Variational Data Assimilation in Shelf Circulation Models

Alexander L. Kurapov
College of Oceanic and Atmospheric Sciences
Oregon State University
104 COAS Admin Bldg.
Corvallis, OR, 97331-5503
phone: (541) 737-2865 fax: (541) 737-2064 email: kurapov@coas.oregonstate.edu

Gary D. Egbert
College of Oceanic and Atmospheric Sciences
Oregon State University
104 COAS Admin Bldg.
Corvallis, OR, 97331-5503
phone: (541) 737-2947 fax: (541) 737-2064 email: egbert@coas.oregonstate.edu

John S. Allen
College of Oceanic and Atmospheric Sciences
Oregon State University
104 COAS Admin Bldg.
Corvallis, OR, 97331-5503
phone: (541) 737-2928 fax: (541) 737-2064 email: allen@coas.oregonstate.edu

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LONG-TERM GOALS

The long-term goals of this research project are to advance data assimilation (DA) methods for coastal ocean circulation models. After several years of research focused on various aspects of advanced, variational DA with nonlinear coastal ocean models, we are coming close to development of an optimal, versatile, and relocatable DA system based on a primitive equation model with a turbulence submodel. The system can be used efficiently both for operational needs (forecasting, search and rescue, environmental response) and for fundamental studies of coastal ocean dynamics. The modeling system will have the capability to assimilate time-series measurements from moorings and coastally-based high frequency (HF) standard- and long-range radars, satellite information (SSH, SST), and hydrographic survey data (including observations from underwater gliders).

OBJECTIVES

Scientific and technological objectives of this project include:

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- Development of a data assimilation system that utilizes the advanced variational representer method with a nonlinear three-dimensional model of ocean circulation over shelf and in the adjacent interior ocean energized by coastal flows (a coastal transition zone, CTZ).

- Testing this data assimilation system with observations available along the Oregon coast.

- Understanding the impact of assimilating satellite observations (alongtrack SSH, SST composites) and in-situ observations (HF radar surface velocities, moored velocities, glider hydrographic transects) to improve accuracy of prediction of the oceanic currents and hydrographic conditions, including short term (3-6 day) forecasts.

- Understanding co-variability of shelf and interior ocean processes, using assimilation results and computations of representers (elements of the time- and space-dependent model error covariance) in idealized and realistic ocean conditions.

APPROACH

The proposed research involves a systematic continuation of work in progress that has included assimilation of current measurements from moored instruments, surface velocities from an array of HF radars deployed along the Oregon coast, and satellite SSH and SST. Additional data types, including in-situ sections of hydrographic and turbulence observations, have been used to verify results of data assimilation. Studies of the data assimilation methodologies have been focused on the effectiveness of various methods, from simple (albeit suboptimal) “optimal interpolation” to more advanced variational methods. These methods have been utilized with models of increased complexity (linear models, a nonlinear shallow water model, and, presently, a three-dimensional nonlinear model of stratified flows with a turbulence submodel). The data assimilation results have been reported by Scott et al., (2000), Oke et al. (2002a), and Kurapov et al. (1999, 2002, 2003, 2005a, 2005b, 2005c, 2007, 2009a). These data assimilation studies have been complemented by the dynamical analyses of wind-driven upwelling (e.g., Oke et al., 2002b, 2002c, Kurapov et al., 2005c, Springer et al., 2009), jets in the CTZ (Koch et al., 2009), and internal tides in interaction with coastal upwelling (Kurapov et al., 2003, 2009b).

Our present approach is based on the use of the variational representer method (Chua and Bennett, 2001, Bennett, 2002) with the nonlinear Regional Ocean Modeling System (ROMS), a free-surface, hydrostatic, primitive-equation model featuring terrain-following coordinates and advanced numerics (Shchepetkin and McWilliams, 2005). The variational method with a nonlinear model requires implementation of a companion tangent linear model and its adjoint counterpart. We have developed and tested our own version of the tangent linear and adjoint codes, AVRORA (Advanced Variational Regional Ocean Representer Analyzer). The dynamics of these stand-alone codes are consistent with the nonlinear ROMS. Availability of our own tangent linear and adjoint codes has allowed us considerable flexibility in the choice of the critical details of our data assimilation system, including (i) ways in which observations are interpreted by the model and (ii) nontrivial hypotheses about error covariances for the corrected initial conditions and atmospheric forcing. Although tangent linear & adjoint ROMS codes have been distributed to the research community, those codes do not allow us similar flexibility.

