

# **Assessing the Impact of GODAE Boundary Conditions on the Estimate and Prediction of the Monterey Bay and California Central Coast Circulation**

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## **LONG-TERM GOALS**

The practical demonstration of basin-scale ocean state estimation has been realized through the Global Ocean Data Assimilation Experiment (GODAE) whose projects provide complete descriptions of the temperature, salinity, and velocity structure of the global ocean. The ocean circulation, temperature and salinity distributions of coastal regions are characterized by smaller scale processes typically not resolved by basin-scale estimates of the ocean structure. The overarching goal of this project is to assess the impact of the large-scale ocean structure (as produced by GODAE), when used in conjunction with satellite observations, on the numerical prediction of the coastal ocean environment.

## **OBJECTIVES**

Although the coastal circulation of the Monterey Bay and greater California central coast is in part driven by strong local forcing when present, the generally narrow continental shelf and open coastline of this region also leave it exposed to the energetic circulation of the California Current System offshore and more generally to the stratification and transports of the eastern Pacific ocean. The objective of this proposal is to use the Regional Ocean Modeling System (ROMS) and a recently developed suite of numerical tools (the ROMS 4 Dimensional variational data assimilation, ensemble prediction, and generalized stability analysis toolkits) to quantitatively explore the influence that open boundary conditions from Global Ocean Data Assimilation Experiment (GODAE) products and satellite-derived data have on the observability and predictability of the circulation in this coastal region.

## **APPROACH AND WORK PLAN**

Using ROMS and its newly developed set of analysis tools, this project will (1) investigate the sensitivity of specified metrics to the imposed boundary conditions and surface forcing fields using the ROMS adjoint model and ROMS 4-dimensional variational assimilation capability; (2) measure the mean and variance of metrics obtained from perturbed ensemble calculations; (3) analyze representor functions to identify regions observable and unobservable to boundary (GODAE) or surface forcings and recommend observations of particularly high or valuable information content for future ocean observing systems. In addition, we will (4) explore feedbacks between the ocean temperature and atmosphere for weather prediction; and (5) develop oceanographic feature tracking capability useful for both model and data analysis. Our domain of interest is the central California coast, and the time-period of focus is 2002-2004 which represents a period of excellent overlap between the basin-scale state estimate and existing coastal observations.

Several partners are responsible for the key components of the program. Dr. C. Edwards (UCSC) and Dr. A. Moore (formerly at CU, now at UCSC) carry out the development and execution of the high resolution modeling, data assimilation, sensitivity analysis, and ensemble prediction of the central California coast region. Dr. C. Wunsch (MIT) is responsible for the basin-scale ocean state and uncertainty estimates from the global ocean model as produced by the GODAE project, Estimating the Circulation and Climate of the Ocean (ECCO-GODAE). Dr. J. Doyle (NRL) provides best-estimate atmospheric fluxes from a high resolution, data-assimilative atmospheric model (COAMPS<sup>TM</sup>- the Coupled Ocean/Atmosphere Mesoscale Prediction System), and will analyze feedbacks to meteorological prediction. Dr. F. Schwing (NOAA/ERD) and D. Foley (NOAA/ERD) provide support for satellite data products and will develop methods of analysis for tracking mesoscale ocean features.

In the first two years of the project, we have made significant progress toward several components of the research. In particular, we have (1) coupled the ECCO-GODAE output to the ROMS California coastal region implementation; (2) carried out sensitivity calculations using the ROMS adjoint model to understand the sensitivity of chosen metrics to open ocean and surface forcing; (3) completed COAMPS reanalysis simulations to provide ocean fluxes from January 2002 through July 2003; (4) developed a new, blended sea surface temperature product; (5) developed a strong-constraint 4-Dimensional data assimilative model within the ROMS California central coast model, and (6) created the project website.

Over the next year, we will (1) complete our investigation of circulation sensitivities using the ROMS adjoint model; (2) analyze the sensitivity of the data assimilative model to boundary conditions; (3)

analyze circulation metrics using ensembles of California central coast model runs; (4) examine the feedback from ocean SST to regional atmospheric motions using the COAMPS adjoint model; (5) continue to provide support for ECCO-GODAE products; and (6) finalize our oceanographic feature tracking capability.

