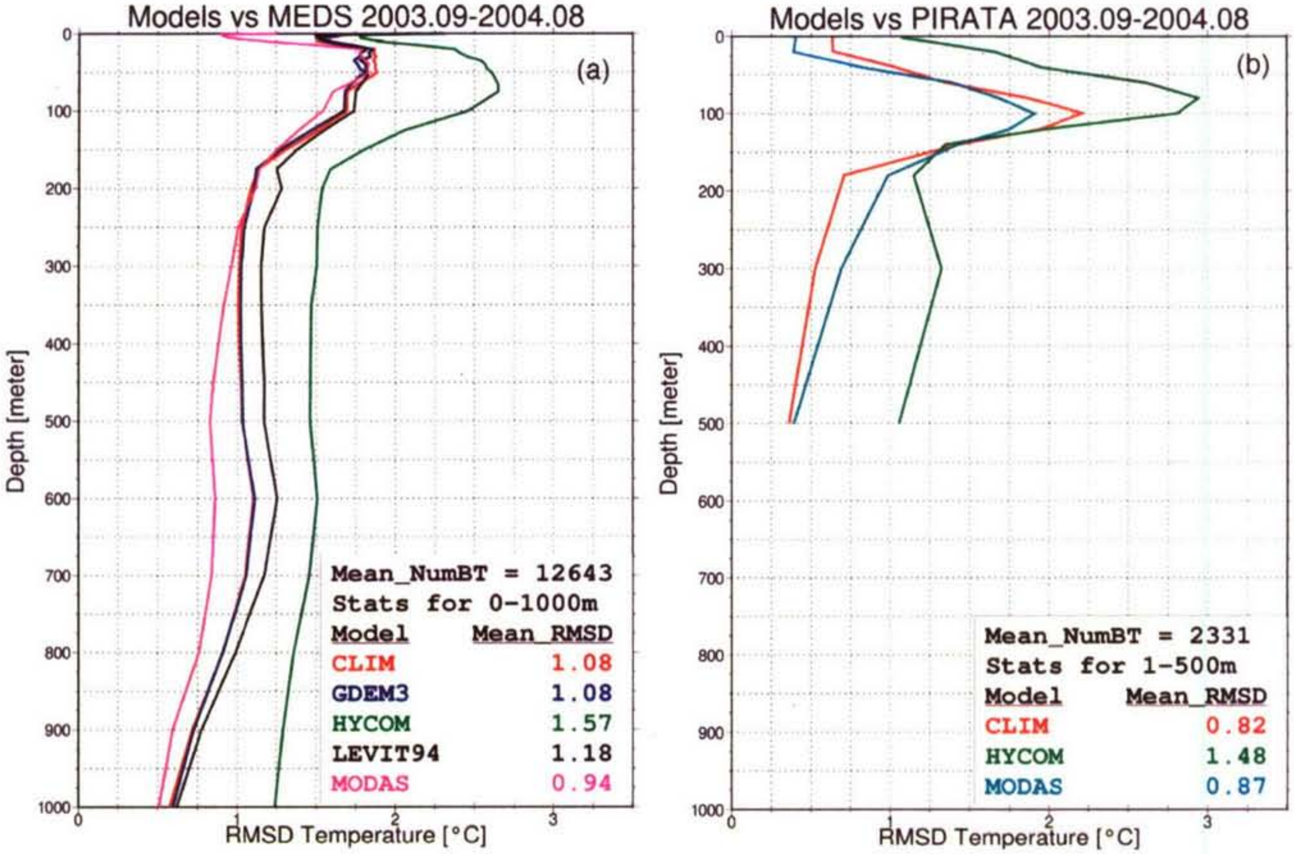

Fig. 12. (a) Statistics for September 2003 through August 2004 between the 1/12° HYCOM system and available Marine Environmental Data Service (MEDS) profile observations. The RMS difference between the MEDS data and different climatologies, MODAS climatology (CLIM), MODAS synthetics (MODAS), Levitus et al. (1994), and the Generalized Digital Environmental Model (GDEM3) is also shown. (b) Statistics for September 2003 through August 2004 between the 1/12° HYCOM system and available PIRATA profile observations. The RMS between the PIRATA data and the MODAS climatology (CLIM) and MODAS synthetics (MODAS) is also shown.

occurred during the spin-up (Crosnier and Le Provost, 2006-this issue). Model velocity cross-sections can be evaluated through qualitative and quantitative comparisons of biases when data are available. Two examples of mean velocity comparisons are provided: one in Fig. 13 for a cross-equatorial section at 35°W and one in Fig. 14 for a section across the Yucatan channel. 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 Fig. 15 for the Florida Straits).