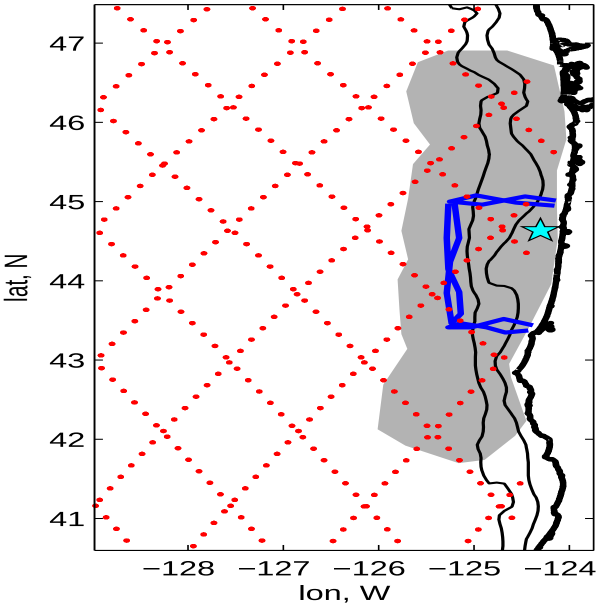

Figure 1. The Oregon coastal model domain and observations available in 2009: (shaded) area covered by HF radar surface currents (P. M. Kosro, OSU), (red dots) Jason-1 and Jason-2 SSH altimetry tracks (AVISO), (blue) glider paths (J. Barth, OSU), (star) mooring NH10 – velocity profile time series (P. M. Kosro). Bahtymetric contours shown are 200 and 1000 m.

In variational data assimilation, the improved ocean state estimate is found by solving a least-squares problem. The optimal ocean state minimizes a cost function defined as a sum of quadratic penalty terms on errors in model inputs (generally including initial conditions, boundary conditions, forcing, also possibly time- and space-distributed errors in model equations) and data-model misfits, all integrated over space and a specified time interval. Formulation of each penalty term requires specification of a corresponding error covariance. In particular, the error covariances for the model inputs can provide smoothing (filtering) of the model correction and also possibly dynamical balances in the corrected fields.

The representer-based method approaches the nonlinear optimization problem as a series of linearized optimization problems, each solved efficiently in the data subspace of the state space. The resulting optimal solution can be viewed as an objective mapping of the assimilated observations utilizing time- and space-variable model error covariances (representer functions) that depend on the assumed input error covariances and background nonlinear ocean state. The method is economical in that the model state error covariance (a very large matrix) is not computed explicitly. Utilizing the indirect represetenter algorithm (Egbert et al. 1994) as a linear solver, the method is applicable with large data sets. As for any variational method applied to a nonlinear dynamical model, the representer method requires repeated solution of the corresponding tangent linear and adjoint systems.

Our studies have been focused on an area centered on the Oregon shelf and CTZ extending between 41-47N and 124-129W (Figure 1). In preparation for assimilation tests, a 3 km resolution ROMS model has been set. Boundary information has been provided from the 9-km resolution Navy Coastal Ocean Model of the California Current System (NCOM-CCS) run at NRL (Shulman et al., 2009). Model studies without data assimilation were leveraged by efforts on the recent NOPP and GLOBEC modeling projects (Springer et al., 2009; Koch et al., 2009). Model-data comparisons using mooring, HF radar, satellite, and hydrographic section data showed that the nested model reproduces variability on the shelf and in the CTZ qualitatively correctly, including separation of jets into the CTZ (e.g., Figure 2, middle).

Following completion of the idealized tests with the AVRORA-ROMS system (Kurapov et al., 2009), we have approached assimilation of actual observations in the 3D system. To facilitate faster progress, in these initial tests AVRORA and nonlinear ROMS were implemented at 6-km resolution. Assimilation of HF radar surface currents has been done in a series of 3-day time windows (a period of summer 2008). Daily averaged maps of surface currents derived from a series of HF radars have been provided by P. M. Kosro (OSU). In a separate set of experiments, alongtrack SSH altimetry has been assimilated in 6-day time windows. A period of May-October 2005 was used for these assimilation tests since the SSH data coverage in 2005 was comparable to that in the current year (after Jason-1 and Jason-2 tracks were separated). In the 2005 study, we have utilized AVISO data from the Jason, Topex, and Envisat satellites. Currently, the work is being done to assimilate satellite SST in combination with SSH. The SST data are 5-day multi-satellite composites provided by D. Foley (NOAA).

