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 **U. of Miami** (E. Chassignet, G. Halliwell, M. Iskandarani, T. Chin, A. Mariano, Z. Garraffo, A. Srinivasan, 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 will be developed into a full-featured coastal ocean model in collaboration with a partnering 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), (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 with atmospheric forcing only (Figure 1). Data assimilation will be added in FY06. Until now, data assimilative model runs have been using existing basin-scale configurations: .08° Atlantic HYCOM (28°S-70°N including the Mediterranean Sea) and .08° Pacific HYCOM (north of 20°S). This work is being performed in close collaboration between NRL, E. Chassignet's group (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

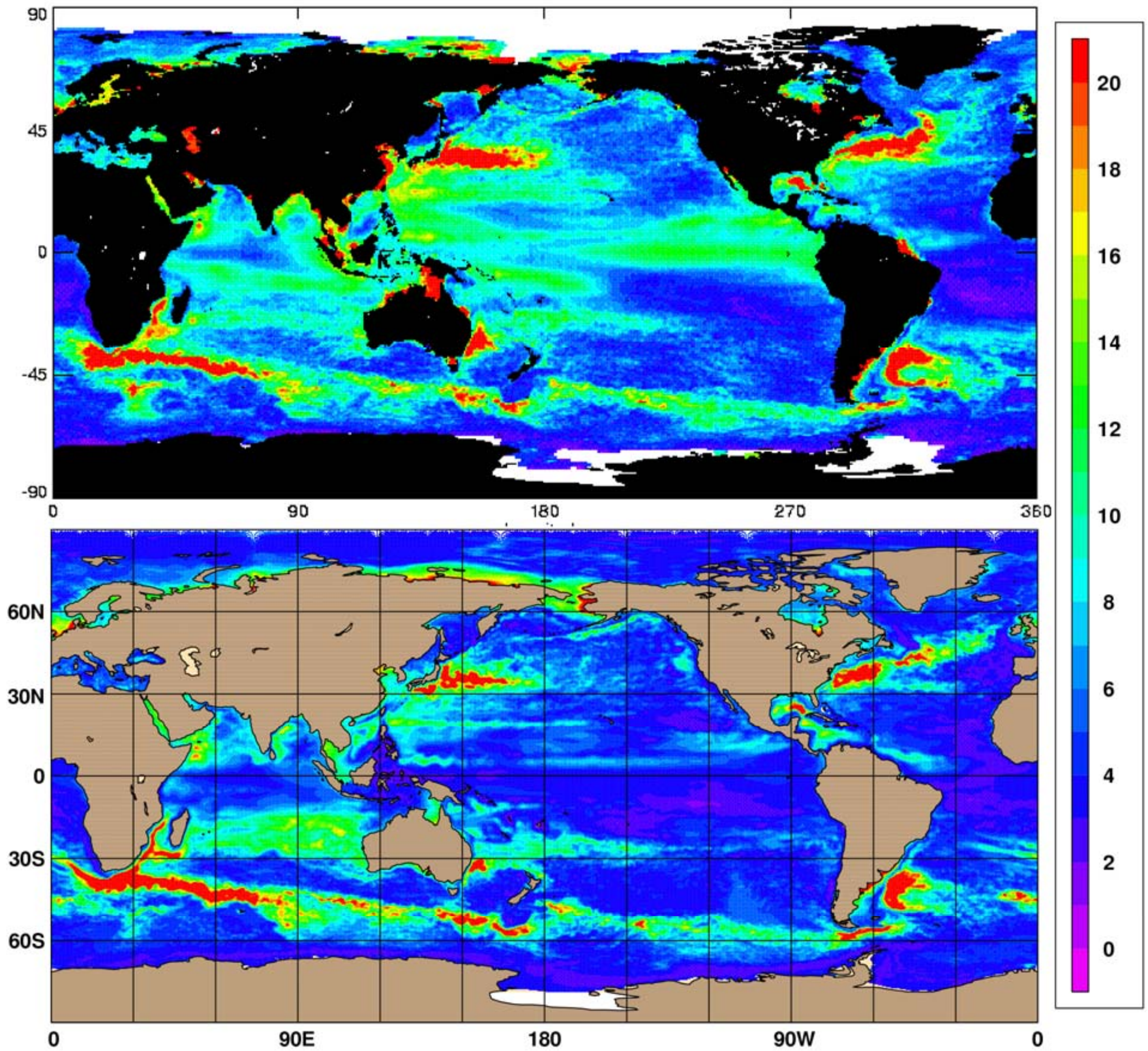

Figure 1: Oct 92 – Nov 98 SSH variability (top) based on Topex-Poseidon, ERS-1 and ERS-2 altimeters (derived by CLS, France) versus 3-year sea surface height variability from the climatologically-forced 1/12° global HYCOM (bottom). Overall, the modeled regions of high variability are in good agreement with the observations, especially in the Antarctic Circumpolar Current region. The equatorial Pacific is an exception because the altimeter data include interannual variability not present in the model, e.g., the large variability associated with the 1997-98 El Niño.

RESULTS

The present near real-time data assimilative 1/12° Atlantic version of HYCOM is a first step towards the fully global 1/12° 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.

The chosen horizontal and vertical resolution for the global and basin-scale HYCOM prediction systems only marginally resolves the coastal ocean (7 km at mid-latitudes, with up to 15 terrain-following σ-coordinates over the shelf), but provides an excellent starting point for even higher resolution coastal ocean prediction systems. The model resolution should increase to 1/25º (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. The inner nested models may or may not be HYCOM, so the coupling of the global and coastal models must be able to handle dissimilar vertical grids. Coupling HYCOM to HYCOM is now routine via one-way nesting (Zamudio et al., 2006). 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 are stored in HYCOM archive format. Layers can be added to these archive files to increase the vertical resolution of the nested model and to 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 then provides boundary conditions during the nested run, insuring consistency between initial and boundary conditions. Coupling HYCOM to other finite difference models, such as the Navy Coastal Ocean Model (NCOM) or the Regional Ocean Model System (ROMS) has already been demonstrated, and coupling of HYCOM to unstructured grid/finite element models is in progress.

