U.S. GODAE: GLOBAL OCEAN PREDICTION WITH THE HYBRID COORDINATE OCEAN MODEL (HYCOM)

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LONG-TERM GOALS

A broad partnership of institutions is collaborating in developing and demonstrating the performance and application of eddy-resolving, real-time global and basin-scale ocean prediction systems using the HYbrid Coordinate Ocean Model (HYCOM). These systems will be transitioned for operational use by the U.S. Navy at both the Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS, and the Fleet Numerical Meteorology and Oceanography Center (FNMOC), Monterey, CA, and by NOAA at the National Centers for Environmental Prediction (NCEP), Washington, D.C. The systems will run efficiently on a variety of massively parallel computers and will include sophisticated, but relatively inexpensive, data assimilation techniques for assimilation of satellite altimeter sea surface height (SSH) and sea surface temperature (SST) as well as in-situ temperature, salinity, and float displacement.

The project partnership represents a truly broad spectrum of the oceanographic community, bringing together academia, federal agencies, and industry/commercial entities, spanning modeling, data assimilation, data management and serving, observational capabilities, and application of HYCOM prediction system outputs. The institutions participating in this partnership have long histories of supporting and carrying out a wide range of oceanographic and ocean prediction-related research and data management. All institutions are committed to validating an operational hybrid-coordinate ocean model that combines the strengths of the vertical coordinates used in the present generation of ocean models by placing them where they perform best. This collaborative partnership provides an opportunity to leverage and accelerate the efforts of existing and planned projects, in order to produce a higher quality product that will collectively better serve a wider range of users than would the individual projects.

This effort is part of a 5-year (FY04-08) multi-institutional National Ocean Partnership Program (NOPP) project which includes the **Florida State University** (E. Chassignet, A. Srinivasan), **U. of Miami** (G. Halliwell, M. Iskandarani, T. Chin, A. Mariano, Z. Garraffo, W. Schmitz), **NRL/STENNIS** (H. Hurlburt, A. Wallcraft, J. Metzger, T. Townsend, B. Kara, J. Cummings, G. Jacobs, H. Ngodock, L. Parent, C.A. Blain, P. Hogan, J. Kindle), **NAVOCEANO** (E. Johnson, J. Harding), **FNMOC** (M. Clancy), **NRL/MONTEREY** (R. Hodur, P. May, J. Pullen), **NOAA/NCEP/MMAB** (D.B. Rao, C. Lozano), **NOAA/NOS** (F. Aikman, J. Sienkiewicz), **NOAA/AOML** (C. Thacker), **NOAA/PMEL** (S. Hankin), **Planning System Inc.** (O.M. Smedstad), **NASA-GISS** (R. Bleck), **SHOM** (R. Baraille), **LEGI** (P. Brasseur), **OPeNDAP** (P. Cornillon), **U.**

of N. Carolina (C. Werner), **Rutgers** (J. Wilkin), **U. of S. Florida** (R. Weisberg), **Fugro-GEOS/Ocean Numerics** (D. Szabo, L. Bertino), **Horizon Marine Inc.** (J. Feeney, S. Anderson), **ROFFS** (M. Roffer), **Orbimage** (L. Stathoplos), **Shell Oil Company** (M. Vogel), **ExxonMobil** (O. Esenkov).

OBJECTIVES

The main ojective is to use the HYbrid Coordinate Ocean Model (HYCOM) with data assimilation in an eddy-resolving, fully global ocean prediction system with transition to the Naval Oceanographic Office (NAVOCEANO) at .08° equatorial (~7 km mid-latitude) resolution in 2007 and .04° resolution by 2011. The model will include shallow water to a minimum depth of 5 m and provide boundary conditions to finer resolution coastal and regional models that may use HYCOM or a different model. In addition, HYCOM will be coupled to atmospheric, ice and bio-chemical models, with transition to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) for the coupled ocean-atmosphere prediction. Basin-scale configurations will also form the backbone of the NOAA/NCEP/MMAB Ocean Forecast System. All the systems will be transitioned with assimilation of sea surface height (SSH) from satellite altimeters, sea surface temperature (SST) and temperature (T)/salinity (S) profiles, including profiles from ARGO floats. In addition, 30-day forecasts are planned once a week. The global system will include two-way coupling to an ice model and a version with two-way coupling to an atmospheric model for transition to FNMOC. The project will ensure that an accurate and generalized ocean model nesting capability is in place to support regional and littoral applications when global HYCOM becomes operational. This will include the capability to provide boundary conditions to nested models with fixed depth z-level coordinates, terrain following coordinates, generalized coordinates (HYCOM), and unstructured grids. To facilitate this goal, HYCOM is presently being developed into a fully-featured coastal ocean model in collaboration with a partnering NOPP project. The project is participating in the multinational Global Ocean Data Assimilation Experiment (GODAE) and international GODAE-related ocean prediction system intercomparison projects.