In these data assimilation experiments, ROMS initial conditions have been corrected at the beginning of each assimilation time window with help of a multivariate dynamically consistent covariance, constructed using the balance operator and its adjoint (Weaver et al., 2005). Using this covariance, corrections to SSH, 3D velocities, and tracer fields have been provided in approximate geostrophic and thermal wind balance. The data assimilation (“analysis”) solution in every assimilation window has been compared against unassimilated data (e.g., in case of HF radar surface velocity assimilation, against SST and alongtrack SSH). Also, the forecasts have been validated against the observations in the next time window.

The work assimilating actual observations has been complemented by the analyses of the representers as functions that show zones of influence of assimilated observations. In particular, in these analyses we looked at the effect of the initial condition error covariance (balanced vs. unbalanced) and also at the propagation of the coastally trapped waves that would carry assimilated information from south to north in a realistic coastal environment.

Our progress on this multi-facet problem (involving nonlinear ocean dynamics, development of the adjoint code, optimization algorithms, massive data sets, statistical and dynamical analyses) would not be possible without coordinated work of all the collaborators. Involvement of Dr. J. S. Allen, an expert on coastal ocean dynamics and modeling, has been instrumental to the development of the dynamically balanced error covariance and interpretation of results of data assimilation. Dr. Gary Egbert has brought his expertise in variational data assimilation, in particular, effective minimization algorithms, statistical interpretation of data assimilation, and in-depth knowledge of aspects of remote sensing. Dr. Peng Yu, formerly a PhD student of Dr. O’Brien (Florida State U.) and then a JPL employee, has been hired as a post-doctoral associate in February 2009 to work on this project. Thanks to his unique combined expertise in computer science, oceanography, and variational data assimilation, he has been able to grasp the essence of our research in a very short time, to lead the effort on HF radar surface velocity data assimilation. Dr. Kurapov, the lead PI on this project has developed and advanced the tangent linear and adjoint codes AVRORA and assimilation algorithms, has provided training of the new research associate and has led the effort assimilating the satellite observations.

WORK COMPLETED

- The development of a workable version of the tangent linear and adjoint codes AVRORA has been completed. The first manuscript using these codes has been published (Kurapov et al., 2009) as part of the special issue on Data Assimilation and Modeling in Support of Coastal Ocean Observing Systems (Kurapov and Moore, 2009). Latest modifications included the radiative Flather conditions for the barotropic mode, to allow surface gravitational waves present in the initial condition correction leave the domain.

- The code implementing the initial condition error covariance based on the use of the balanced operator and its adjoint has been developed, based on ideas of Weaver et al. (2005). Since Weaver's application relies on the assumption of a reference depth with no motion, it is valid only for the deep ocean. We have introduced modification to permit application of the balanced operator in shallow water.

- The AVRORA and initial error covariance codes have all been integrated in a variational data assimilation system, using unix c-shell scripts, and tested with the actual observations off Oregon coast.

- Cases assimilating surface currents derived from a series of standard- and long-range HF radars have been run for a period of June-August, 2008. The effect of balanced vs. multivariate unbalanced covariance has been investigated. Analysis and forecast fields have been verified against the surface velocity fields and unassimilated SST maps.

- Cases assimilating alongtrack SSH altimetry have been run for a period of May-October 2005. The observed mean SSH is not directly comparable to ROMS, e.g., since ROMS uses the Boussinesq approximation and does not reproduce steric height variations, associated with water thermal expansion. To exclude assimilation of the alongtrack SSH mean level, the alongtrack SSH slope derived from the satellite data was assimilated, scaled appropriately to obtain measurements of the surface geostrophic velocity (in the direction normal to the track). Results with data from one (Jason), two (Jason and Topex), and three (Jason, Topex, Envisat) satellites have been compared. The results have been verified against satellite SST that was not assimilated. The 6-day forecasts have also been verified against SSH data from the next assimilation window. The tests assimilating SST in combination with SSH have been started.

- Representers (elements of the time- and space-variable model error covariance) have been analyzed to verify (a) the temporal extent of influence of observations, depending on the use of the balanced or unbalanced covariance, and (b) the significance of the coastally trapped wave propagation in the covariance fields.

