APPLICATIONS IN COASTAL MODELING AND FORECASTING

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ABSTRACT. During the Global Ocean Data Assimilation Experiment (GODAE), numerical modeling and prediction in coastal and shelf seas benefited from development of state-of-the-art, data-assimilative, and data-validated large-scale models that can supply initial and boundary conditions to nested domains. Rather than attempting an exhaustive synthesis, this article illustrates the progress in coastal ocean modeling and prediction made possible by GODAE, either directly by providing estimates, or more subtly by rendering coastal forecasting more feasible and its applications more obvious.

INTRODUCTION

Coastal ecosystems have been subject to unprecedented stresses in recent decades. Increasing activity in the coastal zone (e.g., Nicholls and Small, 2002) and climate change have resulted in changes in shorelines and nearshore bathymetry, increased coastal flooding, habitat modification, loss of biodiversity, eutrophication, increased probability of harmful algal blooms and chemical contamination, reduction in the abundance of exploitable living marine resources, and public health problems associated with water quality, beach and storm-water pollution, and increased seafood contamination. As a result of advances in data-assimilative global and basin-scale ocean models such as those brought about by the Global Ocean Data Assimilation Experiment (GODAE), there are increasing demands for routine monitoring and forecasting of currents and marine parameters in shelf seas, over the shelf slope, and beyond to support of a variety of applications (e.g., Holt, 2002). These applications include:

- Weather prediction: tropical cyclone forecasts
- Military needs: sonar range prediction
- Oil industry issues: platform maintenance, oil spills
- Nuclear industry assistance: radionuclide spills
- Coastal management: fish stock estimates (including larval dispersal), aquaculture, bathing-water quality, sewage spills, coastal flooding, harmful algal blooms, beach erosion
- Maritime safety and efficiency: iceberg drift, search and rescue, ship routing
- Biogeophysical parameter estimates and forecasts: temperature and currents, primary production, air/sea interaction, sediment transport

Despite their relatively young age, physical and interdisciplinary coastal ocean modeling and forecasting are under increasing pressure to address these issues. This pressure has led to the development of a wide range of coastal ocean models operated by scientists and engineers. Although the GODAE large-scale systems are targeted at estimating the global ocean, they also provide routine solutions in coastal and shelf seas. However, coastal ocean models are often distinct from their larger-scale counterparts because they have specific requirements that are almost never met by the large-scale systems in their present state. One reason is that many phenomena of interest are specific to the coastal and shelf seas, for example, tides and storm surges, tsunamis, shoreline change, coastal currents and hydrography, coastal upwelling, river plumes and regions of freshwater influence, and coupling with surface waves. Another important reason is that the spatial and temporal resolution required to make realistic predictions of coastal conditions is generally much higher than the resolution required for the adjacent deep ocean. For example, tides, breaking of internal waves, and the barotropic response to high-frequency atmospheric forcing often dominate sea level and current variability on shelves and can control mixing and transport; these processes have time scales of hours and horizontal scales that can be of order 100 m or less. Most large-scale ocean models also have poor representation of shelves in addition to poor cross-shelf exchanges. Finally, the use of temperature and salinity constraints is common in large-scale models, but not suitable in coastal/shelf models that instead rely on improved coastal physics and forcing to better represent air-sea and land-sea fluxes.

For a realistic simulation, coastal ocean models need to be initialized and constrained at their lateral boundaries. From the experience acquired during the last decade (e.g., Robinson and Lermusiaux, 2002; Pinardi et al., 2003; Le Hénaff et al., 2009), specifying the offshore boundary conditions of physical

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coastal models by using forecasts from a realistic hydrodynamical large-scale ocean model (such as a GODAE system) can provide consistent local estimates, extend predictability, and enhance the usability and representative character of local observations. Nesting in a data-assimilative, large-scale system is only one of several elements affecting predictability; others include using local observations not assimilated by the larger-scale systems, atmospheric forcing, river runoff, and inflows through straits, as well as the coastal ocean model physics themselves and the nesting methodology. Given the central importance of physical variables in coastal prediction, extending the predictability of physical variables has the potential to extend the predictability of interdisciplinary variables (e.g., biology, sediments).