APPROACH AND WORK PLAN

1. Ocean model design: HYCOM is a generalized (hybrid isopycnal/σ/z) coordinate ocean model. It is isopycnal in the stratified ocean, but reverts to a terrain-following (σ) coordinate in shallow coastal regions, and to z-level coordinates in the surface mixed layer. The vertical coordinate is dynamic in space and time via the layered continuity equation, which allows a dynamical transition between the coordinate types. Like its predecessor, the Miami Isopycnic Coordinate Ocean Model (MICOM), HYCOM allows isopycnals intersecting sloping topography by allowing zero thickness layers. HYCOM was developed from MICOM using the theoretical foundation for implementing a hybrid coordinate system set forth in Bleck and Boudra (1981), Bleck and Benjamin (1993), Bleck (2002), Chassignet et al. (2003), and Halliwell (2004). Alan Wallcraft (NRL) is in charge of developing and maintaining the standard version of the model, one that is scalable/portable and can run on the latest computer architectures. HYCOM is maintained as a single source code with the maximum feasible backward compatibility.

2. Data assimilation techniques: The effort is focusing on (1) multi-variate optimum interpolation (MVOI) (Daley, 1991; Cummings, 2005), (2) the Singular Evolutive Extended Kalman (SEEK) filter (Pham et al., 1998), the Reduced Order Information Filter (Chin et al., 1999), and (4) the

ensemble Kalman filter (EnKF) (Evensen, 1997). The MVOI is used in the NRL Coupled Ocean Data Assimilation (NCODA) system of J. Cummings (NRL) which is being adapted for use in HYCOM in collaboration with O.M. Smedstad (Planning Systems, Inc.), C. Thacker and H. Kang at NOAA/AOML, and C. Lozano at NOAA/NCEP/MMAB. For all the techniques, the primary data types are SSH from satellite altimetry, SST, and subsurface T & S profiles.

3. Ocean model and prediction system configurations: A fully global configuration of HYCOM is the primary model domain used in this project. It consists of an Arctic dipole patch matched to a standard Mercator grid at 47°N. The target resolution is .08°cosθ in latitude (θ) south of 47°N by .08° in longitude or ~7 km resolution for each model variable at mid-latitudes and 3.5 km at the North Pole. The array size is 4500 x 3298 with 32 hybrid layers in the vertical. This configuration is presently being run using an FY05-07 DoD High Performance Computing (HPC) Challenge grant including data assimilation. This work is being performed in close collaboration between NRL, E. Chassignet's group (FSU and U. Miami), and O.M. Smedstad (PSI), including evaluation of results. W. Schmitz is also part of the evaluation effort.

4. Boundary conditions for littoral and regional models: Work on this topic is highly collaborative with project partners and partnering projects. At NRL, it includes a nesting capability for the following models: (1) HYCOM, (2) the Navy Coastal Ocean Model (NCOM) which allows mixed z-level and terrain following coordinates, (3) the ADvanced CIRCulation model for shelves, coasts and estuaries (ADCIRC), an unstructured grid model, and (4) the Regional Ocean Model System (ROMS), which has predetermined non-Lagrangian hybrid coordinates in the vertical. NCOM is also the model component of the regional Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS™) developed at NRL-Monterey (Hodur, 1997), a project partner for nesting NCOM in HYCOM.

5. GODAE: The project is participating in GODAE and the related prediction system intercomparison projects, e.g. the European MERSEA. The purpose of GODAE is to help justify a permanent global ocean observing system by demonstrating useful real-time global ocean products. Consistent with this goal, real-time HYCOM prediction system output will be made available to the public within 24 hours via the U.S. GODAE and Miami Live Access Servers (LAS). HYCOM is represented on the U.S. and International GODAE Steering Teams by E. Chassignet, J. Cummings (U.S. co-chairman), and H. Hurlburt.

