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.

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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 representer 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™- the Coupled Ocean/Atmosphere Mesoscale Prediction System), and will analyze feedbacks to meteorological prediction. Dr. F. Schwing (NOAA/PFEL) and D. Foley (NOAA/PFEL) provide support for satellite data products and will develop methods of analysis for tracking mesoscale ocean features.

In this first full year 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; and (5) created the project website.

Over the next year, we will (1) continue to investigate circulation sensitivities using the ROMS adjoint model; (2) develop the strong constraint data assimilation capability within the ROMS California central coast model, focusing on assimilation of satellite-derived products (sea surface height and temperature); (3) perform COAMPS reanalysis simulations from August 2003 through December 2004; (4) continue to provide support for ECCO-GODAE products; (5) begin investigation of oceanographic feature tracking; and (6) continue to enhance the project website.

WORK COMPLETED

In the first year 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. 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 regional circulation model of the U.S. west coast. Note that this accomplishment also required the partial fulfillment of Task 7, the support of the ECCO-GODAE team.

Task 2 concerns the strong constraint data assimilation. This task has been delayed due to a change in employment of co-PI Andrew Moore (formerly at CU and now at UCSC). Despite the resulting delay in funding associated with necessary institutional and agency approvals, progress on this task has begun through improvements in the ROMS adjoint sensitivity driver and will proceed more rapidly in year 2 of this project.

Task 3 centers on the adjoint sensitivity studies themselves. Circulation sensitivity must be defined relative to some metric characterizing the ocean circulation. We have defined two local measures of the circulation relating to coastal upwelling. The first is a horizontally averaged Sea Surface Temperature squared ($J_1=\langle SST^2\rangle_{xy}$) and the second is section-averaged, cross-shore velocity squared ($J_2=\langle u^2\rangle_{yz}$), where <> indicates averaging in the plane indicated by the subscripts. With these metrics we have calculated the sensitivity to changes in the ocean state and forcing fields for the year 2002.

Task 6 concerns the COAMPS runs and analysis. We have performed high-resolution simulations using NRL's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®[1]). 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. For historical periods, 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 allows ocean researchers to use high-resolution COAMPS fields for forcing ocean models 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 July 31 2003.

While the main thrust of Task 8 is oceanographic feature tracking, a necessary precursor is a surface field of highest quality. As a result, the satellite data team spent much of 2006 developing and generating a blended sea surface temperature product for use in feature tracking and ultimately

1 COAMPS® is s registered trademark of the Naval Research Laboratory.

assimilation into the ROMS models. The product combines data from a variety of platforms, and includes both infrared and microwave-based measurements. The data are combined in 5-day mean values, inversely weighted by the nominal errors associated with each instrument. For example, for a given pixel centered at longitude $x_{i,j}$ and latitude $y_{i,j}$ we find the mean temperature, T_n to be

$$T_{ij} = \Sigma_n \; a_n \; \Sigma_k \; T_{ijk} \quad * \; (\Sigma_n \; a_n)^{-1}$$

for all k such that the time, t_k is within a given 5-day period, and for all n independent measurement devices, where a_n gives the weights applied. In general, data from four platforms were used: (1) The Imagers carried aboard the NOAA Geostationary Operational Environmental Satellites (GOES); (2) the Advanced Very-High Resolution Radiometers carried aboard the NOAA Polar-orbiting Operational Environmental Satellites (POES); (3) the Moderate resolution Imaging Spectrometer (MODIS) carried aboard the NASA's Aqua spacecraft; and (4) the Advanced Microwave Scanning Radiometer (AMSR-E), carried aboard the Aqua spacecraft.

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. As the project proceeds, the webpage will be further populated with research results.

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. Although we expect to learn considerably more about the ways in which these heterogeneous models interact at the open boundary as this project proceeds, our initial implementation of their coupling is a very positive development. Forward model runs on the outermost grid of Figure 1 were evaluated against hydrographic data collected by the California Cooperative Fisheries (CalCOFI) cruises for the year 2002 following a 10-year spinup using NCEP Reanalysis forcing 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.

