Modeling the Central California Coastal Upwelling System: Physics, Ecosystems and Resource Management

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LONG-TERM GOALS

1. To develop better methods for management and protection of the California coast ecosystem as a valuable natural resource.
2. To better understand the physical and biogeochemical dynamics of the California coastal upwelling system and how it responds to changes in local and large-scale atmospheric forcing, and global change.

OBJECTIVES

To develop a coupled physical-biological model that can utilize available data to accurately simulate physical, chemical and biological processes within the Monterey Bay National Marine Sanctuary (MBNMS). To use the model to better understand the central California coastal upwelling ecosystem, its physical-biological processes, and biogeochemical and ecological material flow.

APPROACH AND WORK PLAN

The project integrates high spatial and temporal resolution simulation models of coastal ocean circulation, biological, chemical, and optical processes with rich data sets provided by earth-observing satellites and *in-situ* sensor platforms. Ultimately the model established will be a general-purpose coupled physical-biological model for regional and global application. The role of each partner is briefly described. Dr. Barber, Duke Univ. and Dr. Chai, Univ. Maine: Development and integration of a nine-component biological model; Dr. Chao, JPL: Data assimilation, operational modeling, QuikSCAT, and blended QuikSCAT/COAMPS wind products, basin-scale retrospective modeling; Dr. Chavez, MBARI: Project management, *in situ* sensors, bio-optic, biological, physical, atmospheric, and nutrient data sets, bio-optical model component integration; Dr. De Vogelaere, MBNMS: Resource management; Dr. Kindle, NRL: Production, analysis, and dissemination of high-resolution surface flux fields for the eastern Pacific, physical and biogeochemical modeling; Dr. Maffione, HOBI Labs: Development and validation of the bio-optical model component; Dr. Marinovic, UCSC: Zooplankton closure data set; Dr. McWilliams, UCLA: ROMS – Regional Ocean Modeling System; nested coupled circulation-ecosystem model; Dr. Paduan, NPS: Physical oceanography and modeling of the California coast.

Our focus continues on the implementation of a four-level (basin-50km, regional-15km, sub-regional-5km and local-1.5km) three-dimensional physical/biogeochemical/bio-optical ocean model. The models are forced with a blended high-resolution atmospheric model (COAMPS) and satellite (QuikSCAT) winds, and careful analysis of the model output. During 2003 we operated the sub-regional and local nests in operational real-time mode in collaboration with the Autonomous Ocean Sampling Network (AOSN) experiment in Monterey Bay. We continue to investigate interannual to multi-decadal variability in the California Current System (CCS), both through data analysis (Chavez et al., 2002, 2003; Marinovic et al., 2002; Nezlin and McWilliams, 2002) and with Pacific basin ROMS simulations forced by NCEP Reanalysis (National Centers for Environmental Prediction 50 year reanalysis) fields. Validation datasets for the atmospheric, physical, biogeochemical and bio-optical models are continuously updated.

WORK COMPLETED

Computer simulations that capture the structure and dynamics of physical and biological variability in the CCS remain the major focus of this effort (Marchesiello et al., 2002, 2003; Chao et al., 2003). Studies of local processes along the United States West Coast (USWC) such as those in Monterey Bay (MB) require careful attention to basin-scale and regional dynamics. Development of ROMS (Shchepetkin and McWilliams, 2003a,b) has continued in this direction within an open-boundary and embedded-grid approach (Marchesiello et al., 2001; Penven et al., 2003a). We continue development of a four-level nested model operating for Monterey Bay, at 50 km Pacific basin, at 15 km (Alaska to Baja California), 5 km (Cape Mendocino to Point Concepcion) and 1.5 km (San Francisco Bay to Point Sur) resolutions. We have been working for the past two years on a notorious problem for terrain-following atmospheric and oceanic models, i.e., sigma-coordinate pressure-gradient errors, and continue to make significant progress (Ezer et al., 2002; Shchepetkin and McWilliams, 2003a).

We have spent considerable effort verifying different atmospheric forcing products and the model sensitivities to these different products. Naval Research Laboratory (NRL) scientists produced, analyzed, and disseminated high-resolution surface flux fields for the eastern Pacific using the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS). The atmospheric portion of COAMPS and the sea-surface temperature (SST) analysis component were used to construct a multi-year time series of analyses and forecasts on a triply nested horizontal grid with resolutions of 81, 27 and 9 km (Kindle et al, 2002). The forecast model produced, on an hourly basis, all the surface fields necessary to force an ocean model: the 10-m winds, 2-m air temperature and relative humidity, surface sensible and latent heat fluxes, surface stress, precipitation, short and long-wave radiation, and sea-level pressure. A 2-dimensional variational method was developed (Chao et al., 2003) to blend the COAMPS simulated and satellite scatterometer (QuikSCAT) measured surface vector winds. The product was validated off the central California coast (Chao et al., 2003). More recently during the Autonomous Ocean Sampling Network (AOSN) experiment in August 2003 in Monterey Bay we used 3 km COAMPS winds. The analysis of the very high resolution forcing is ongoing.