In the remainder of this section, we demonstrate the use of near real-time HYCOM nowcasts and forecasts as boundary and initial condition providers to a nested coastal simulation in the South Atlantic Bight (SAB) region of the eastern US coast. The nesting of higher-resolution models within the data assimilative HYCOM allows limited-area, regional forcings (tides, terrestrial buoyancy inputs), physics (wetting and drying), and coastal geometry (tidal inlets, estuaries) to add value to the larger-scale HYCOM ocean-state estimates. The quasi-operational regional-scale modeling system for the University of North Carolina (UNC)-SAB (NOPP-funded SABLAM, SEACOOS, Blanton, 2003) uses the finite element coastal ocean model QUODDY (Lynch et al., 1996). Terrestrial buoyancy inputs to the continental shelf, strong tides, and a vigorous western boundary current contribute to the complexity of this region. Boundary and initialization data for the SAB regional-scale model are obtained from the above-mentioned HYCOM GODAE data server and are mapped to the finite element regional model domain. Figure 2 shows the sequence of nests for the UNC-SAB system. Evaluation of the near real-time HYCOM outputs relative to available observations in the SAB consists of comparisons to CODAR surface velocities in the Cape Hatteras region, National Ocean Service water levels along the coast, and mid-shelf temperature from the SABSOON observational network. In the SAB, tides account for at least 90% of the total water level variability. Figure 3a shows *subtidal* coastal water levels for 2 stations in the SAB. Lower-frequency, seasonal-scale variations are well captured by HYCOM. Weather-band fluctuations are also reasonably well represented. Observations of *in situ* water fields (salinity, temperature) are comparatively less available in the SAB. The SABSOON observational network, situated on the Georgia continental shelf, has been making routine and real-time observations of water properties for 3 years. Figure 3b shows observed SABSOON R2 near-surface temperature and HYCOM mixed later temperature. The summer of 2003 exhibited strong cooling along the eastern US coast (note the summer 2003 cooling in HYCOM in Figure 6b), attributable to a variety of coincident environmental conditions (see Aretxabaleta et al., 2005, for a review). Initial results from this hindcast run show that upwelled, cool water is present in HYCOM (along the Georgia/Florida coast) and is enhanced in the higher-resolution limited-area model system.