## WORK COMPLETED

In the first two years of this project, we have made significant progress in several tasks. Task 1 is finished, Task 9 is substantively completed, and tasks 2, 3, 6, 7, and 8 are at various stages of completion. Task 1 refers to the linkage between the ECCO-GODAE output and the regional ocean model whose domain is shown in Figure 1. We have linked the global ocean estimates of ocean velocity, temperature and salinity as produced by the ECCO-GODAE project as a boundary condition for the 10 km resolution regional circulation model of the U.S. west coast.

Task 2 concerns the development of a regional data assimilation system. A substantial portion of this task has been accomplished during this reporting period. Our data assimilative implementation applies an incremental strong constraint approach for the California central coast model. Although important modifications to the details of the procedure will continue over the next year, remotely sensed data products (sea surface temperature and sea surface height) are now being assimilated into the 10 km model grid, providing best estimates for the 2000-2004 period.

Task 3 centers on the adjoint sensitivity studies. Circulation sensitivity must be defined relative to some metric characterizing the ocean circulation. Over the last year, we have examined several metrics that represent either local measures of the circulation (e.g., due to coastal upwelling) and larger scale California Current System processes. We have investigated both seasonal changes to these sensitivities as well as characterized their multi-annual variability over the 2000-2004 period.

For Task 6, we have performed high-resolution simulations using NRL's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS<sup>®1</sup>). COAMPS is made up of the 3-dimensional NRL Atmospheric Variational Data Assimilation System (NAVDAS) for constructing atmospheric analyses; the NRL Coupled Ocean Data Assimilation (NCODA) analysis system for constructing ocean analyses; a nested, nonhydrostatic model for the atmosphere; and the NRL Coastal Ocean Model (NCOM). In this project, we have used the atmospheric components of COAMPS to generate historical datasets of high-resolution atmospheric forcing fields and provide these to ocean models for evaluation in ocean models. We established a COAMPS area using 4 nests (81, 27, 9, and 3 km) for the eastern Pacific to provide forcing fields for the NOPP ocean modeling activities on the west coast of the U.S. 15-hour forecasts are being generated twice-daily in real-time (0000 and 1200 UTC), with the fields necessary for ocean model forcing transferred to a ftp server. Completion of this historical dataset will allow ocean researchers to use high-resolution COAMPS fields for forcing ocean models

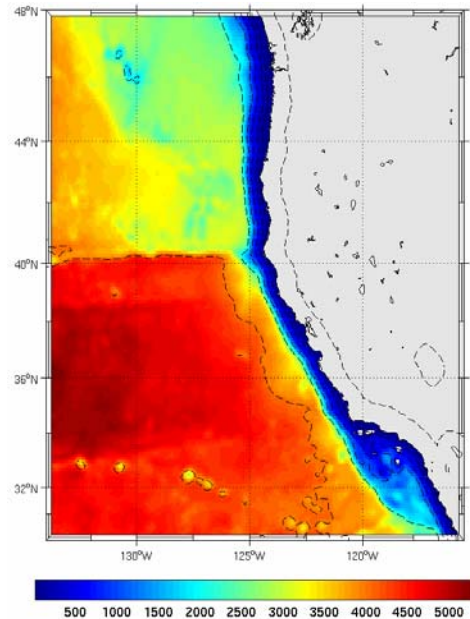


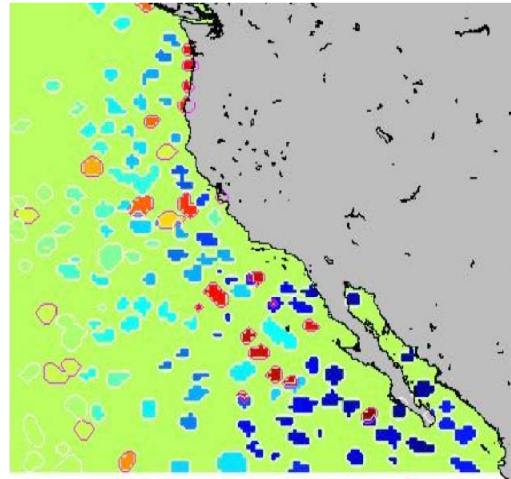
Figure 1: Ocean bathymetry (m) for ROMS grid; nominal resolution of 10 km.

<sup>1</sup> COAMPS<sup>®</sup> is a registered trademark of the Naval Research Laboratory.

for historical cases and/or long-term spin-up runs. We have also evaluated these atmospheric forcing fields using existing observations such as NWS buoys. To date, the forecasts have been completed for the time period 1 January 2002 through 30 November 2006.