WORK COMPLETED

a) Global, basin-scale, and regional simulations
b) Implementation of data assimilation capabilities for HYCOM
c) Evaluation of the ability of the North Atlantic ocean prediction system to provide boundary conditions to coastal models
d) Model outputs available via a Live Access Server

RESULTS

The present near real-time data assimilative .08° Atlantic version of HYCOM is a first step towards the fully global .08° HYCOM prediction system. The system assimilates the daily MODAS SSH anomaly analysis and SST of available real time satellite data. The atmospheric forcing of the near real time system comes from the Fleet Numerical Meteorology and Oceanography Center (FNMOC) Navy Operational Global Atmospheric Prediction System (NOGAPS). The system runs every Wednesday and consists of a 10-day hindcast and a 14-day forecast. The results are displayed on the HYCOM Consortium web page at http://www.hycom.org. It includes comparisons to unassimilated observations and data from the system are available via the HYCOM Consortium web page at http://hycom.rsmas.miami.edu/dataserver.

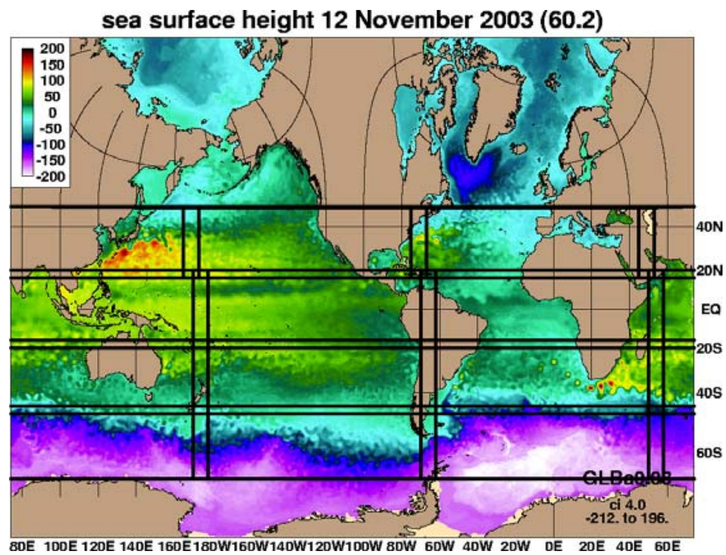

Figure 1. The SSH field from the .08° Global HYCOM domain on 12 November 2003. The 12 overlapping regions used for the NCODA analysis are shown.

The Navy Coupled Ocean Data Assimilation (NCODA) (Cummings, 2005) system has been implemented as the next generation assimilation technique in HYCOM by O.M. Smedstad and J. Cummings. The NCODA system is a fully three-dimensional multivariate optimum interpolation system. The three-dimensional ocean analysis variables include temperature, salinity, geopotential, and the vector velocity components (T, S, U, V), which are all analyzed simultaneously. In support of HYCOM, a new analysis variable was added to NCODA that corrects the model layer pressure of the hybrid vertical coordinates. The NCODA horizontal correlations are multivariate in geopotential and velocity, thereby permitting adjustments (increments) to the mass fields to be correlated with adjustments to the flow fields. The velocity adjustments are in geostrophic balance with the geopotential increments, and the geopotential increments are in hydrostatic agreement with the temperature and salinity increments. The present implementation interpolates the HYCOM vertical coordinate to z-space, performs the NCODA analysis, and then maps the z-level NCODA T, S U, V and layer pressure analysis increments to the appropriate HYCOM vertical coordinate. The HYCOM update program applies the temperature and salinity analysis increments in the model mixed layer, and applies the layer pressure analysis increments in the isopycnal part of the domain to correct the model interface layer pressures. An incremental updating scheme has been developed where a fraction of the analysis increments can be added to the HYCOM forecast variables at each model time step. The increments can be added over a given number of time steps, ranging from 1 (direct insertion) to the number of time steps in one day. The NCODA assimilation experiments with the .08º Global HYCOM is presently splititng the NCODA analysis into 12 overlapping regions covering the Mercator part of the global HYCOM grid, see Figure 1. The experiment is initialized on 12 November 2003 using a model field from a run without data assimilation. The GODAE server is used as the source of the MCSST and in situ observations. The altimeter data come from the NRL satellite altimeter data archive. The NCODA analysis is performed every 24 hours, assimilating all available observations within 12 hours of the analysis time. Figure 2 shows the SSH in the Kuroshio.