In GODAE, downscaling was explored in several coastal regions of the world ocean. The ad hoc GODAE Coastal and Shelf Seas Working Group (CSSWG) examined the added value of using initial and boundary information from GODAE large-scale systems in coastal ocean modeling and forecasting (De Mey and Proctor, 2009). A total of 40 such coastal ocean systems in many coastal regions of the world ocean were identified. Additionally, the GODAE CSSWG White Paper (De Mey et al., 2007) provides state-of-the-art background on the key issues influencing realistic modeling and predictability. The White Paper and details on the coastal systems can be obtained on the CSSWG Web page http://www.godae.org/CSSWG.html.

Rather than attempting an exhaustive synthesis, this article illustrates the progress in coastal ocean modeling and prediction made possible by GODAE, either directly by providing estimates, or more subtly by rendering coastal forecasting more feasible and its applications more obvious. First, we give examples of how GODAE estimates add value to coastal ocean systems, and vice versa. Next, we list other important elements that potentially affect predictability in the coastal ocean systems, and whose interplay with nesting is important. Lastly, we provide a summary and perspective.

ADDED VALUE OF DOWNSCALING FROM GODAE SYSTEMS

Downscaling to regional and nearshore systems expands the utility of GODAE global and basin-scale models to end users. Smaller computational domains permit higher resolution and computationally more expensive additional physics such as tides. Typical resolution improvements from 1/12° to 1/36° reveal significant increases in eddy activity and realism compared to observations.

Coupled atmosphere-coastal ocean systems allow examination of small-scale effects of atmosphere-ocean interaction. The Relocatable Ocean-Atmosphere Model (ROAM; Schiller and Smith, 2006; Mike Hertzfeld, CSIRO, Australia, *pers. comm.*, 2009) is a tool developed in the framework of BLUElink> (also in Schiller and Smith, 2006) to improve prediction of sonar range in the ocean and radar in the atmosphere. The ocean model within ROAM is one-way nested to the operational GODAE ocean model OceanMAPS (Dombrowsky et al., 2009). Although ROAM can replicate general circulation and SST features present in OceanMAPS, as expected, greater detail in mesoscale structure and sharpness of gradients is available in ROAM due to its higher resolution. ROAM includes the tide, which is absent from OceanMAPS. It also uses high-resolution atmospheric fluxes from the Regional Atmospheric Modeling System (RAMS; Pielke et al., 1992); it is capable of resolving fine-scale flow such as sea breezes, which cannot be captured in the global model.

In Kourafalou et al. (2009), boundary conditions from the North Atlantic (NA) HYbrid Coordinate Ocean Model (HYCOM; http://www.hycom.org, US contribution to GODAE, 1/12° resolution) were employed for simulations around South Florida (SoFLA) coastal seas. The nested SoFLA-HYCOM model (http://coastalmodeling.rsmas.miami.edu, 1/25° resolution and 2-m coastline; see Kourafalou et al., 2009) includes shelf areas, shallow embayments, and the deep Straits of Florida (between Florida and Cuba). Modeling activities aim to predict circulation and water properties around the ecologically fragile Florida Keys coral reefs and the changes that may be brought about by the proposed Comprehensive Everglades Restoration Project in the adjacent shallow Florida Bay. The nested approach was found necessary to address impacts of oceanic currents on coastal processes. The Gulf Stream, starting as the Loop Current in the Gulf of Mexico and passing through the Straits as the Florida Current, imposes strong coastal to offshore interactions. Figure 1a illustrates the large-scale current system, showing sea surface height (SSH) for the Gulf of Mexico region of the NA-HYCOM GODAE model for June 4, 2004. Figure 1b shows the same field for the nested model; there is generally close agreement, with the exception of a mesoscale eddy that is present in the nested model only. The presence of this value-added feature is important to the GODAE product, as these eddies are crucial for supplying nutrients and larvae to the Florida Keys Reef Tract (Sponaugle et al., 2005), and they are an important mechanism for fish recruitment. The higher-resolution, shallower coastal depths and better atmospheric forcing of the nested