Task 7 concerns the support of the ECCO-GODAE community which has been continual and ongoing since the start of the project. An example over the last year is facilitating access to daily snapshot model output to be compared with the more standard monthly output to test if regional model dynamics are significantly altered through inclusion high temporal frequency information at the boundaries.

Task 8 relates to oceanographic feature tracking. During FY07, the feature analysis team concentrated on developing feature recognition tools using the satellite data alone. This included the development of eddy detection and tracking software (courtesy of Stephanie Hanson, U. Maine) which has been applied successfully to altimetric data for the California Current System. An example of this new capability, which reveals eddy positions from an image of sea surface temperature, is shown in Figure 2. Accordingly, we think this may form the basis for a bulk metric appropriate for evaluation of model dynamics. During FY08, we plan to develop a tool box of such metrics, using other data fields such as temperature and salinity.



*Figure 2: Eddies detected in the California Current System using the developed technique.*

Task 9 refers to the project website. This task is substantively finished though ongoing modifications will continue throughout the duration of the project. A website has been created and posted (<http://codae.pmc.ucsc.edu>). This website provides an overview of the project. One subpage describes the geographical setting of Monterey Bay and the Central California coast. A second presents the ROMS model, the COAMPS effort, and ECCO-GODAE project. Another page covers the observational data that is relevant for this region. And a final page briefly describes methods applied in this project. Several links to related projects, institutions, and agencies are easily accessible and direct reference to NOPP and other funding agencies is provided on each page.

## **RESULTS**

The completion of Task 1 represents a meaningful accomplishment as it is a demonstration of interoperability between ocean models of highly different structure. The ECCO-GODAE product derives from an ocean model discretizing the equations of motion using horizontal levels. In contrast, the regional model of the central California coast has a coordinate system that follows ocean bathymetry. Forward model runs forced by COAMPS atmospheric model output on the grid shown in Figure 1 were evaluated against hydrographic data collected during California Cooperative Fisheries (CalCOFI) cruises for the period from 2000 to 2004. Model-data misfit in the upper 100 meters was largely influenced by surface forcing, but deeper hydrographic structure showed greatest agreement with observations using ECCO-GODAE, as opposed to climatological, boundary conditions. When using ECCO-GODAE output and compared to all CalCOFI cruises in the 5-year period, we find a maximum mean temperature error of 0.5 degrees at about 100 m depth and a maximum mean salinity error of 0.2 psu at about 200 m depth.

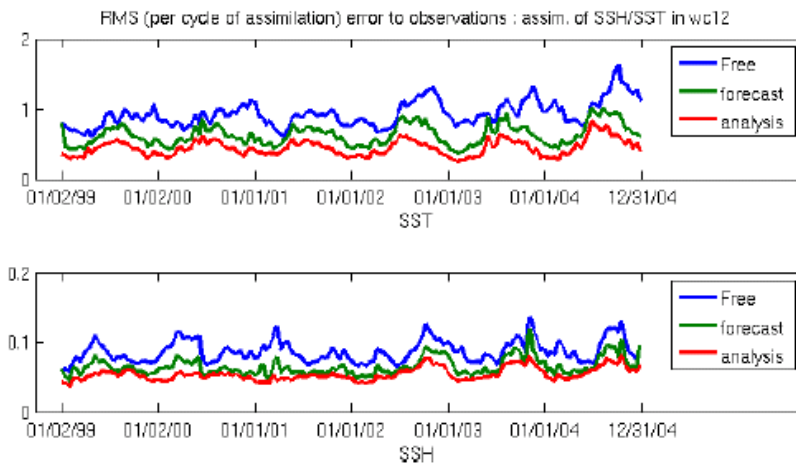


Figure 3: Time series of root-mean square (RMS) error between model and data. Top: sea surface temperature (degrees); Bottom: sea surface height (m). Blue: forward model. Red: model with assimilation. Green: forecast following assimilation

(RMS) error between the 10 km CCS model and observations of SST (degrees; top panel) and SSH (m; bottom panel). In each panel, the blue curve represents the RMS error of the forward model with no data assimilation, and the red curve indicates the error when data is assimilated. As expected, model runs assimilating data always result in smaller error than free running simulations. The green curve in the figure represents the RMS error of forecasts created using the forward model but initialized with an ocean state that results from assimilation of the previous assimilation cycle; as a result, this green curve reveals the impact of data assimilation using independent data. As shown in the figure, improvements to SST and SSH persist for the 14-day cycle following assimilation. This result is an important demonstration in a coastal model of the value of data assimilation beyond the period in which data is directly assimilated.