3.2. Model outputs

The near real-time North Atlantic basin model outputs are made available to the community at large within 24 h 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. Boundary conditions for regional models

An important attribute of the data assimilative HYCOM simulations is the capability to provide boundary conditions to regional and coastal models. The chosen horizontal and vertical resolution for the forecasting system marginally resolves the coastal ocean (7 km at mid-latitudes, with up to 15 terrain-following (σ) coordinates over the shelf), but is an excellent starting point for even higher resolution coastal ocean prediction systems. To increase the predictability of coastal regimes, several partners within the HYCOM consortium are therefore 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

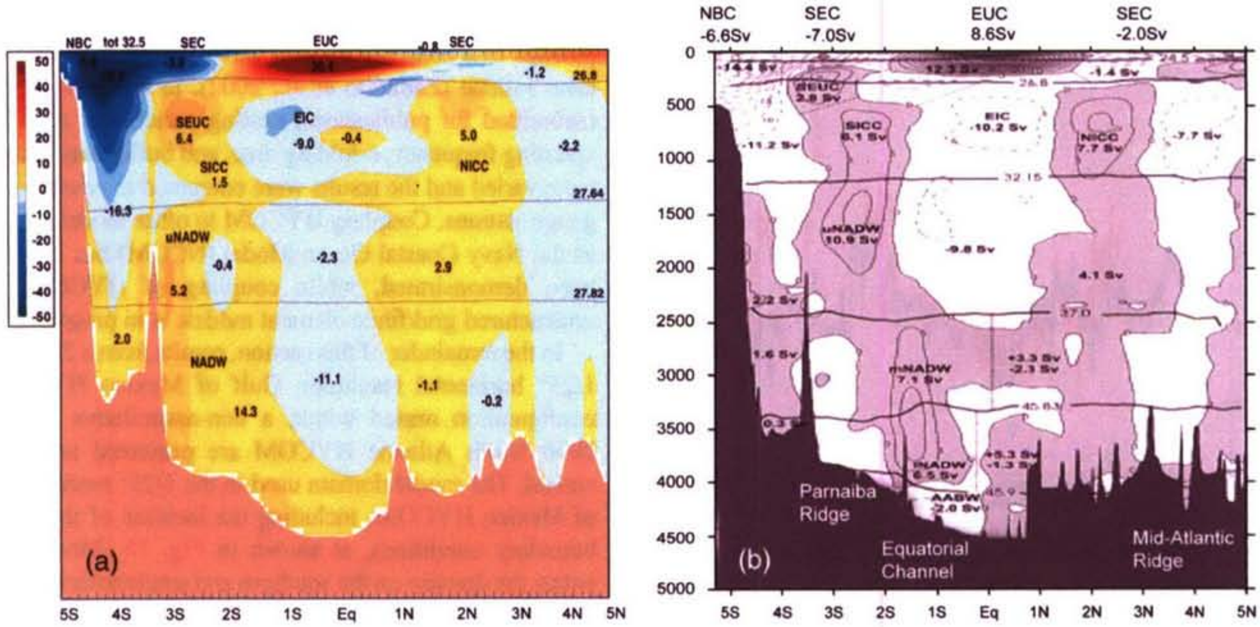

Fig. 13. (a) Vertical section of the mean velocity across the Equator at 35°W from 5°S to 5°N from the 1/12° Atlantic system over the time period of September 2003 through August 2004. (b) Observations of transports across the Equator at 35°W (Schott et al., 2003).

coastal models needs to be able to handle unlike vertical grids. Coupling HYCOM to HYCOM is now routine via one-way nesting. Outer model fields are interpolated to the horizontal mesh of the nested model throughout the entire time interval of the nested model simulation at a time interval specified by the user, typically once per day in our evaluations to date, and stored in HYCOM archive format. Layers can be added to these archive files to

