A National Oceanographic Partnership Program Award

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 primary tasks for the next year are implementation of the fully coupled four-level three-dimensional physical/biogeochemical/bio-optical model forced with the blended high-resolution atmospheric model (COAMPS) and satellite (QuikSCAT) winds, and careful analysis of the model output. We expect to show that the full integration of multiple nests and modules will enhance the capability of the model in future applications. We will further investigate interannual 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 will be continuously updated.

Work Completed

Our research has focused on the structure and dynamical mechanisms of regional and mesoscale physical variability in the CCS (Marchesiello et al., 2002, 2003; Chao et al., 2003), and their biogeochemical and ecological consequences. Studies of small, near-shore regions along the United States West Coast (USWC) such as the Monterey Bay (MB) region require close coupling between the basin-scale and regional dynamics, and their local manifestations. Therefore, we continued the development of ROMS (Shchepetkin and McWilliams, 2003a,b) in this direction within an open-boundary and embedded-grid approach (Marchesiello et al., 2001; Penven et al., 2003a). We currently have a three-level nested model operating for Monterey Bay, 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. In parallel we have developed a Pacific basin-wide ROMS with a spatial resolution of 50 km. Using the NCEP/NCAR (National Center for Atmospheric Research) atmospheric reanalysis fields, we have forced the basin-scale model with 55-years of data (1948-2002). We will soon couple the three level fine-resolution model for the California Current region with the coarse-resolution Pacific Ocean basin-wide model to investigate coupling and feedback mechanisms between the large- and small-scale processes. 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 have now made 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).

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) and ecosystem dynamics (nitrogen cycle) 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.

A nine-component (diatoms, small phytoplankton, microzooplankton, mesozooplankton, nitrate, ammonium, silica, and two classes of detritus) biological model has been coupled with the three-dimensional ROMS physical model of the central California upwelling system. The biological model has also been developed into a biogeochemical model that includes the additional chemical tracers, phosphate, dissolved oxygen, total CO_2, and total alkalinity. The newly developed biogeochemical model has been used to calculate the air-sea CO_2, O_2 gas exchange, the flow of inorganic carbon, oxygen, nitrate, phosphate and silicate, and to examine the function of the biological pump. The role of the coastal upwelling system in the global biogeochemical cycle has been examined. The current biogeochemical model has recently been implemented in the basin scale (Pacific Ocean) model.

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 basic approach was to develop polynomial regression coefficients of the average cosine of the light field, $\bar{\mu}$, as a function of optical depth. These polynomial coefficients were tabulated as a function of sun angle and the single-scattering albedo of the water, ω_0, which is a function of the total scattering coefficient, *b*, and *c* the beam attenuation coefficient. By modeling $\bar{\mu}$, the irradiance attenuation coefficient is easily computed from the well-known relationship, $K(\tau) = \bar{\mu}(\tau)/a(\tau)$, where $\tau = cz$ is the optical depth. The spectral irradiance, as a function of depth, is then calculated from the relationship:

$$E(\lambda,\tau) = E(\lambda,\tau=0)\exp\left[-\int_0^{\tau}\frac{\bar{\mu}(\lambda,\tau')}{a(\lambda,\tau')}d\tau'\right].$$

Our results show that $\bar{\mu}$ is a smooth and well-behaved function that can be regressed to a polynomial; and that $\bar{\mu}$ is likewise a smooth and well-behaved function of sun angle as well. By tabulating the polynomial regression coefficients, $K(\lambda,\tau)$ can be rapidly computed as a subroutine in a coupled ocean dynamic ecosystem numerical model.

The model will eventually be capable of assimilating real-time data. A preliminary version of the ROMS adjoint data assimilation code 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 will allow us to assimilate both *in situ* and satellite observations into ROMS.

<u>Results</u>

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 preliminary 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-interdecadal variability of the California Current system. Model-data comparisons have shown that a correct representation of the wind stress curl at the shore is mandatory to obtain realistic coastal dynamics (Penven et al., 2002). These comparisons have also revealed the limitations of the 5km grid resolution 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, as well as better resolved frontal dynamics interacting with these geographical features (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 (Figure 1). 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 (Figure 1). The chlorophyll concentration profiles and integrated primary production of the model better match the data. As Monterey Bay is a partly enclosed area, an important issue is water retention and residence time, which is addressed 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 et al., 2002).

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.

Impact and Applications

National Security

With the integration of the bio-optical component, the potential exists for use in the prediction of submarine and diver visibility.

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.

Transitions

National Security

The spectral light model developed by Dr. Maffione is now being incorporated into the coupled ocean circulation-ecosystem model developed by Dr. Kindle's group at NRL. It is also being incorporated into the West Florida Shelf model developed under ONR's HyCODE program.