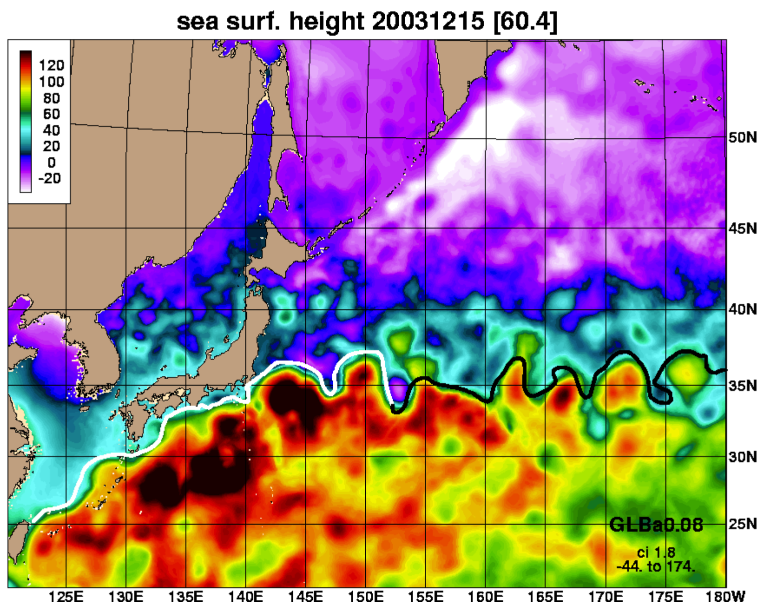

Figure 2. The SSH field from the .08º Global HYCOM domain on 15 December 2003 in the Kuroshio region. The white black line represents the frontal analysis of MCSST observation performed at the Naval Oceanographic Office. A black line represents data more than four days old.

Evaluation of ocean model simulations without data assimilation is essential because ocean model simulation skill is critical to dynamical interpolation skill in ocean data assimilation and to model forecast skill, the latter lasting ~1 month for mesoscale variability because it is largely a nondeterministic response to atmospheric forcing (Hurlburt et al., 2005; Chassignet et al., 2006; Hurlburt et al., 2006; Shriver et al., 2006). In addition, ocean model simulation skill is essential in representing ocean features that are insufficiently observed (e.g., mixed layer depth and other subsurface features) and for converting atmospheric forcing and topographic/coastline constraints into oceanographic information. An accurate mean SSH field is required for addition to the deviations provided by satellite altimetry. Mean SSH from an eddy-resolving global ocean model is desirable because it can represent the mean currents/SSH fronts more sharply than is presently possible from an observation-based mean, even the state-of-the-art mean of Maximenko and Niiler (2005) vs the global HYCOM mean (Fig. 3). However, simulating a sufficiently accurate mean SSH from ocean models is extremely challenging and corrections for biases and errors in the position and strength of mean currents are required. Overall, the agreement between the .08° global HYCOM and the .5° Maximenko and Niiler (2005) mean SSH is remarkably good and the standard deviation of the difference is only 9 cm. The atmospheric forcing is a significant source of error in the model mean, e.g. the obvious difference in the South Pacific is a longstanding problem where the ECMWF forcing drives a South Equatorial Countercurrent (SECC) that is too strong (Metzger et al., 1992). In the North Atlantic it drives a western boundary current that is too weak; hence the effort to correct the ECMWF wind speed using QwikScat data and the new simulation driven by the corrected product. Finally, a rubber sheeting software was used to produce an updated mean SSH field that increase the agreement with the 5° Maximenko and Niiler (2005) mean SSH and that is presently used for data assimilation.