- Dr. Peter Oke, an expert on operational data assimilation from CSIRO, Australia, visited OSU this summer. During his stay, we transferred the AVRORA-based assimilation system to him and provided training on the use of our system. Dr. Oke will intend to test our system in a regional application off Australia, as part of the ONR-funded international partnership project.

RESULTS

Tests of the AVRORA-ROMS assimilation system with a 6-km resolution coastal ocean model and actual observations of HF radar surface velocities, satellite SSH and SST have demonstrated feasibility of the application of the variational representer-based method in a real-time coastal ocean forecast system. The convergence rates are good, requiring only 5-20 iterations of the tangent linear and adjoint AVRORA models in each assimilation window to obtain sensible improvement of the initial conditions. With improved parallelization and minimization algorithm preconditioning, assimilation can be approached at better (2-3 km) resolution.

Assimilation of HF radar surface velocities (daily averaged mapped velocity fields) in a series of 3-day time windows helps to improve accuracy of both analysis and 3-day forecast surface velocity fields (Figures 2 and 3). Velocity assimilation also helps to improve the SST structure, as confirmed by statistical comparisons with the unassimilated daily SST fields. Cases with the initial error covariance based on the use of the balance operator yield better SST forecasts than the cases with the multivariate unbalanced covariance, in which initial SSH, velocity, temperature, and salinity fields are corrected independently.

Assimilation of alongtrack SSH altimetry, interpreted by our data integration system as the surface geostrophic velocity (in the direction normal to the satellite track) allows to improve the SSH model-data rms error compared to the free-run model case (in both analyses and 6-day forecast fields). Also, the geometry of the SST front in the CTZ is improved qualitatively (Figure 4). Despite each satellite provides very limited spatial and temporal coverage, compared to the scales of the coastal ocean processes (see Figure 1), observations from several satellites provide useful data density in the study area that allows constraining intensity and location of the jets and eddies in the coastal ocean. The use of the balanced covariance keeps SST values in a reasonable range even if SST observations are not assimilated. Assimilation of SST in combination with SSH would be beneficial, to inhibit unwanted extreme variations in the SST fields in the frontal region, emerging due to the limited character of the multivariate covariance and limited SSH data density.

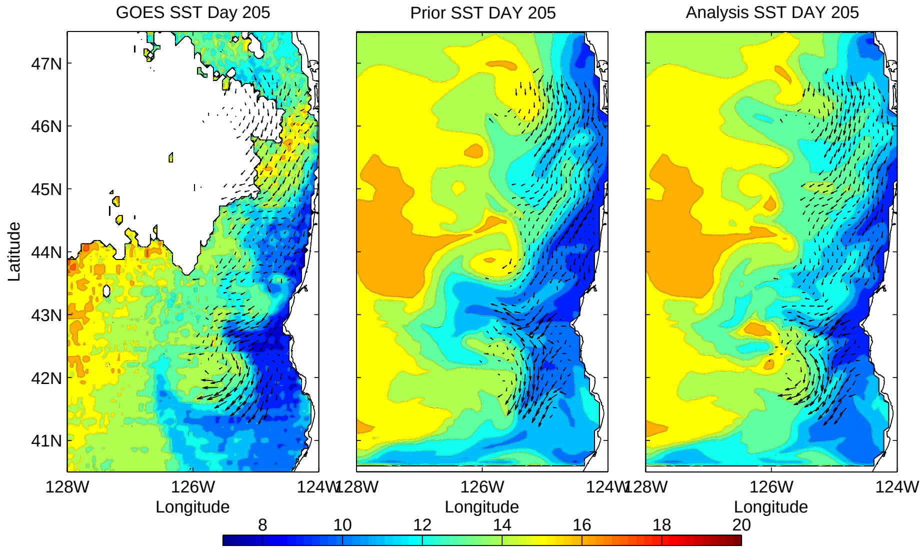

Figure 2. Assimilation of HF radar surface currents helps to improve prediction of not only currents, but also SST: (a) GOES SST (degrees C) and HF radar mapped surface velocities, day 205, 2008, (b) prior model SST and currents (shown at the same locations as observed currents), and (c) forecast (SST and surface currents), after initial conditions on day 201 were corrected assimilating HF radar currents for days 201-203 [P. Yu].