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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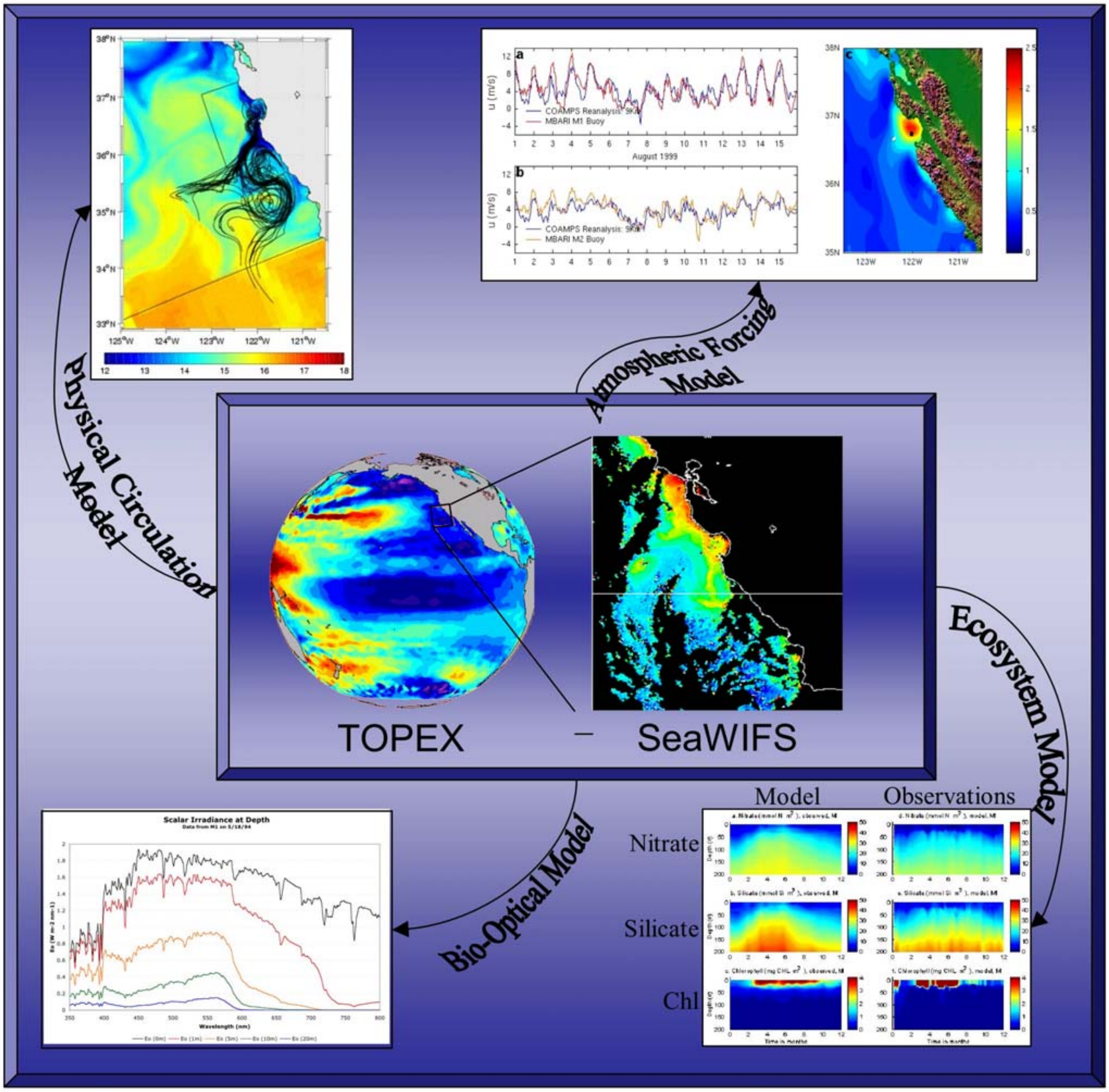

Figure 1. Central figure: Satellite derived data products e.g., TOPEX (TOPography EXperiment for ocean circulation) and SeaWIFS (Sea-viewing WIde Field-of-view Sensor). Upper left: Material trajectories for one month after release in June at 1m depth and 10 km off the coast. The colored field is a snapshot of surface temperature during the same period. The simulation has been performed over 3 levels of nested grids whose resolution is 15km (USWC), 5km (Cent. Cal. Coast) and 1.6km (MB). The grids boundaries are marked by straight black lines. Upper right: A time series of u-component of 10m wind for COAMPS (blue) and observed (red) for the moorings at M1 (upper) and M2 (lower) for August 1-15 1999. Contours (right) of amplitude (m^2/s^2) of diurnal period for August 1999 from COAMPS 9km 10m winds. Lower right: Comparison between observed and modeled vertical

distributions of nitrate, silicate, and chlorophyll concentrations at M1. Lower left: Spectral scalar irradiance ($E_0(\lambda)$; $Wm^{-2}nm^{-1}$) at various of depths (surface, 1m, 5m, 10m, 20m) at M1 for 18 May 1994.