Physical-Biological-Optics Model Development and Simulation for the Pacific Ocean and Monterey Bay, California

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LONG-TERM GOALS

Modeling and predicting ocean optical properties requires linking optical properties with the physical, chemical, and biological processes in the upper ocean. Our long-term goal is to incorporate optical processes into coupled physical-biological models for both open ocean and coastal waters, develop and improve integrated ocean forecasting systems, including prediction of ocean optical properties.

OBJECTIVES

1) To improve performance of the coupled physical-biological model, which is based on the Navy Coastal Ocean Model (NCOM) for the California Current System and Indian Ocean, and Regional Ocean Model System (ROMS) for the Pacific Ocean;

2) To incorporate optical variables into the improved coupled 3D physical-biological model for the Pacific Ocean and California Current System;

3) To evaluate physical-biological-optical models with remote sensing and available in situ observations;

4) To use these variables to drive a radiative transfer model (EcoLight) that will simulate and predict the subsurface light field as well as the ocean's color.

APPROACH

To achieve the first objective, we have conducted a series of 3D physical-biological model simulations for the Pacific Ocean, California Current System and Indian Ocean to test the model performance. Collaborating with Sergio Derada and Igor Shulman at the NRL, we have incorporated the Carbon, Silicate, and Nitrogen Ecosystem (CoSiNE) model into both the Navy Coastal Ocean Model (NCOM) for the California Current System and Indian Ocean, and Regional Ocean Model System (ROMS) for the Pacific Ocean. The CoSiNE model (Chai et al., 2002; 2003, and 2007) was developed originally for the equatorial and Pacific Ocean. During the past several years, we have improved the CoSiNE model performance, and investigated the seasonal and interannual variation of biological productivity and carbon cycle in response to both local and remote climate forcing (Chai et al., 2009; Liu and Chai, 2009a, b; Fujii et al., 2009). We have successfully transferred the updated CoSiNE model into a modular structure, which has been incorporated into other ocean models (ROMS, POM, NCOM, POP, HYCOM).

To achieve the second objective, we incorporate spectrally-resolved inherent optical properties (IOPs) into the existing ROMS-CoSiNE model. We have successfully incorporated an optical module along with a commercially available radiative transfer model (EcoLight) into a one-dimensional ecosystem model which is flexible enough that can be applied to three-dimensional circulation model (Fujii et al., 2007). Based on the success of one-dimensional model, the next step was to further improve the optical module to explicitly resolve color dissolved organic matter (CDOM) dynamics, which was treated as a constant value in the one-dimensional model, and to apply this advanced ROMS-CoSiNE-Optics model in a full three-dimensional environment. We collaborate with Dr. Curt Mobley at Sequoia Scientific to implement the updated version of EcoLight into an idealized 3D configuration of ROMS-CoSiNE model, and later on for application to the Pacific Ocean, California Current System, Indian Ocean, and the Gulf of Maine. The newly developed optical model explicitly represents spectrally-resolved IOPs including absorption, scattering, and attenuation. The optical model requires input from ROMS-CoSiNE model, such as phytoplankton associated chlorophyll and non-algal particles (NAP), and it provides outputs such as phytoplankton absorption coefficient, detritus absorption coefficient, particulate backscattering coefficient. One important improvement of this ROMS-CoSiNE-Optics model is that we have modified CoSiNE model and incorporated color dissolved organic carbon (CDOC) as a state variable, since CDOM plays an important role in absorption spectra both in the open ocean and coastal regions. The details of CDOM treatment in the model were presented in our 2009 annual report.

To achieve the third objective, the performances of the coupled ROMS-CoSINE-Optics model are evaluated by comparing the model results with synchronous MODIS AQUA measured data provided by NRL. There are a lot of algorithms being used to calculate ocean optical properties from satellite data. What we used for the model-satellite data comparison is the one called quasi-analytical algorithm (QAA) (Lee et al., 2002), which is a promising algorithm for deriving inherent optical properties from ocean color.

WORK COMPLETED

We evaluated the 3D ROMS-CoSiNE model performance for the Pacific Ocean and compared the model results with available in-situ observations. These evaluation activities comprehensively include carbon cycles (Chai et al., 2009; Fujii et al., 2009), ecosystem productivity (Liu and Chai, 2009a; Bidigare et al., 2009), biological responses to physical environment (Liu and Chai, 2009b; Palacz et al., 2010), and meso-scale eddy activities (Xiu et al., 2010).