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SoFLA-HYCOM model contribute to resolving the effects of the dominant circulation forcing mechanisms around South Florida coastal seas. Kourafalou et al. (2009) also employed an intermediate model of the Gulf of Mexico (GoM-HYCOM) to provide boundary conditions for the SoFLA model and examined the effects of boundary conditions, data assimilation, resolution, and forcing on the nested model predictions; they used observations from moorings for model evaluation.

Halliwell et al. (2009) documented the impact of initial and boundary conditions provided by data-assimilative GODAE products on nested simulations of the West Florida Shelf (WFS). WFS simulations nested in three GODAE hindcast products using HYCOM in different domains and grids were first compared to simulations nested in a nonassimilative outer shelf model that does not correctly reproduce offshore boundary currents and eddies to identify improvements provided by the GODAE hindcasts. In that configuration, the choice of an outer shelf model was found to have limited influence on simulated velocity fluctuations over the inner and middle shelf where fluctuations are dominated by the deterministic wind-driven, coastally trapped wave response. Improved representation of alongshore flow variability over the outer shelf driven by the intrusion of the Loop Current and associated cyclones at the shelf edge near the Dry Tortugas was realized in the simulation nested in the GODAE product that most accurately represented the path and transport of the Loop Current at the offshore boundary of the nested model. To achieve this result, the GODAE product had to reproduce the Loop Current transport associated with both the wind-driven gyre circulation and the warm upper limb of the Atlantic Meridional Overturning Circulation. The WFS simulations nested in GODAE products more accurately represented temperature over the WFS because they imposed more accurate upper-ocean temperature profiles at the offshore boundary than did the nonassimilative outer shelf model.

In several other systems examined, the positive impact of downscaling could be seen, although much work remains to be done. For instance, both the NRL Coastal Ocean Model (NCOM) and HYCOM global models (described in Dombrowsky et al., 2009) were found in a zoom (nested simulation) of the California Current System to be viable providers of boundary values for coastal