From its inception, ROMS has been intended to be a multi-purpose, multi-disciplinary oceanic modeling tool. A major aspect of our current focus is the investigation of biogeochemical cycling (carbon cycle primarily) and ecosystem dynamics in a coupled mode with the physical model. Recently, however, the scope of ROMS has been extended further by the incorporation of suspended sediment transport. This submodel came with a new ability to realistically simulate tidal forcing and even wave-current bottom-boundary layer modeling. We have developed a new asymptotic theory for how to represent the dynamical coupling between surface waves, currents, and material properties (McWilliams and Restrepo, 2003) that we intend to incorporate into ROMS. In addition this year, we have developed and tested a Lagrangian model for particle trajectories in physical, biogeochemical and ecosystem problems. To take full advantage of our high-resolution solutions that exhibit small-scale structures such as localized fronts and submesoscale eddies, we have implemented an on-line, parallelized, and nested Lagrangian model.

We have implemented a ten-component multiple nutrients and plankton ecosystem model developed by Chai et al. (2002) into the 5-km resolution ROMS for the central California and Monterey Bay region. This ecosystem model consists of two classes each of phytoplankton (P1, P2) and zooplankton (Z1, Z2), dissolved inorganic nitrogen in the form of nitrate (NO_3) and ammonium (NH_4), detritus nitrogen (DN), detritus silicate (DSi), and total CO_2.

The development of a computationally rapid model for calculating the spectral irradiance attenuation coefficient of ocean waters based on the concentrations and types of constituents in the water column has been completed. This spectral light model is a quantum leap over earlier light models that have been incorporated into ecosystem or circulation and mixing numerical models. The effort during the last year has been to integrate the bio-optical and biogeochemical models.

An early version of the ROMS adjoint 3-D variational method has been developed and tested. We have conducted adjoint sensitivity analysis using the gradient of a certain measure of the model output computed with respect to perturbations in the model parameters. In addition to identify and estimate key model parameters and boundary conditions, the ROMS adjoint model has allowed us to assimilate both *in situ* and satellite observations into ROMS.

An important issue for the CCS is water retention and residence time. We have addressed retention and residence time by computing Lagrangian trajectories. At larger scales, we found that the alongshore topographic variability in Central California constrains the alongshore structure of coastal upwelling and underlying biological activity. Our coupled physical/ecosystem model shows that upwelling-induced mesoscale physics may have a strong negative feedback on nutrient input, plankton retention, and possibly larval retention in the coastal zone (Marchesiello, 2004). We have also successfully run a first test case of the coupled physical/ecosystem modelwith synoptic forcing at high resolution (Frenzel et al., 2004).

RESULTS

We have conducted extensive model and data comparisons of the regional nested fine-resolution ROMS over the Monterey Bay. The data sets include moorings, ship observations, and satellite surface measurements. Our results show that both the mean and annual cycles in the Monterey Bay can be reasonably reproduced by ROMS. These results can be viewed online at: http://www.mbari.org/bog/NOPP/models.htm. With the side boundary conditions provided by the Pacific basin-wide ROMS, we are in the process of investigating the interannual-to-multidecadal variability of the California Current system. Model-data comparisons have shown that a correct representation of the wind at the shore is mandatory to obtain realistic coastal dynamics (Penven et al., 2002). We show that COAMPS winds represent an essential improvement since they contain small-scale wind patterns (notably the sheltering of Monterey Bay), however, our solutions have revealed that the oceanic dynamical sensitivity to coastal winds justifies continued systematic wind product investigations (Capet et al., 2004). In particular, the very severe nearshore wind drop off exhibited by COAMPS winds may require further validation. We have also shown the limitations of the 5 km solutions for local areas such as Monterey Bay, and the need for better defined coastline and topography (Chao, Song et al., 2003), particularly the Monterey Canyon. Frontal dynamics, that result partly from the interaction with these geographical features, will require further attention (at high resolution the model starts producing an unstable frontal mode pattern not present in the coarser simulations).