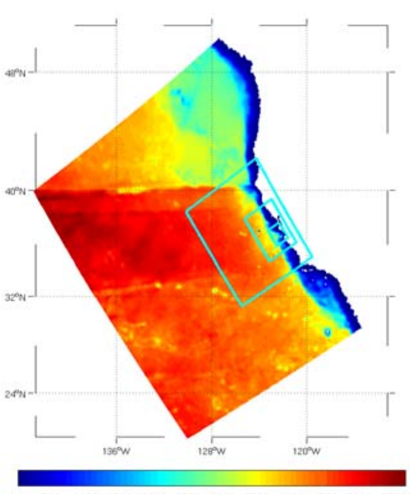

Figure 1: Ocean bathymetry for 4 ROMS grids with nominal resolution of 10, 3, 1, 0.4 km

To carry out Task 3, metrics that characterize the coastal circulation are defined, and their sensitivity to state variables and forcing fields are determined using the ROMS adjoint model. Thus far, the sensitivity of two metrics have been examined, one for sea surface temperature over a region off the central California coast and one for cross-shelf transport across a section just beyond the continental shelfbreak. Both show a seasonally dependent sensitivity to surface momentum and heat fluxes. During summertime, for example, the cross-shore transport metric is increased with equatorward winds, consistent with an enhancement to an upwelling circulation. We have found that this dependence is most clear during summertime. During non-upwelling periods, the mean sensitivity is reduced and can change sign. Figure 2 shows an example of the SST metric sensitivity: for the July-September period of 2002, SST^2 averaged within the black polygon changes most rapidly for the indicated structure of alongshore wind stress. These particular metrics, which depend on nearshore fields, have shown dominant sensitivity to local forcing, with very small quantitative impact associated with the open boundary conditions. Our project will continue to explore how these and other measures of the regional circulation depend on larger-scale and local forcing.

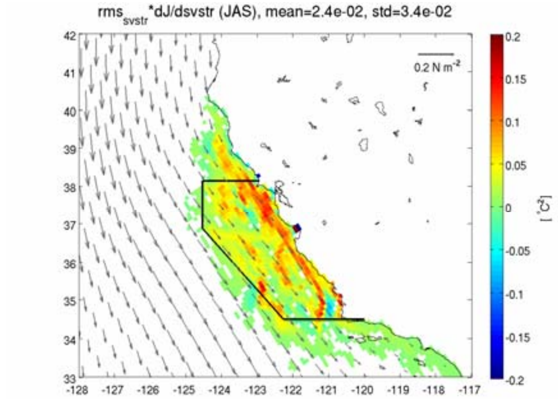

Figure 2: The change in SST^2 averaged within the polygon to local changes in alongshore windstress for the July-September period, 2002. Vectors show mean windstress.

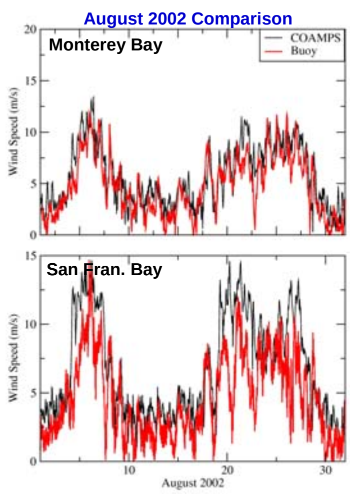

Figure 3 *Comparisons between NWS buoys at Monterey Bay and San Francisco Bay and the COAMPS 1-12h forecasts (hourly data) during August 2002.*

In Task 6, COAMPS reanalysis was performed to provide fluxes for ocean model experiments. The COAMPS domain using 4 nests (81, 27, 9, and 3 km) over the eastern Pacific used 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 available observations. An example of a comparison between the simulated and observed wind speed is shown in Fig. 3. The COAMPS model captures the episodic strong wind periods, which are considered upwelling favorable because of the prevailing northwesterly wind direction, as well as the weak flow periods. Also apparent, the model simulates a realistic diurnal cycle in the sea breeze circulation that is forced by the coastal temperature contrast. 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 m s^{-1}, direction biases of approximately 10-30 degrees, and temperature biases of 0.1 to 1.5°C for August 2002.