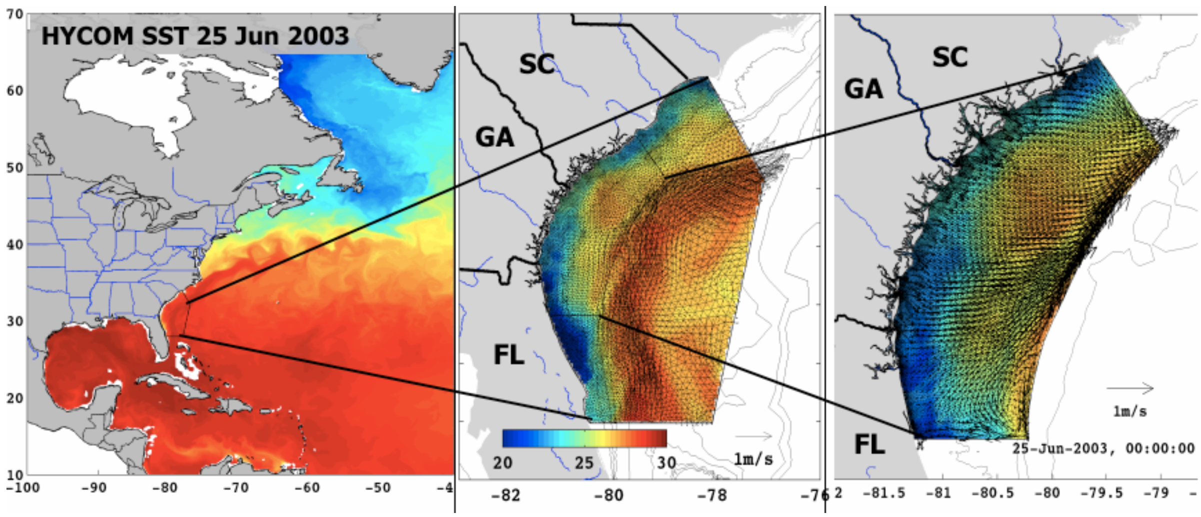

Figure 2: UNC-SAB modeling system sequence that nests the regional-scale QUODDY implementation (middle) within the 1/12 deg operational HYCOM-GODAE model (left). The limited-area QUODDY implementation (right) includes the estuary and tidal inlets along the Georgia/South Carolina coast and extends to the shelf-break.

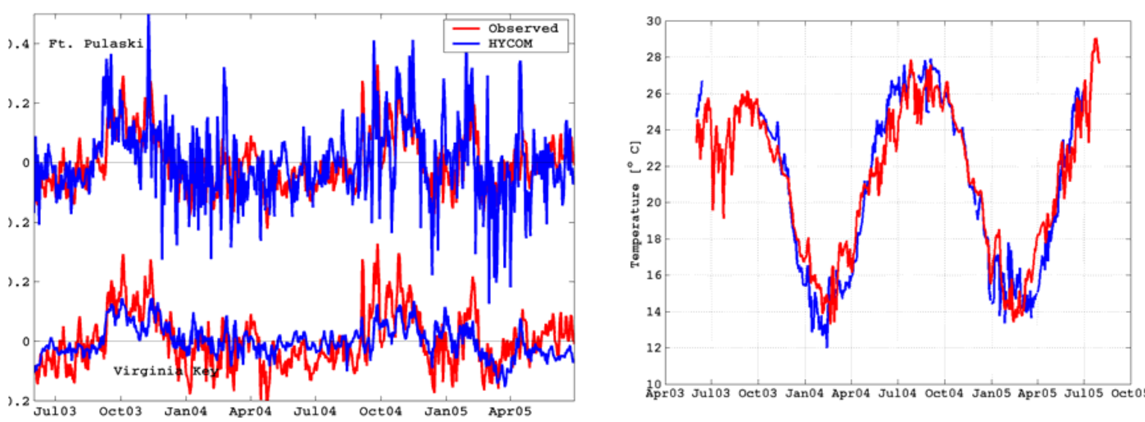

Figure 3: (left) Water level comparison for two stations in the SAB. Daily HYCOM best-estimate water levels (blue) and observed NOS water levels (red) are shown for Fort Pulaski GA (top) and Virginia Key FL (bottom). The two stations are arbitrarily offset for clarity; (right) Observed, near-surface temperature (blue) and HYCOM mixed-layer temperature (red) for the SABSOON mid-shelf station R2. The RMS error at this location is 1.4 deg C. The strong, prolonged cooling of the SAB continental shelf during summer 2003 is seen in the HYCOM temperature.

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.

TRANSITIONS

RELATED PROJECTS

PARADIGM

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