We incorporated and updated bio-optical module and CoSiNE code in the Navy Coastal Ocean Model (NCOM) for the California Current System (CCS) and Indian Ocean. Chai visited the NRL in December 2009 and discussed NCOM-CoSiNE modeling progress with Igor Shulman and Sergio

Derada. In August 2010, Sergio Derada came to University of Maine and spent two weeks to work with Chai and his group. We have made significant progress on updating CoSiNE code and parameters and improving the optical module in the NCOM framework.

We linked the optical module, based on 1D configuration (Fujii et al., 2007), with the 3D ROMS-CoSiNE model, and incorporated CDOC into the CoSiNE and bio-optical module innthe ROMS for the Pacific Ocean. We evaluated the ROMS-CoSiNE-Optical model results with remote sensing derived IOPs and other biological variables for the Pacific Ocean with focusing on California Current System.

We have collaborated with Dr. Curt Mobley to incorporate EcoLight-S (Ecosystem Light Subroutine) into an idealized ROMS-CoSiNE model. EcoLight-S has been completely rewritten from scratch in Fortran 95 by Dr. Curt Mobley to bring it up to the standards of the ROMS-CoSiNE code. Some initial results were reported at a bio-optical modeling workshop held at the NATO Undersea Research Center in La Spezia, Italy, December 14-18, 2009. Dr. Curt Mobley also visited the University of Maine for a week in January 2010, and he plans to visit the UMaine again in November to work on the integration of ROMS-CoSiNE-Optics-EcoLight-S for the idealized model configurations.

RESULTS

There have been many publications related to the ROMS-CoSiNE modeling work, we are not including these results in this report. Here, we report the results related to the optical model development and model evaluation with remote sensing observations. Performance of the coupled ROMS-CoSINE-Optics model are evaluated by comparing the model results with synchronous MODIS AQUA measured data provided by NRL. CalCOFI region is chosen as the model evaluation area, where ocean processes has been studied extensively for the past several decades. We compose our 3-day model outputs into weekly products in order to compare with satellite data. The model is initialized with climatological data and has been forced by realistic wind, air-sea fluxes of heat and freshwater. Figure 1 shows the spatial averaged of the model outputs for CalCOFI region. On seasonal basis, the model successfully captures the temporal variations of both biological activities and associated optical properties. Modeled CDOM absorption coefficient coincides with QAA CDOM product very well, which shows a different pattern from phytoplankton absorption, which is due to the photobleaching effect in the surface layer. Particulate inorganic carbon (PIC) is an additional product in this new model, which is mainly produced by the coccolithophorids. By adding PIC in the model, the underwater light field becomes more realistic, because PIC is thought to scatter light strongly.