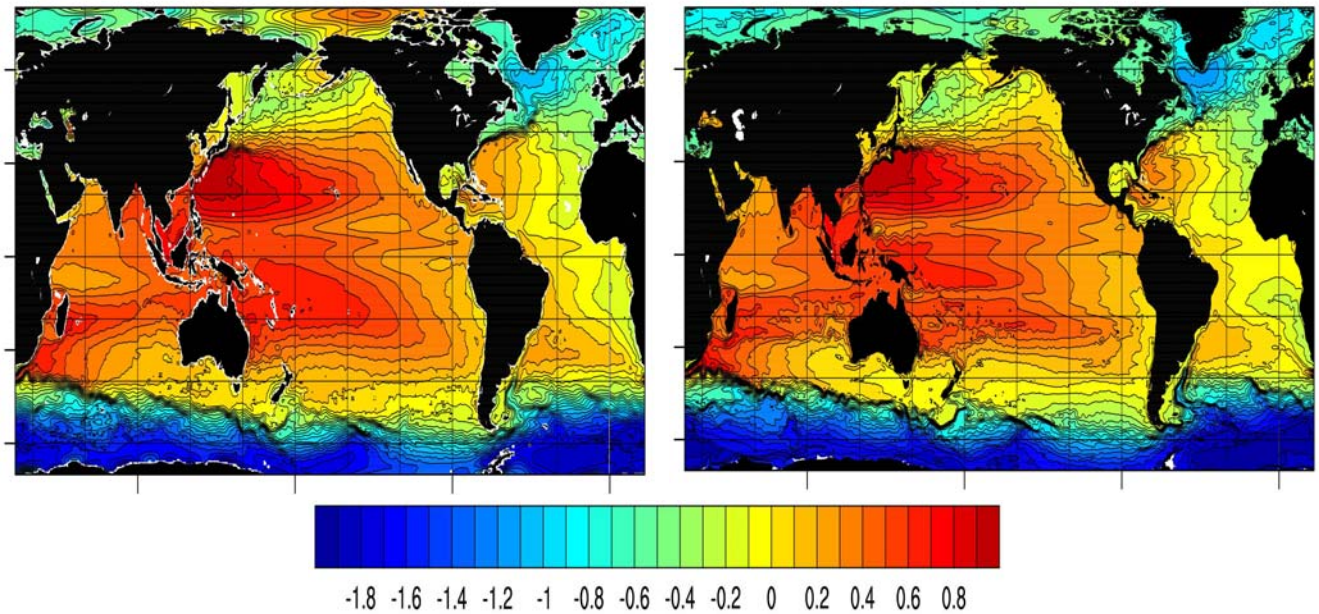

Figure 3. Mean sea surface height (SSH) from (left) Maximenko and Niiler (2005) based on satellite altimeter, drifting buoy and wind data spanning the years 1992-2002 and a newly improved geoid, GRACE (Gravity Recovery and Climate Experiment) Gravity Model 01 (GGM01), and (right) simulated by .08° global HYCOM using ECMWF climatological wind and thermal forcing.

The horizontal and vertical resolution chosen for the above forecasting systems 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. The resolution should increase to .04º (3-4 km at mid-latitudes) by the end of the decade. An important attribute of the data assimilative HYCOM simulations is therefore the capability to provide boundary conditions to regional and coastal models. In order to increase the predictability of coastal regimes, several partners within the HYCOM consortium are developing and evaluating boundary conditions for coastal prediction models based on the HYCOM data assimilative system outputs. As stated above, coupling HYCOM to other models, such as the NCOM or ROMS, has already been demonstrated and is now routine, while coupling of HYCOM to unstructured grid/finite element models is in progress.

A West Florida Shelf (WFS) model based on the Regional Ocean Model System (ROMS) was nested by A. Barth (USF) in the .08° North Atlantic HYCOM forecasting system. In addition to currents, temperature, salinity and elevation, the model now provides simulations of Lagrangian drifter tracks for drifters released near the surface, at mid-depth and near the bottom. All forecasts are available at http://ocgmod1.marine.usf.edu/WFS/ and at http://ocgweb.marine.usf.edu.