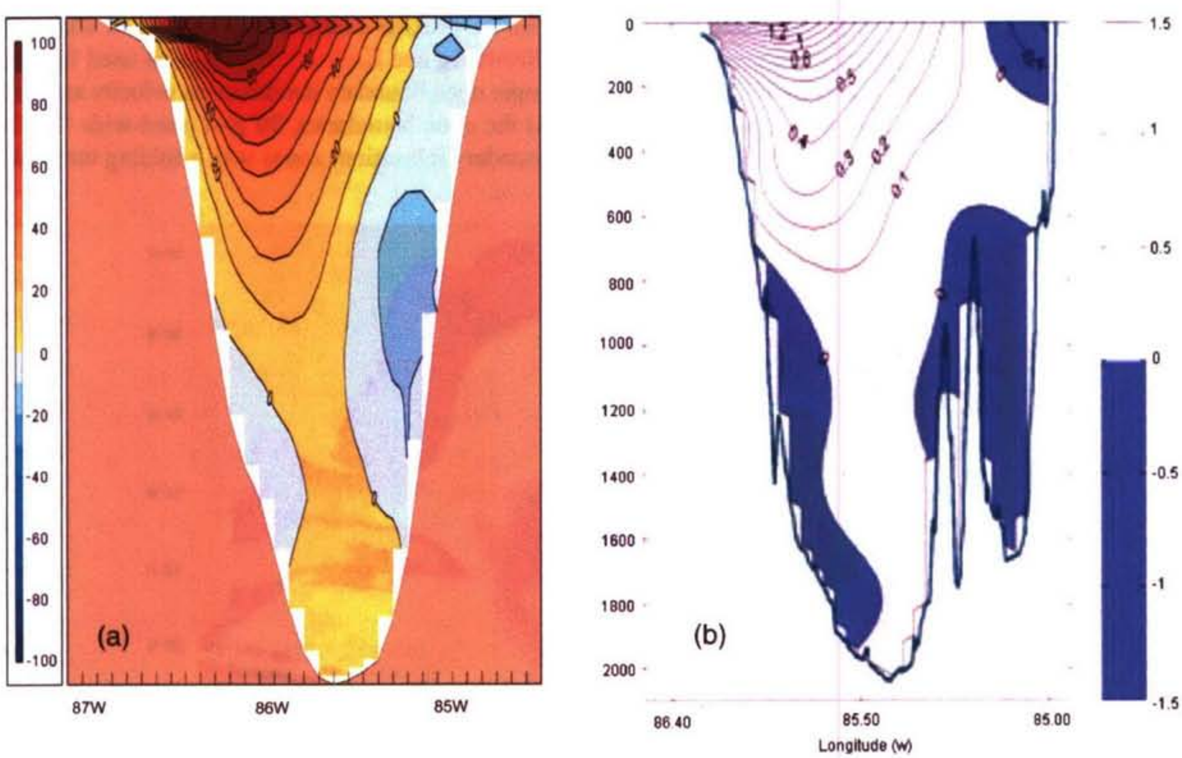

Fig. 14. (a) Vertical section of the mean velocity across the Yucatan Channel from the 1/12° Atlantic system over the time period of September 2003 through August 2004. (b) Observations of velocities from Abascal et al. (2003).

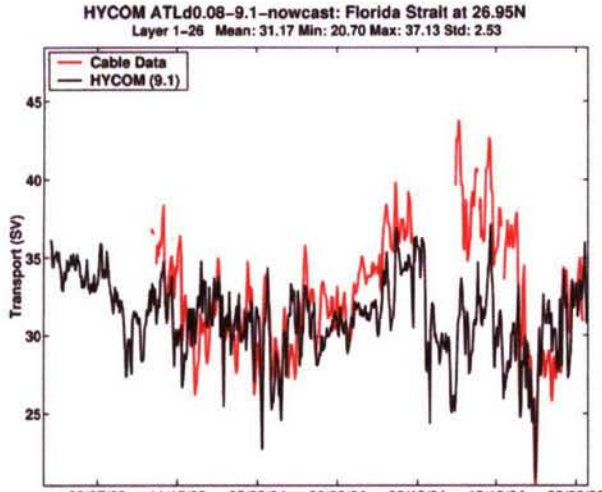

Fig. 15. The transport in the Florida Current at 27°N from the 1/12° Atlantic near real-time system is in black. Observed transport variations in the Florida Current are being monitored by measuring the cross-stream voltages using an undersea cable between Florida and the Bahamas. Daily transport data are available from March 1982 to October 1998, and from March 2000 onward (Baringer and Larsen, 2001). Observations from the cable data are shown in red.