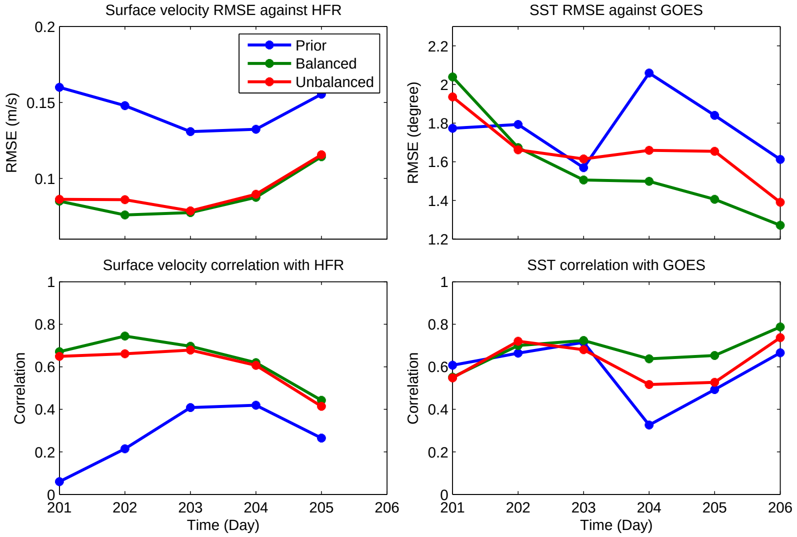

Figure 3. Improvement in the area-averaged model-data rms error (top) and correlation (bottom) with respect to assimilated HF radar surface currents (left) and unassimilated GOES SST (right). Velocities are assimilated over a 3-day period (days 201-203, 2008). Compared to the prior solution (blue), the larger improvement is obtained with implementation of the balanced initial error covariance (green) than unbalanced error covariance (red) [P. Yu].

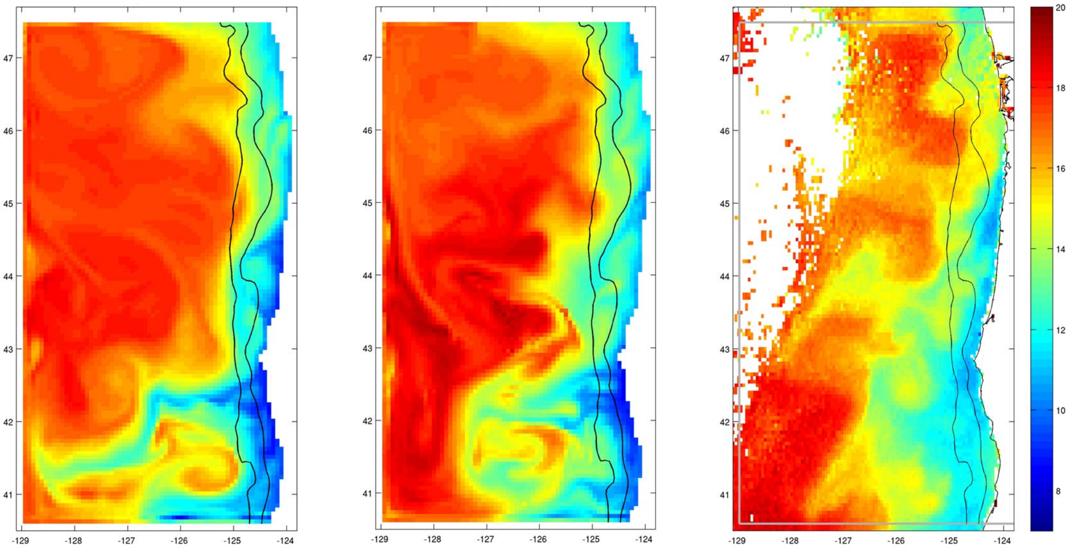

Figure 4. Assimilation of alongtrack SSH altimetry in the coastal transition zone off Oregon qualitatively improves the geometry of the SST front: (left) prior, free run 6-km resolution model, (center) model constrained by assimilation of SSH altimetry beginning June 2005, (right) verification GOES SST daily composite (all images are for 25 September 2005).

Analysis of spatio-temporal evolution of the representers has suggested that applications using the balanced covariance can utilize the observations more effectively, since the covariance (representer) loses less energy to establish the dominant balance in the correction field, compared to a case using the unbalanced initial error covariance. In a representer computation corresponding to altimeter-derived surface geostropic velocity at the location over the continental slope (Figure 5), we find that the correction is predominantly quasi-stationary, modulated by the background currents. At the same time, the propagating component is present, associated with coastal trapped waves (CTW). This analysis allows determining the dominant speed (≈3 m/s) of the CTWs in a limited-area model using realistic background hydrographic conditions. The separation of the first and second modes is also apparent.