Validation was performed against water column currents by ADCP, surface currents by HF-Radar, and water column T/S by BSOP profiling floats, and all showed quantifiable agreements. In particular the model was able to simulate the strong vertical T/S stratification observed prior to Hurricane Katrina and associated with a benthic die-off due to the trapping of red tide organisms (K. brevis) beneath the pycnocline. In anticipation of future data assimilation applications, USF began investigations into the use of surface currents measured on the WFS by HF-radar (long range CODAR). Two types of analyses were performed. The first was a tidal analysis, the results from which were compared against an available tide model. The second was to use this tidal analysis to remove the tides from the CODAR data so that the CODAR data could be compared with the nested WFS ROMS model. For this exercise, two-day averaged radial current maps prepared for the three available CODAR stations (at Redington Shores, Venice, and Naples) were used. Also the 2005 red tide event was investigated using numerical drifters - the experiments demonstrated the three-dimensional nature of advection of K. brevis to the near shore. Beginning with the location of cell counts at an offshore frontal location west of the Tampa Bay region, it was found that subsequent observations near shore to the southeast could only be accounted for by advection along the bottom. Near surface particles were advected offshore, whereas particles in the bottom Ekman layer matched the subsequent observed locations of K. brevis. The model study showed the importance the 3D structure of ocean currents. This model experiment demonstrated the downscaling of global circulation models to the coastal ocean is able to address a question of strong societal concern.

HYCOM nowcast products have been used by G. Halliwell (U. Miami) to provide initial and boundary conditions for ocean hurricane response simulations. This effort is undertaken to take advantage of observational programs designed to sample the ocean pre- and post-hurricane and because HYCOM is scheduled to become the ocean component of the next-generation hurricane prediction model (HWRF) in the near future. Evaluation of the HYCOM Atlantic nowcast product prior to hurricanes Isidore and Lili in 2002 demonstrated that, although important features such as the Loop Current and associated eddies in the Gulf of Mexico were situated at their approximately correct locations, large biases existed in upper ocean temperature and salinity. In particular, the upper warm layer was much too thin, which caused the upper ocean to cool much more than observed in simulated responses to Isidore and Lili. The latest HYCOM MVOI NCODA nowcast system has been run by O.M. Smedstad (PSI) from mid-2003 to the present. Evaluation of these fields prior to hurricane Ivan in 2004 determined that the large biases present in the original Atlantic assimilation have been substantially reduced. This is demonstrated in a simulation of the ocean response to Ivan that used NCODA fields for initial and boundary conditions. The model was driven by fields from the 0.5-degree NOGAPS atmospheric model blended with the HWIND product of NOAA/AOML (Uhlhorn and Black, 2003). Blending was required because the 0.5-degree forcing did not resolve the eye and the maximum winds present in the eyewall while the HWIND analysis did resolve these features. The GISS vertical mixing model was used. The pattern of SST cooling in the Gulf of Mexico is critically dependent on the location of the Loop Current and its associated anticyclonic (warm) and cyclonic (cold) eddies. Prior to and during Ivan, the Loop current extended northward to about 25.5°N (Figure 5). Three strong eddies were present, with a warm eddy south of Louisiana that recently detached from the Loop Current and two cold eddies, one northeast and one southeast of the warm eddy. The cooling pattern particularly reflects the influence of these eddies, with the largest cooling found within the two pre-existing cold eddies. Overall, the SST cooling pattern and magnitude is consistent between the HYCOM simulation and microwave satellite measurements (Figure 4). This result is very encouraging, both for the NCODA product scheduled to become operational at NAVO next year and for the prospect of using HYCOM GODAE nowcasts to initialize coupled ocean prediction models in the future.