increase the vertical resolution of the nested model and insure that there is sufficient vertical resolution to resolve the bottom boundary layer. The nested model is initialized from the first archive file and the entire set of archives provides boundary conditions during the nested run, insuring consistency between initial and boundary conditions. This procedure has proven to be very robust. Nested Gulf of California simulations (Zamudio et al., submitted for publication) were used to investigate the ability of the existing HYCOM nesting capability to allow accurate passage of a coastally trapped wave generated by Hurricane Juliette (Zamudio et al., 2002). In Zamudio et al. (submitted for publication), nesting parameters such as updating frequency, e-folding time, and buffer zone width were varied and the results were compared to coastal tide gauge stations. Coupling HYCOM to other models, such as the Navy Coastal Ocean Model (NCOM) has already been demonstrated, while coupling of HYCOM to unstructured grid/finite element models is in progress.

In the remainder of this section, results from a 20-layer 1/25° horizontal resolution Gulf of Mexico HYCOM configuration nested within a non-assimilative 1999–2000 North Atlantic HYCOM are presented and discussed. The model domain used in the 1/25° nested Gulf of Mexico HYCOM, including the location of the open boundary conditions, is shown in Fig. 16. Most flow enters the domain on the southern and southeastern boundaries and exits through the Florida Strait. Currently the nesting of HYCOM to HYCOM is one-way (information is only passed from the outer grid to the inner grid) and "off-line", meaning that the nested model does not run concurrently with the outer model. An advantage of this approach is that the nested region does not need to be known in advance, but a disadvantage is that the updating frequency of the boundary information is limited by how often outer grid model output is archived. In this nested Gulf of Mexico example, the method of characteristics (Browning and Kreiss, 1982, 1986) is used for the barotropic open boundary condition on velocity and pressure. At the open boundaries, 20 grid point-wide "buffer" (or boundary relaxation) zones with e-folding times of 0.1 to

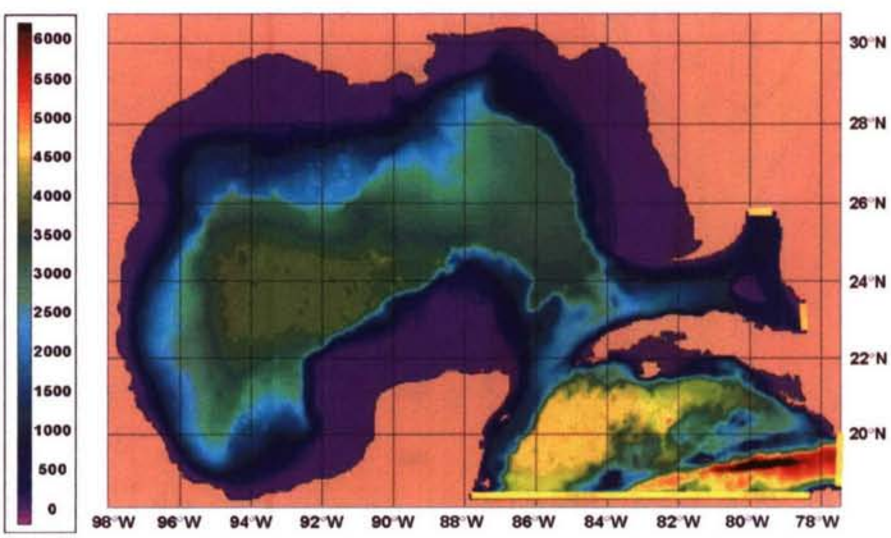

Fig. 16. Bathymetry used in the 1/25° nested Gulf of Mexico simulation. The yellow lines indicate the locations of the open boundaries that are updated from a 1/12° Atlantic HYCOM simulation.

10 days (outer to inner grid) are used to relax the baroclinic mode temperature, salinity, pressure and velocity components once per baroclinic time step towards a non-assimilative interannually forced 1/12° Atlantic HYCOM solution that is linearly interpolated in time. Although the buffer zone is located on the fine grid mesh, the bottom topography and aforementioned variables are constrained to the coarse outer grid solution and thus should be considered part of the boundary condition, not part of the fine inner grid solution. Concurrent 6-hourly NOGAPS was used for surface forcing in both the nested Gulf of Mexico model and the interannually forced 1/12° Atlantic HYCOM simulation.