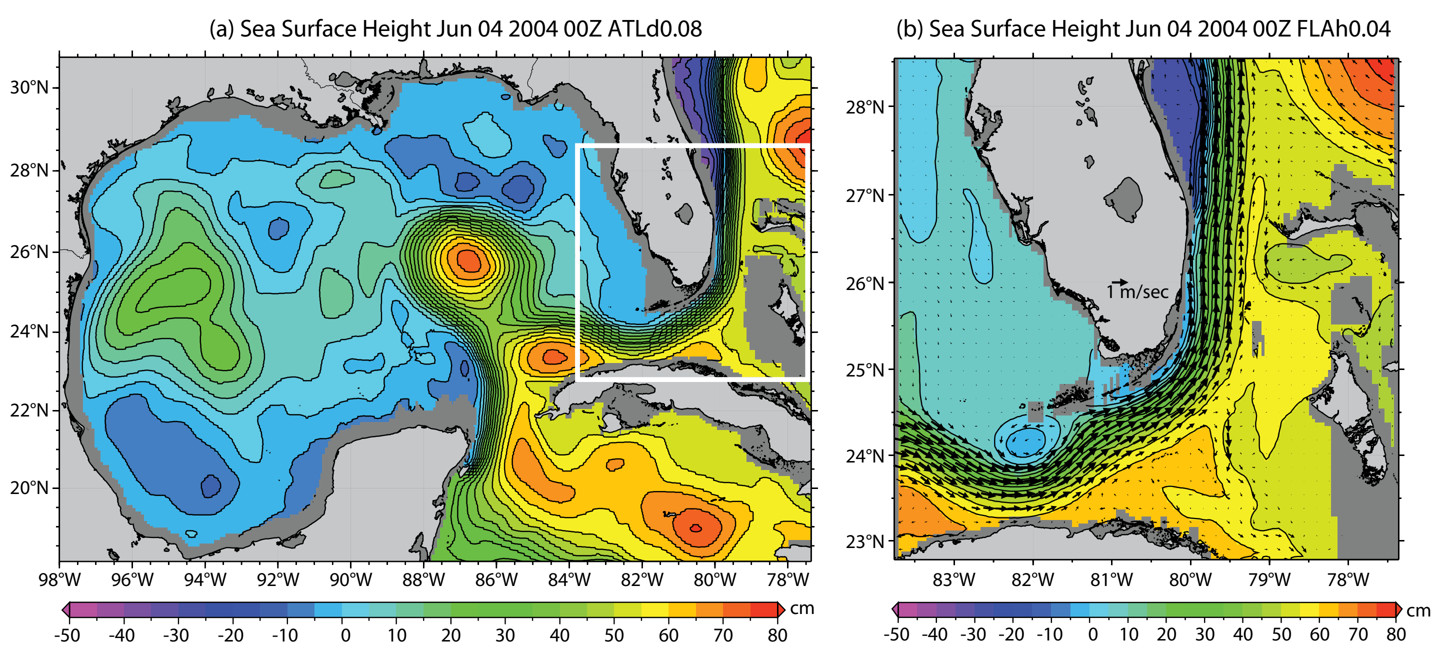

Figure 1. (a) Sea surface height (SSH) for the Gulf of Mexico domain of the North Atlantic HYbrid Coordinate Ocean Model (HYCOM), June 4, 2004. The white box marks the nested model domain. (b) SSH for the nested South Florida HYCOM, June 4, 2004. Vectors larger than 50 cm s^{-1} are superimposed to highlight major circulation features, namely the Florida Current and a mesoscale cyclonic eddy near the Florida Keys. *Courtesy V. Kourafalou, RSMAS, University of Miami*

ocean models with some differences (e.g., regarding the more accurate representation of Kelvin waves in HYCOM). Figure 2 shows another example of model performance evaluation for a nested model of the California Current System (Regional Ocean Modeling System [ROMS] nested in Estimating the Circulation and Climate of the Ocean [ECCO]-GODAE; http://codae.pmc.ucsc.edu; details given in Veneziani et al. 2009a) and data from the California Cooperative Fisheries Investigations program (CalCOFI; http://www.calcofi.org). Over five years, the model hydrographic bias is small at all depths, model variability is similar to that of nature, and the model root-mean-square (RMS) error is of the same order as the RMS itself, revealing intrinsic variability influencing the underlying eddy field.

ENHANCEMENTS TO PREDICTABILITY

Elements Influencing Realistic Behavior and Prediction Capabilities in Coastal Models

Several types of applications in the coastal ocean require forecasts of ocean variables, with the targeted forecast range depending on the application. Besides the quality of the forecasts derived from the large-scale GODAE model that provides the boundary information (Hurlburt et al., 2009), several key elements (reviewed in De Mey et al., 2007, and not detailed here) can help to keep a nested numerical model on a realistic trajectory, therefore potentially enhancing its predictability performance and range. These elements include the initialization procedure from the coarser solution, assimilation of local data not (or imperfectly) incorporated into the large-scale model, adequate atmospheric forcing products, high-resolution processes, wave-current interactions, the actual numerical specification of the boundary conditions, and lateral forcing (including both rivers and inflows through straits). A multiscale modeling strategy can also help, such as two-way nesting and unstructured-grid modeling. The first two elements are briefly discussed below. The nested models must also include improved coastal physics that might be totally missing from other models, such as tides and river plumes.