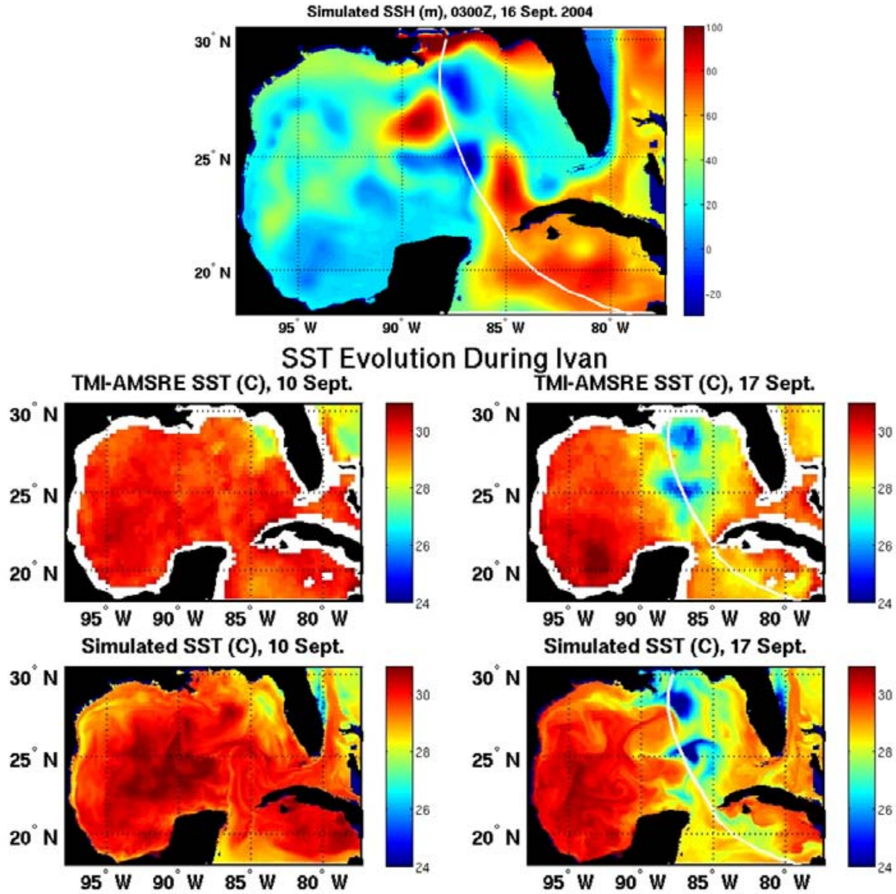

Figure 4. SSH field simulated by HYCOM at the time of hurricane Ivan landfall (top panel). SST before and after Ivan measured by microwave satellite sensors (middle two panels) and simulated by HYCOM (bottom two panels).

IMPACT/APPLICATIONS

HYCOM with data assimilation is planned for use in an eddy-resolving, fully global ocean prediction system. It will provide boundary conditions to finer resolution coastal models that may use HYCOM or a different model. HYCOM is designed to make optimal use of three types of vertical coordinate, isopycnal, σ and z-level. Isopycnals are the natural coordinate in stratified deep water, terrain-following (σ) coordinates in shallow water, and z-levels within the mixed layer. The layered continuity equation allows a smooth dynamical space and time varying transition between the coordinate types. HYCOM permits isopycnals intersecting sloping topography by allowing zero thickness layers and it should allow accurate transition between deep and shallow water, historically a very difficult problem for ocean models. It also allows high vertical resolution where it is most needed, over the shelf and in the mixed layer. The isopycnal coordinate reduces the need for high vertical resolution in deep water. The project is represented by E. Chassignet (U. Miami), J. Cummings (NRL), and H. Hurlburt (NRL) on the U.S. and International GODAE Steering Teams, a multinational effort designed to help justify a permanent global ocean observing system by demonstrating useful real-time global ocean products.

Web outreach is also a strong component of the HYCOM initiative. A significant issue in ocean modeling and data assimilation is making both the observational data and model output available to (a) the members of our consortium for HYCOM and data assimilation code development, (b) the wider oceanographic and scientific communities, including climate and ocean ecosystem researchers; and (c) the general public. The real-time model outputs are made available to the community at large within 24 hours via the Miami Live Access Server (LAS). Software development and integration of the server system is performed by the NOAA/PMEL group (S. Hankin) in collaboration with those in charge of the U.S. GODAE and Miami servers. Collaboration with the OPeNDAP (formerly named DODS) group (URI, P. Cornillon) is ensuring that the remote data sets and model outputs are accessible in real time, despite their size.

National Security

Global real-time generation of optimal estimates of the time-varying ocean state in support of U.S. The U.S. Navy needs on spatial scales typically of 10-1000 km (mesoscale) with forecasts up to 30 days.

Economic Development

Precise knowledge and prediction of ocean mesoscale features are used by the oil industry and fisheries for risk avoidance and optimal use of their resources.

Science Education and Communication

Web-access to an up-to-date description of the world ocean currents.

RELATED PROJECTS

PARADIGM, CODAE

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