The work by Kindle et al. (2002) utilized the observed winds from the MBARI moorings in Monterey Bay to help validate the COAMPS model winds and to demonstrate the ability of the finest COAMPS grid (9km) to accurately represent the diurnal sea breeze along the central California coast. Based on this study, a new understanding of the behavior of the sea breeze along the US west coast has been provided. When compared with independent *in situ* observations, the blended wind product (Chao, Li et al., 2003) shows consistently higher correlation and smaller RMS errors than the QuikSCAT or

COAMPS wind. The proposed wind-blending algorithm has been implemented over the Northeast Pacific Ocean in near real-time (within 24 hours) and the data can be accessed through an interactive web server at JPL (http://ourocean.jpl.nasa.gov).

The coupled ecosystem model has been validated by the comparison of the model output with data from the MBARI moorings and the California Cooperative Oceanic Fisheries Investigation (CalCOFI) Line-67 transect. Vertical distributions of nitrate, silicate, and chlorophyll concentrations generally agree. However, the model produces a lower upwelling flux in the spring and, therefore results in lower nutrient (nitrate, silicate) concentrations in the surface layer during this season. The chlorophyll concentration profiles and integrated primary production of the model better match the data. The chlorophyll concentration profiles and integrated primary production of the model better match the data. The ecosystem model also contains a formulation of the carbon cycle, which has been used to assess air-sea exchange of CO2 (Plattner et al., 2004). The 5-km coupled physical-ecosystem model has been simulated for the period from January 1999 to August 2003. The coupled physical-biological model captures the spring upwelling-driven bloom of phytoplankton along the California coast and it compares well with the SeaWiFS satellite derived surface chlorophyll estimates.

The bio-optical model has been validated against another model (Hydrolight) that solves the full radiative transfer equation, but is unsuitable for inclusion into coupled models. Comparisons of modeled attenuation coefficients with those measured *in situ*, have shown good agreement, with improvement of this agreement with the use of MBARI bio-optical datasets as model input rather than "typical" values derived in other regions.

A major effort in 2003 was our involvement in the August 2003 AOSN experiment (http://www.mbari.org/aosn and http://ourocean.jpl.nasa.gov). The AOSN experiment was an intensive experiment that occurred in Monterey Bay and the contiguous waters of the California Current System. The experiment was significant for several reasons: 1) it was the largest deployment of autonomous underwater vehicles (gliders, AUVs) to date, 2) these deployments were complemented by a wide variety of measurements from aircraft, moorings, satellites and ships, 3) coupled physical-biological models were forced by high resolution (3 km) atmospheric data in real-time, 4) the in situ data was assimilated by the models and predictions made that were verified in real-time as well, 5) a portion of the in situ assets were used to sample adaptively to improve the model predictions, 6) the combined observation and model "system is similar to that envisioned for a long-term integrated coastal US observing system, and 7) the observations and models were applied to understanding the high-frequency variations in the process of coastal upwelling and its biological consequences. The analysis efforts are a work in progress.

IMPACT AND APPLICATIONS

National Security

The ability to nowcast and forecast currents and water clarity is of great interest to Navy applications.

Quality of Life

A primary goal of the project is to aid the National Oceanographic and Atmospheric Administration (NOAA) in the management, regulation, and protection of the Monterey Bay National Marine Sanctuary (MBNMS) ecosystem. The central California coastal waters host myriad public recreational activities – i.e., surfing, swimming, kayaking, SCUBA diving, fishing, marine mammal and bird watching – which depend upon the health of the ecosystem.

Science Education and Communication

A version of the model can be used by the Monterey Bay National Marine Sanctuary it its education and outreach programs to demonstrate oceanographic and ecological principles to schools and the public at large.

CONSIDERATION FOR EXCELLENCE IN PARTNERING AWARD

1. **Ocean Sector Diversity:**
   The program is a collaboration between academic (Duke Univ., UCLA, UCSC, and Univ. of Maine), industrial (HOBI Labs), non-profit (MBARI), and governmental (MBNMS, JPL, NRL, and NPS) institutions.

2. **Partner Involvement**: The effort has been broadly distributed among the partners. UCLA has been responsible for model development, both physical and biogeochemical, JPL has taken the lead in operational modeling, NRL has contributed to atmospheric forcing as well as providing a second model for physical and biogeochemical modeling, University of Maine and Duke have implemented ecosystem models in ROMS and NCOM and further developed their state-of-the-art biogeochemical model, HOBI has been the lead in the development of the bio-optical model, MBNMS has provided guidance on management issues and MBARI has provided leadership and model validation data sets.