In support of the ocean modeling effort and as initial steps toward completion of Task 8 (oceanographic feature tracking), the NOAA SWFSC/ERD group developed a new SST product for model/data comparison. An example of the blended product can be seen in Figure 4.

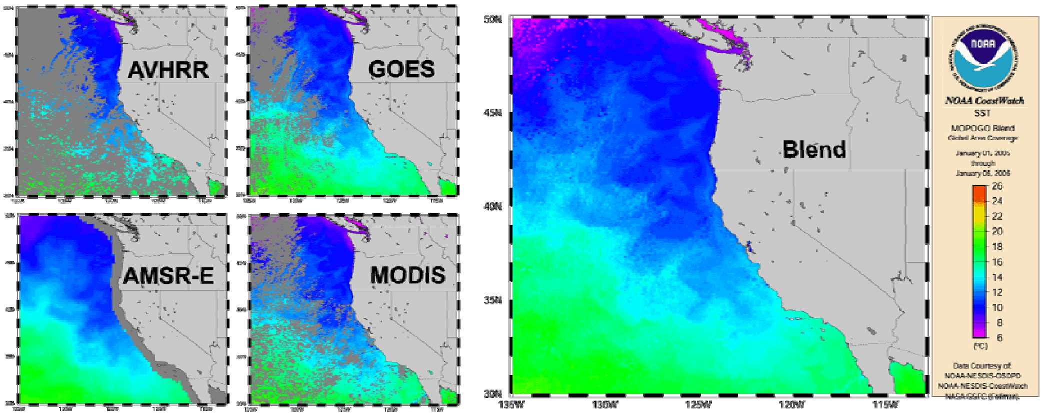

Figure 4: A sample suite of images, including the blended product, is shown for the first five days of 2005.

The Blended SST data set can be found on the SWFSC/ERD THREDDS server at: http://oceanwatch.pfeg.noaa.gov:8081/thredds/Satellite/aggregsatBA/ssta/catalog.html?dataset=satellite/BA/ssta/5day.

At the mid-year team meeting, it was clear from the sample model runs presented that the blended product was working very well as an independent check on forward model calculations (and potentially as a field for data assimilation). In fact, the averaged forward model performance was better than the base accuracy of the satellite data (Figure 5). Accordingly, the satellite team processed the entire data set from July 2002 (when the AMSR-E data begins) through December 2005 (when the pathfinder AVHRR data set ends). These data have been posted on the OceanWatch web site and are now served by a variety of means recommended by the Data Management and Communications Committee of the Integrated Ocean Observing Systems (IOOS). This product has already found extensive use by projects researching the tracks of satellite-tagged marine life (e.g., NOPP project NOPP-BAA 04-022, and the Census of Marine Life's Tagging of Pacific Pelagics Program). Applications include refinement of geolocation techniques, and the identification of essential habitat. Additionally, an analogous near-real time product has been developed and deployed to support attempts at running such models in real time. While this is beyond the scope of the current project, it is the ultimate goal of the program.

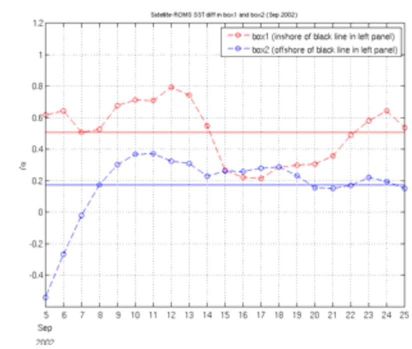

Figure 5: Satellite SST minus ROMS SST for Sept 2002, averaged over separate nearshore (red) and offshore (blue) regions.

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

By evaluating new tools to rigorously constrain general circulation models with oceanic observations, this project will contribute to science education both as a result of these new methods and through the broader oceanographic processes that they illuminate. This project contributes directly to graduate education at the partner institutions as well as to the greater public through the project website.

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 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 Carribean 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.

The NRL-supported Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) (http://www.nrlmry.navy.mil/coamps-web/web/home). COAMPS 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 initiative as well as the ONR Assessing the Effects of Submesoscale Ocean Parameterizations (AESOP) program.