We are only starting to discover which of these elements are more important and how they interplay with each other. As noted by Wakelin et al. (2009), the right ingredients for realistic behavior in coastal regions vary as a function of geographic location. On the shelf, predictability is largely dependent on local elements, and is not as sensitive to downscaling as, for example, the slope current and coastal mesoscale. The Atlantic Margin Model (AMM) implementation of the Proudman Oceanographic Laboratory Community Model (POLCOMS; Holt and James, 2001) extends from the open ocean of the Northeast Atlantic to the coast of Northwest Europe and is a useful tool for investigating the impact of the deep ocean on the coastal environment. Experiments using different boundary forcing data and initial conditions show the effects of changes in the open ocean on the physical characteristics of the Northwest European continental shelf. Two different GODAE ocean models and a hybrid data set that uses a combination of ocean model sea surface elevations, currents, and climatological temperature and salinity fields are used

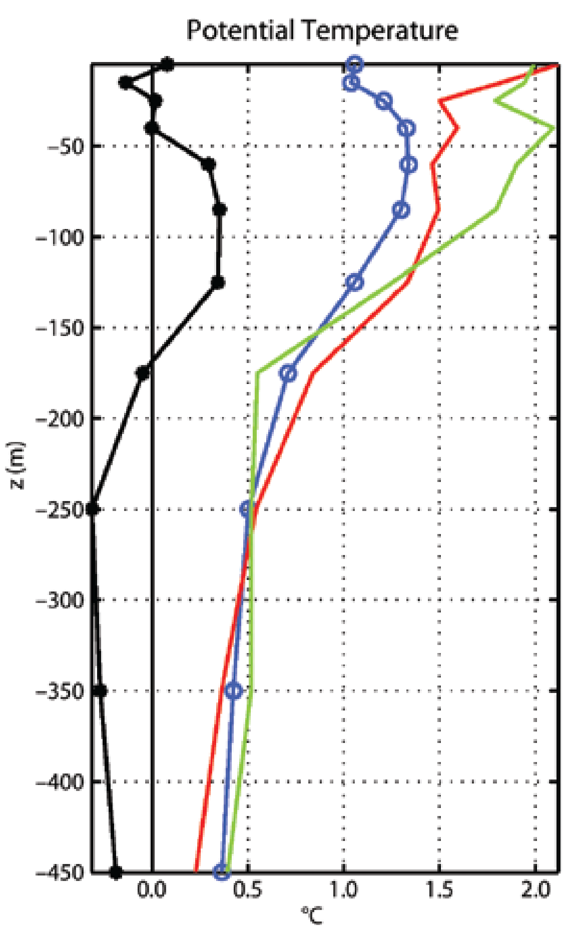

Figure 2. Performance metrics for a model of the California Current System (see text) over five years compared to data from the California Cooperative Fisheries Investigations (CalCOFI) program: four hydrographic surveys per year, each with six sections and a total of 58 stations. Model (red) and data (green) root mean square variability as functions of depth are presented along with model bias (black) and error standard deviation (blue). *Courtesy C. Edwards, UC-Santa Cruz*

to force the AMM. Although large-scale features remain the same, the resulting temperature fields and circulation in the open ocean change depending on which boundary forcing is used, while there are few differences over the shallow shelf region due to using different boundary data. The steep slopes bounding the continental shelf inhibit ocean-shelf exchange, and the temperature and circulation characteristics on the shelf are strongly determined by local topography, location of fronts, and atmospheric forcing.

Initialization from a Coarser Solution

Care must be exercised when specifying the initial and boundary values of a free-surface coastal ocean model from a coarser solution to avoid triggering unphysical gravity transients. The large-scale solution is unbalanced with respect to local physics, due to differing resolution, bathymetry, coastlines, vertical discretization, and other parameters. Simple interpolation may lead to problems, and a specific initialization procedure must be applied. To optimally solve for such difficulties, the operational Mediterranean Forecasting System (Dombrowsky et al., 2009) and several other projects involving nested modeling use a variational balanced analysis method (Auclair et al., 2006). It is based on minimizing a cost function that involves data constraints (including the ocean general circulation model [OGCM] solution used as "data" with its error characteristics, if available) as well as a term penalizing the fast barotropic transients over the first time step. This approach leads to a dramatic short-term decrease in spurious numerically generated external gravity waves and a decrease in the amplitude of some of the model biases such as horizontal pressure gradient truncation errors.