Compared to similar 1/12° simulations, the 1/25° simulation shows that the higher resolution results in more realistic cyclonic eddies that often are associated with the Loop Current and Loop Current eddies in terms of eddy size, speed, population, and vertical structure. Fig. 17 depicts the sea surface height (top panel) and sea surface salinity (bottom panel) on June 13, 2000 (although this is a non-assimilative simulation and so the ocean state is not representative of the Gulf of Mexico on that day). At this time, the Loop Current Extension reaches almost 28°N and there is a relatively strong cyclone on its eastern flank at about 25°N. This cyclonic eddy plays a role in the Loop Current shedding an anticyclonic ring the following month (not shown). Several of the cyclonic eddies travel along the Florida Keys and then exit the Gulf of Mexico through the Florida Straits. The surface salinity shows an area of relatively fresh water just north of the Yucatan Peninsula (88°W, 22°N). This is an area of prolific upwelling during June, and it may be associated with the southward Yucatan Undercurrent (Merino, 1997; Ochoa et al., 2001), although Cochrane (1968, 1969) suggested

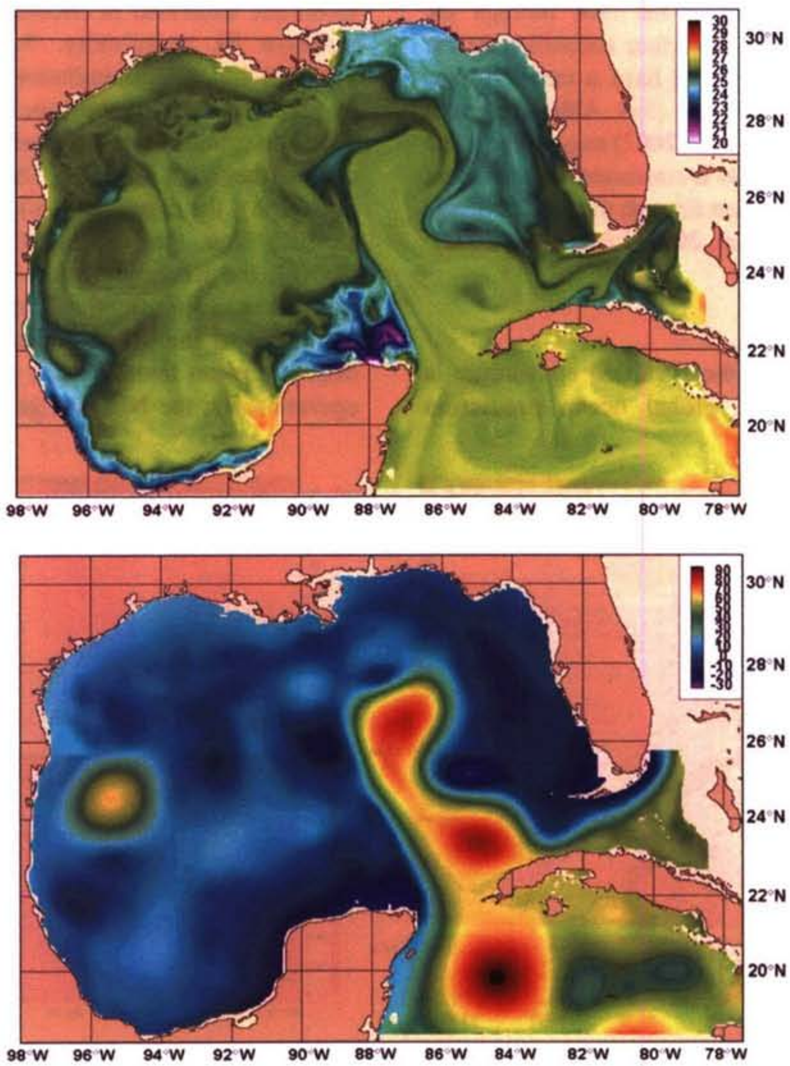

Fig. 17. Sea surface height (top panel) and salinity (bottom panel) on June 13, 2000 from the nested 1/25° simulation.

that bottom friction of the strong Yucatan Current against the slope on the eastern edge of the Yucatan Shelf caused the upwelling instead.