IMPACT/APPLICATIONS

The data assimilation system that we have developed and tested will be incorporated as part of the pilot real-time Oregon coastal ocean forecast system maintained by our group, with partial funding from the regional NANOOS integrated ocean observing system (IOOS) project. The real-time assimilation experiment is planned to begin in May 2010 and run at least until the end of the upwelling season (October). Based on this experience, we will outline requirements for making our assimilation system a relocatable tool for naval and civilian applications.

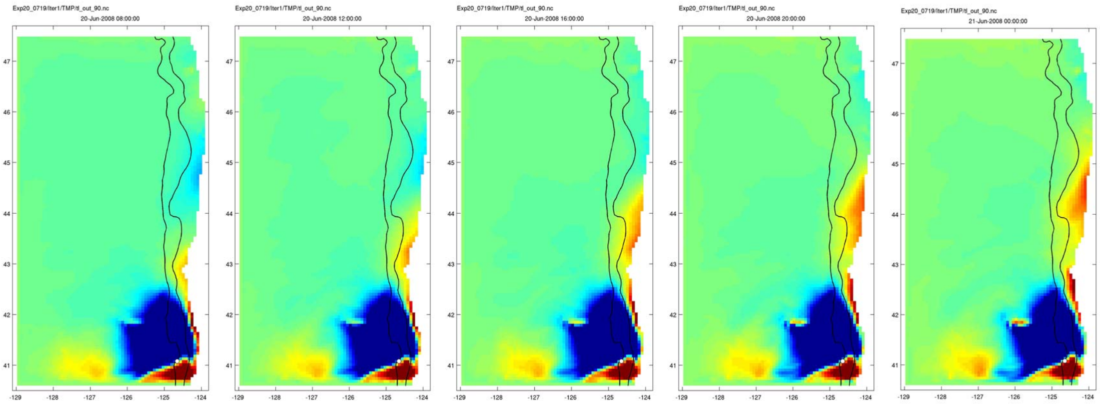

Figure 5. Analysis of the time evolution of the representer function, in this case corresponding to the observation of the SSH altimeter-derived geostrophic velocity on the continental slope near the southern boundary, shows alongshore propagation of the SSH model error with coastally trapped waves (left to right: snapshots of the SSH component of the representer at 6, 10, 14, 18, and 22 h after the measurement was done). The estimated 1st mode phase speed is 3 m/s.

TRANSITIONS

The pilot real-time coastal ocean forecast system that has incorporated our best model option tested in the scope of this project has been run quasi-operationally, providing daily updates of 3-day coastal ocean circulation forecasts (so far, without data assimilation). These forecasts have been transferred to our colleagues in the IOOS project who have developed a series of user-friendly products (www.orcoos.org). A community of local fishermen has visited the forecast website regularly to help plan their fishing trips (in summer 2010, up to 200 unique hits on the forecast web-sites were registered every week). Useful dialogue with these users has been established.

The assimilation system package, including AVRORA, data-processing and minimization software, has been transferred to SCIRO, Australia (Dr. Peter Oke) for testing in a regional application as a part of a US-Australia Navy partnership project.

RELATED PROJECTS

Enhancement of the Northwest Association of Networked Ocean Observing Systems (NANOOS) Regional Coastal Ocean Observing System (RCOOS), NOAA, 2007-2010: Real-time coastal ocean forecast model has been supported and advanced (see section TRANSITIONS above).

Prediction and forecasting of hypoxia conditions along the Oregon coast, NOAA Cooperative Institute for Ocean Satellite Studies (CIOSS), 2009-2010: The Oregon coastal ocean model of the class used in our studies has been coupled with the bio-chemical model, including the oxygen component, to study details of physical-biological interactions that can lead to hypoxia on the Oregon shelf.

Modeling and Assimilation of Internal Tides in Interaction with Subinertial Wind-Forced Flows in the Coastal Ocean, NSF, 2007-2010: As part of this project, we have developed and analyzed a 1-km horizontal model, describing wind- and tide-driven flows in combination. Analyses at this high resolution provide information on possible sources of error in a lower resolution data assimilative model, associated with unresolved horizontal and vertical momentum, heat, and salinity fluxes.

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