3. **Matching Contributions**: The project would not have been possible without many ongoing projects supported by other means. Computer time at JPL, NRL, UCLA and University of Maine has been provided free of charge. Each of these institutions has ongoing programs that have been leveraged for the NOPP effort. MBARI has directly funded ongoing field programs and collected and processed historical data sets that have been invaluable for the present effort.

4. **Partner Long-Term Commitment**: It should be abundantly clear that each of the partners has a long-term commitment to ocean observation and modeling of the US West Coast.

5. **Success in Project Objectives**: While each of the partners has a commitment to the long-term goals of the project, an effort of this dimension requires a multi-institution approach that would not have been possible without NOPP support. As described in item 2 above each of the partners has made significant contributions to the long-term goals.

RELATED PROJECTS

The MBARI Ocean Observing Systems program

The NRL project Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS).

The Innovative Coastal Observing Network (ICON) NOPP project provided the initial roadmap.

The NRL project Coupled Bio-physical processes Across the Littoral Transition (CoBALT).

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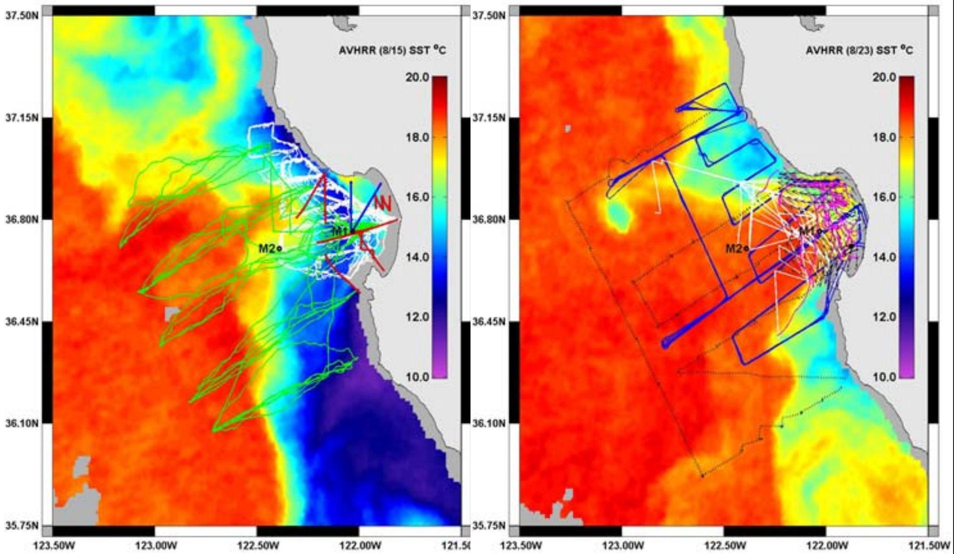

Figure 1. Assets deployed during the August 2003 AOSN experiment. In the left panel The autonomous vehicles are shown over the August 15, 2003 sea surface temperature (SST)-upwelling. In the right panel aircraft, HF radar currents, drifters, moorings, ship CTD and towfish are shown over the August 23, 2003 SST-relaxation.

SST from AVHRR and ROMS

August 15, 2003

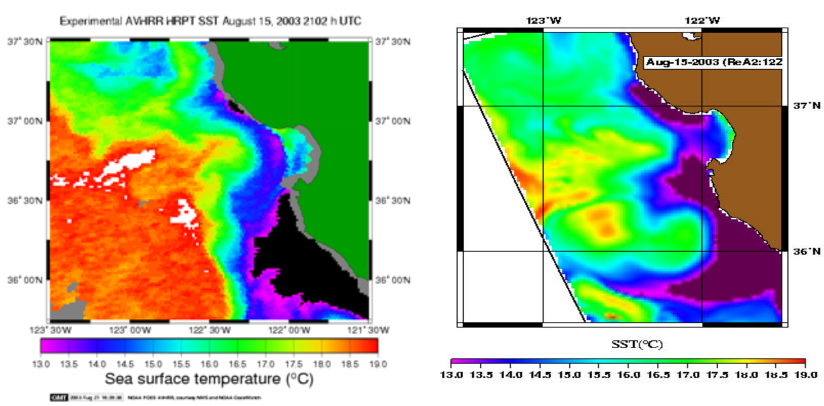

Figure 2. Comparison of satellite and modeled SST fields for August 15, 2003. ROMS assimilated the available *in situ* data except for HF radar and moorings.