An example of the vertical structure of the anticyclonic Loop Current and associated cyclonic eddies on June 1, 2000 is shown in Fig. 18. At this time the Loop Current extends to about 28°N and has cyclones on both the western and eastern flanks. A zonal cross-section of the south to north (v) component of velocity and the salinity are also shown in Fig. 18. The eddy on the eastern flank is propagating along the continental slope but in this case the core of the eddy does not propagate onto the shelf. The salinity depicts a subsurface salinity maximum in the center of the anticyclone, consistent with observations. In all of the nested Gulf of Mexico simulations, realistic flow through the southern boundary (about 4° south of the Yucatan Channel) from the 1/12° Atlantic HYCOM is critical for realistic Loop Current Eddy shedding in the Gulf of Mexico. In particular, the flow through the Yucatan Channel needs to be surface intensified on the western side of the channel and have a mean volume transport of about 28 Sverdrups (Sv). Although recent measurements (Sheinbaum et al., 2002) suggest the value may be lower than this, 28 Sv is consistent with the more extensively observed transport through the Florida Straits at 27°N (Baringer and Larsen, 2001; Johns et al., 2002).

5. 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. The present near real-time system as described in this paper is a first step towards the fully global 1/12° HYCOM data assimilative system. Development of the global 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. The size of the problem makes it very difficult to use sophisticated assimilation techniques since some of these methods can increase the cost of running the model by a factor of 100. The strategy adopted by the consortium is to start with a simple data assimilation approach such as the Cooper-Haines technique described in Section 4, and then gradually increase its complexity. Several of these more sophisticated data assimilation techniques are already in place and are in the process of being evaluated. These techniques are, ordered by degree of sophistication, the NRL 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. This does not mean that all these techniques will be used operationally: the NCODA and SEEK techniques are

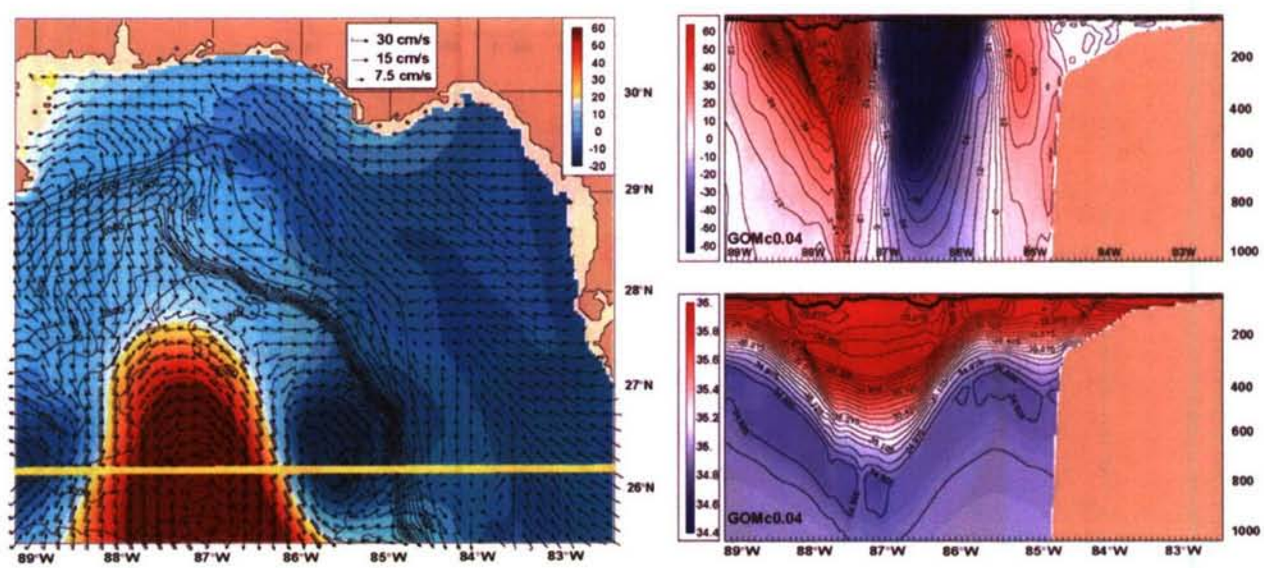

Fig. 18. Northeast Gulf of Mexico zoom-in of sea surface height (color), surface currents (vectors) and bottom topography (black line contours) (left panel) and cross-sections of v-component of velocity (top right) and salinity (bottom right) from the nested 1/25° simulation on June 1, 2000.