Data Assimilation

Data assimilation has the potential to enhance the realism of ocean models and to extend their predictability range (e.g., Cummings et al., 2009). As in the open ocean, the most important practical use of coastal data assimilation is in the estimation of past, present, and future conditions (e.g., Oke et al., 2002), and also in providing associated measures of uncertainty. It is typically used to sequentially update initial conditions and sometimes the open boundary conditions. Data assimilation also provides a rigorous framework suited for designing objective figures of merit to make decisions on future observing systems (Le Hénaff et al., 2009). Data assimilation in coastal models offers the possibility of incorporating information not, or improperly, incorporated in the OGCMs. Depending on the location, a variety of observations can be considered, for example, sea level from coastal tide gauges and bottom pressure gauges; currents from land-based radars and acoustic Doppler current profilers mounted on moorings and moving vessels; water properties from fixed moorings and ferries; multifrequency acoustics and multispectral optics for biological state estimation; satellite observations of sea surface roughness, height, temperature, and color; and measurements from Lagrangian profilers (Argo), gliders, and autonomous underwater vehicles.

A range of methods is currently used to assimilate data in coastal ocean models. Because of the nonstationary, nonhomogeneous error statistics characterizing coastal ocean processes, successful approaches in the systems and regions examined here include at least some degree of built-in physical consistency of the error subspace, such as the Ensemble Kalman filter (e.g., Mourre et al., 2004, 2006; Counillon and Bertino, 2009) and four-dimensional variational methods (Taillandier et al., in press; Kurapov et al., 2005, 2007; Powell et al., 2008, 2009; Broquet et al., 2009; Veneziani et al., in 2009b). Ensemble-based methods are also being used to explore the model error subspace and help specify error covariances (e.g., Echevin et al., 2000; Auclair et al., 2003).

Powell and Moore (2009) present a method for regional estimation of the posterior (or analysis) error that results from using the incremental form of four-dimensional variational data assimilation. Comparison of the posterior error from both GODAE SST and SSH data with independent, non-GODAE-produced data products from nearly one year of continual assimilation revealed that both the near-real-time and delayed-time GODAE products provided slightly greater reduction to the posterior errors than comparable near-real-time products. The patterns of posterior error showed greatest reduction in regions of high oceanic variability, suggesting that observations in regions of high uncertainty provide the greatest influence on the reduction of posterior error. A transect of the Gulf of Mexico (Figure 3) illustrates the difference in posterior uncertainty from assimilating the GODAE product (Donlon et al., 2009) versus a National Oceanic and Atmospheric Administration (NOAA) blended SST. Assimilation of the GODAE Global High-Resolution Sea

Surface Temperature (GHRSST) reduced the uncertainty in the jet of the Loop Current more than did assimilating the NOAA-blended SST. This figure also illustrates the advantage of using an assimilation scheme that incorporates the physics (either variational or ensemble Kalman-based): uncertainty reductions were possible even at locations where data were not assimilated.

DISCUSSION AND PERSPECTIVE

During GODAE, numerical modeling and prediction in coastal and shelf seas have increasingly benefited from the development of state-of-the-art, data-assimilative and data-validated large-scale models that can supply initial and boundary conditions to nested domains.

In the continuation of these activities, we must further develop the notion of a critical path from routinely available information (satellite, in situ, basin-scale estimates) to coastal and littoral applications, and we must better define the role of the coastal ocean link on this path. We must broaden the range of applications by addressing the role of coastal and shelf models in predictions related to climate change, for example, using IPCC scenarios (Lee et al., 2009). Similarly, the biogeochemical implications in coastal and shelf seas are obvious (some applications such as water quality and habitat changes are mentioned above). Assessing and expanding the predictability of biogeochemical variables will be one of the next challenges.