To carry out Task 3, we have defined several metrics that characterize the coastal circulation and determined their sensitivity to state variables and forcing using the ROMS adjoint model. We have specifically defined metrics that we believe characterize both local and larger-scale circulation features. For example,  $J_{SST}$ , the sea surface temperature squared and averaged over 14 days and over in a limited region off the central California coast, is a measure of the local upwelling circulation. In contrast,  $J_{SSH}$ , the square of the sea surface height in a similar coastal region, is more subtly influenced by remote processes through coastal wave propagation. While these statements are consistent with our general understanding of ocean physics, the purpose of our project has been to quantify the relative influences of different forcings and their local and remote nature on seasonal and lower frequency time-scales using the ROMS adjoint. For example, when averaged over the full 5 year period of our

For Task 2, we have constructed an Incremental Strong Constraint 4-Dimensional Variational (IS4DVAR) data assimilation system for the California Current System. We assimilate sea surface temperature provided by COAMPS and sea surface height provided by the Aviso/Altimetry group. Assimilation occurs on 14-day cycles in which the initial model state is adjusted to best fit in a least-squares sense the available data by minimizing a cost-function comprising the sum of the squared model-data misfits and squared deviations from an initial background trajectory. Figure 3 presents the root-mean-squared

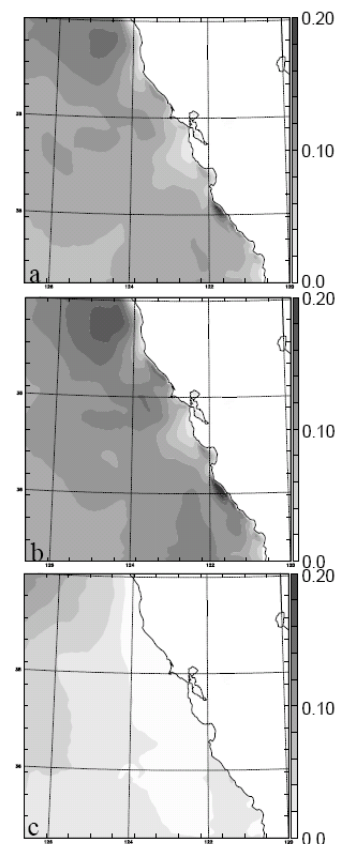


Figure 4: The surface wind stress ( $N m^{-2}$ ) for the a) August 2003, b) upwelling-favorable, and c) relaxation dominated time periods for the fourth grid mesh (3-km resolution). The shading interval is  $0.02 N m^{-2}$ .

study,  $J_{SST}$  described above is influenced nearly equally by wind-stress, heat flux, and initial sea surface temperature conditions, with less than 3% influence arriving from the boundary regions. In contrast,  $J_{SSH}$  described above is most strongly influenced by wind stress and to a lesser extent by initial velocity conditions, with up to 40% of the sensitivity due to the boundary regions. Other metrics examined include one for cross-shelf transport along the central California coast and another for basinwide barotropic kinetic energy. These metrics indicate much greater sensitivity to local forcing than to boundary regions. From analyses such as these, we argue that over 14-day periods the most important forcing for a regional model of the California Current System is the surface forcing with the boundary conditions playing a secondary, though still quantitatively significant role.

In support of Task 6, COAMPS has been run in a domain over the eastern Pacific using 4 nests (81, 27, 9, and 3 km) to provide the high-resolution fields for the ocean models in this project. The simulations were run on an SGI Origin 3900. The simulations used 40 levels in the vertical with high resolution in the lower troposphere to resolve the marine boundary layer and inversion adequately. The COAMPS simulations have been compared with numerous available observations. For example, statistics have been computed for the Monterey, San Francisco buoys as well as the MBARI M1 and M2 moorings. The verification statistics indicate wind speed biases of  $1 \text{ m s}^{-1}$ , direction biases of approximately 10-30 degrees, and temperature biases of 0.1 to  $1.5^\circ\text{C}$  for August 2002. The mean surface stress fields are shown in Fig. 4 for August 2003. The mean stress (Fig. 4a) indicates enhanced maxima in the lee of the Santa Cruz Mountains and downstream of Point Sur. A considerable enhancement to the stress maximum is apparent in the mean fields comprising the upwelling regime (Fig. 4b), particularly in the lee of the capes with a nearly twofold increase in the surface stress magnitude along the Big Sur coastline relative to the monthly mean. Additionally, a broad stress maximum parallels the coast in the stronger flow periods. During the relaxation periods (Fig. 4c), the stress and stress gradients are considerably reduced.