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.

The 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-Poy et al., 2001). For both schemes, the analysis step is multivariate in nature, i.e., all model state variables are modified in a consistent manner after the analysis step. In the SEEK filter, the dominant eigenvectors describing the model variability can be used to specify the initial background error covariance matrix in decomposed form. This leads to fully three-dimensional, multivariate dynamically consistent corrections (see Parent et al., submitted for publication for an application of the SEEK filter to the North Atlantic configuration of Section 4). The ROIF method factors the covariance functions into horizontal and vertical components and represents the correction field *implicitly*, using techniques transplanted from statistical mechanics (Gaussian Markov Random Field). The implicit technique tends to allow a highly efficient way to represent smaller scale dynamic modes. The reduced order aspect of ROIF refers to the fact that the information matrix is approximated as a banded matrix. This allows more realistic tails for the correlation functions than similarly approximating the error covariance matrix.

Finally, another Atlantic configuration is under development to form the backbone of the NOAA/NCEP/MMAB North Atlantic Ocean Forecast System (NAOFS). It mostly differs from the system described in Section 4 in two ways: (a) different horizontal grid and (b) NCEP-based wind and thermal forcing. By taking advantage of the general orthogonal curvilinear grid in HYCOM, the NOAA/NCEP group is using a configuration which, for the same number of grid points as in the regular Mercator projection used in the present 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 than toward the east and southeast (7–13 km).

Acknowledgments

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Appendix A. Controlling minimum layer thickness in the hybrid coordinate generator

The HYCOM vertical grid is controlled by reference isopycnals and the minimum thickness permitted for each layer k:

$$\delta_k = \left\{ \begin{array}{ll} \max[\delta_{2k}, \min(\delta_{1k}, \delta_s)] & (1 \le k \le N_s) \\ \delta_{1k} & (k > N_s) \end{array} \right\} \tag{1}$$

where

$$\delta_{1k} = \left\{ \begin{array}{ll} \min(\delta_1^{\max}, \delta_{11}\alpha_1^{(k-1)}) & (1 \le k \le N_i) \\ \delta_{\text{int}} & (k > N_i) \end{array} \right\}, \tag{2}$$

$$\delta_{2k} = \min(\delta_2^{\max}, \delta_{21}\alpha_2^{(k-1)}), \tag{3}$$

$\delta_s = D/N_s$, D is water depth, and N_s is the number of layers below the surface permitted to transition to σ coordinates in shallow water. To estimate δ_{1k} and δ_{2k}, the minimum thicknesses of layer 1 (δ_{11} and δ_{21}), the largest permitted minimum thicknesses ($\delta_1^{\max}$ and $\delta_2^{\max}$), and the expansion/contraction factors (α_1 and α_2) must be specified. The expansion/contraction factors are often chosen to be greater than 1 to provide the highest resolution near the surface. In this case, the minimum thicknesses will increase with depth until the largest permitted values are reached, and then remain constant with depth. It is also necessary to identify the uppermost model layer that is isopycnic (N_i) and to specify an interior minimum thickness (δ_{int}). Thickness δ_{1k} governs the open ocean transition between P and isopycnic coordinates by maintaining the minimum thickness of the nearsurface P-coordinate layers. In the isopycnic coordinate layers beneath the P domain, minimum thicknesses are specified by δ_{int}, which is typically much smaller than the minimum thicknesses above so that sharp pycnoclines can form in the isopycnic interior. For the present experiments, δ_{int} is set to 1 m.

If N_s is chosen to be zero, then $\delta_k = \delta_{1k}$ everywhere and the coastal transition to σ coordinates is not implemented. If N_s is nonzero, then the coastal transition is implemented in model layers $1 \leq k \leq N_s$. In these layers, the transition to σ coordinates begins where the water depth becomes sufficiently shallow to make $\delta_s < \delta_{1k}$. Where the water depth is shallow enough to make $\delta_s < \delta_{2k}$, a transition back to level coordinates occurs to prevent layers from becoming too thin. Parameter N_i is updated during model runs. The thickness of layer 1 is always restored to a constant thickness δ_1 as given by (1).

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