As far as coastal ocean physics is concerned, we should seek enhancements to nesting approaches and to predictability; resolve rich-scale interactions, tides, and high frequencies; and experiment with novel approaches such as two-way nesting (e.g., Debreu and Blayo, 2008) and unstructured grid modeling. Coastal modeling has a central contribution to bring to the objective design of observing systems for the coastal ocean, such as new satellite sensors (Surface Water Ocean Topography [SWOT], the high-accuracy altimeter AltiKa/SARAL), and coastal observatories. The economic implications of coastal forecasting could provide a strong argument for pushing global coastal observing systems such as these. The forecasting range in the coastal ocean is also very dependent on the quality of atmospheric forecasts. Special high-resolution forcing products are expected to have a positive impact (e.g., Papadopoulos et al., 2002; Veneziani et al., in 2009a,b). Data assimilation could in some cases compensate for deficiencies in the forcing fields. Julien Lamouroux (Laboratoire d'Études en Géophysique et Océanographie Spatiales, NOVELTIS, *pers. comm.*, 2007) has illustrated the positive impact of including surface atmospheric variables in the assimilation state vector onto the short-term forecast range in the Bay of Biscay. Finally, let us mention the interest of probabilistic (ensemble) prediction, a subject only briefly touched on in this article; these methods do not provide a single estimate but rather a posterior distribution of ocean state, given the prior distribution of the state and observations. Such methods have the potential to provide error statistics that are useful for science as well as for applications.

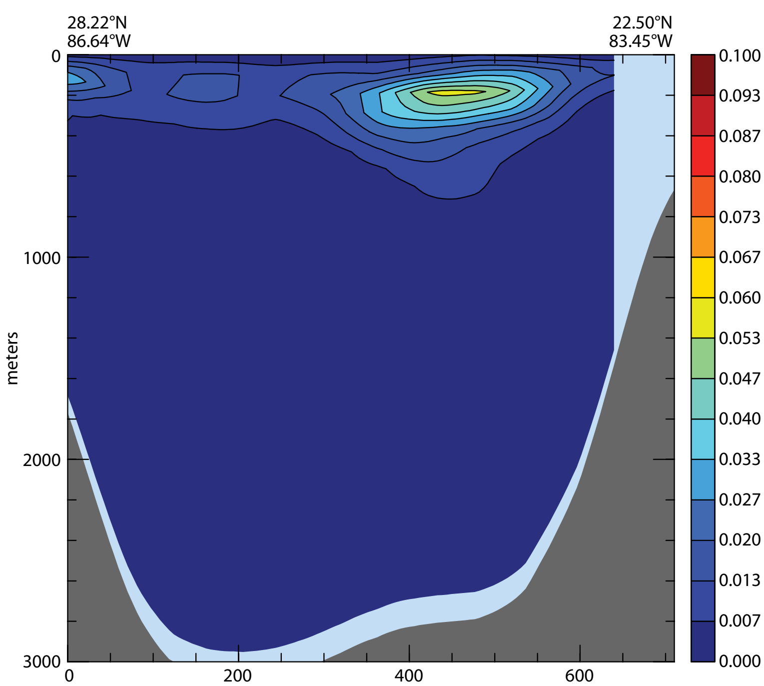

Figure 3. This Gulf of Mexico transect shows the difference in analysis error standard deviation of potential temperature (°C) from assimilating the GODAE sea surface temperature (SST) product versus the NOAA SST product (difference of st. deviations calculated as NOAA-GODAE). The GODAE SST product led to a greater reduction of uncertainty in the core Loop Current jet north of Cuba. *Courtesy B. Powell, UC-Santa Cruz*

ACKNOWLEDGMENTS

We thank the GODAE project and the co-authors' respective institutes for their support of CSSWG activities. We also thank two anonymous reviewers and the special issue editors for useful and constructive comments.

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