## **IMPACT AND APPLICATIONS**

### **National Security**

The improved estimate and prediction of the coastal ocean circulation can contribute toward U.S. Naval operations in coastal waters and U.S. Coast Guard search and rescue.

### **Quality of Life**

Although this project focuses on the sensitivity of the coastal circulation, temperature and salinity structure, with an ultimate goal of improved state estimation and prediction, such information in combination with data assimilative biological models has the potential to contribute positively to ecosystem health and ultimately fisheries management. An understanding of the sensitivity of the coastal circulation to open ocean and surface forcing may aid in the prediction of pollutant dispersion as well as the fate of harmful algal blooms.

### **Science Education and Communication**

Results from this investigation will be incorporated into graduate student education at the partner institutions as well as to the greater public via the project web site.

## RELATED PROJECTS

The NOPP-funded ECCO-GODAE (Estimating the Circulation and Climate of the Ocean – Global Ocean Data Assimilation Experiment) project (<http://www.ecco-group.org/>). The goal of this project is to provide the best estimate of the ocean state (temperature, salinity, 3-dimensional velocity) on a global scale for the period from 1992 through 2004 by assimilating multiple, varied datasets into a 3-dimensional general circulation ocean model (MITgcm). This global ocean state estimate is critical to the present project by supplying necessary initial and boundary conditions for the regional model.

The NOAA-funded Center for Integrated Marine Technology (CIMT) (<http://cimt.ucsc.edu/>). This project, also known as “Wind-to-Whales,” has collected years of physical and biological observations of the Monterey Bay area to characterize the link between physical forcing and biological production at many trophic levels. The datasets collected by CIMT can be used as independent checks on the regional model fidelity.

The NOAA CoastWatch mission (<http://coastwatch.noaa.gov/>). NOAA’s CoastWatch oceanographic satellite data in near real-time and provides access for federal, state, and local marine scientists, coastal resource managers and the general public. CoastWatch represents a critical link to the satellite SST data for the present project.

The provision of sea surface temperature (SST) data for assimilation into the models included the development of a new product blended from a variety of sensors. This blending helps to mitigate the obscuring effects of clouds on infrared measurements without the use of interpolation. The product developed for this project also found application with the Tagging of Pelagic Predators program ([www.topp.org](http://www.topp.org)), and part of the Census of Marine Life ([www.coml.org](http://www.coml.org)) and efforts to model Cetacean populations aimed at eliminating adverse interactions with humans. Work in FY08 will focus on incorporating this product within the auspices of the GHRSSST ([www.ghrsst-pp.org](http://www.ghrsst-pp.org), Global High-Resolution SST Pilot Project), an international program seeking to generate the highest quality SST.

The ONR-funded Intra-Americas Sea (IAS) project (<http://marine.rutgers.edu/po/ias/index.php>). The goal of this project is to demonstrate the utility of ROMS data assimilation and ensemble prediction in a real-time sea-going environment aboard a Royal Caribbean Cruise Line cruise ship, the Explorer of the Seas. It is closely related to the present project in the application of ROMS tools for data assimilation, though in a very different dynamical environment.

COAMPS (<http://www.nrlmry.navy.mil/coamps-web/web/home>) will be used in related 6.1 projects within PE 0601153N that include studies of air-ocean coupling and boundary layer studies, and in related 6.2 projects within PE 0602435N that focus on the development of the atmospheric components (QC, analysis, initialization, and forecast model) of COAMPS. The fields from our atmospheric forecasts over the eastern Pacific will be used by scientists at NRL SSC and at the Naval Postgraduate School within their joint National Oceanographic Partnership Program (NOPP), to study air-ocean coupling processes on the west coast of the United States, as well as with other national and international collaborators. This work complements the CenCOOS ([www.cencoos.org](http://www.cencoos.org)) and COCMP ([www.cocmp.org](http://www.cocmp.org)) initiatives as well as the ONR Assessing the Effects of Submesoscale Ocean Parameterizations (AESOP) program and the Autonomous Ocean Sampling Network II (AOSN II) program.

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