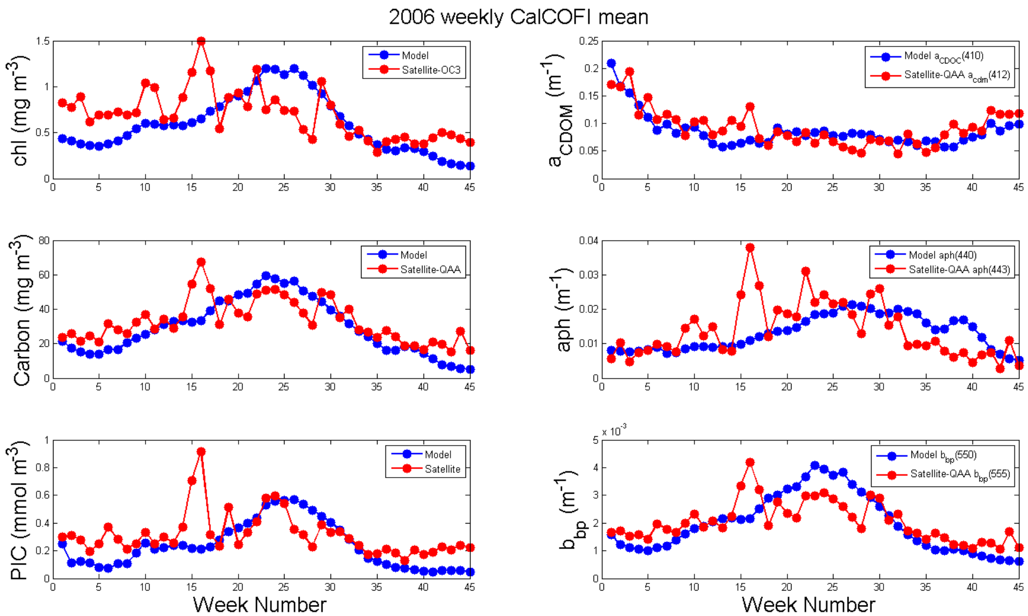

Figure 1: Temporal comparisons of modeled chlorophyll concentration (chl), phytoplankton carbon (Carbon), particulate inorganic carbon (PIC), CDOM absorption coefficient at 410 nm, total absorption coefficient at 440 nm, and particulate backscattering coefficient at 550 nm b_{bp}(550) with satellite derived QAA products. This comparison is for the CalCOFI domain averaged spatially and the time step is one week. Red curves are satellite results and blue curves are model outputs.

Comparisons of spatial distribution patterns between model and satellite data are shown in Figure 2. Overall, the model can reasonably reproduce the variations of IOPs in terms of both magnitude and spatial patterns. Strong absorption is observed to occur mostly in the near-shore region and decreases towards the open ocean. Backscattering is much more even than absorption in the whole domain. However, discrepancy is also observed between the model and satellite data, especially in the coastal region where upwelling happens. Given the good performance of the model, we think this spatial mismatch is largely due to the low resolution of the model (50-km), which couldn't resolve meso- or small- scale structures.

To test the model resolution related issues, we also run the ROMS-CoSiNE model configuration with 12.5 km resolution. Surface chlorophyll concentration obtained from 12.5 km ROMS-CoSiNE model are shown in Figure 3. When compared with the satellite products, 12.5 km model results agree much better than the coarse resolution (50-km) model results, especially for the coastal area, where upwelling dynamics are fully resolved. Optical module is being incorporated into the 12.5 km model configuration, but from the success of modeled chlorophyll, we surely can expect good results once optical process is linked with the high-resolution model (12.5-km).

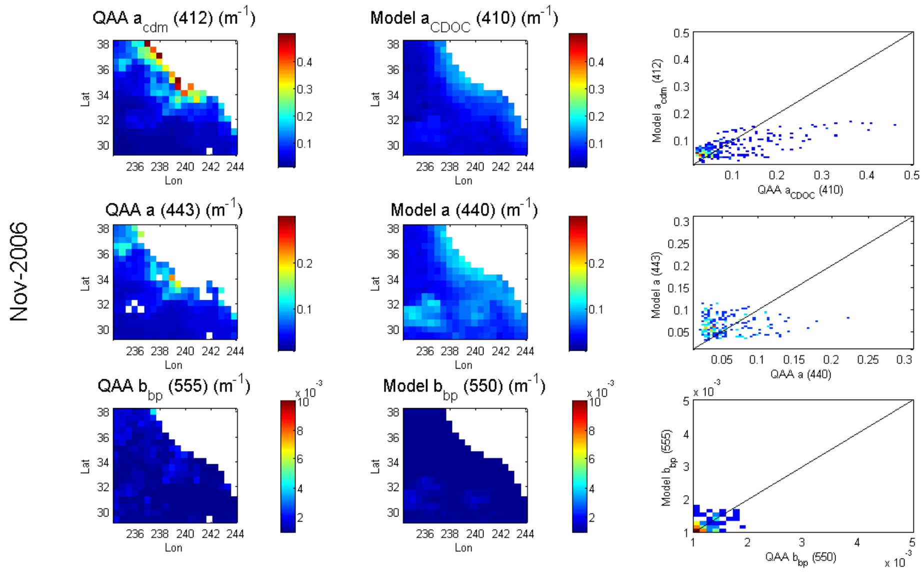

Figure 2: Monthly (November 2006) averaged comparison between the modeled (50-km resolution) and QAA derived CDOM absorption coefficient at 410 nm, total absorption coefficient at 440 nm, and particulate backscattering coefficient at 550 nm $b_{bp}(550)$. The left column is MODIS QAA products, the central column is the ROMS-CoSINE-Optics model outputs, and the right column is the statistical comparison. The colors in the statistical analysis (the right column) denote the data point density distribution.

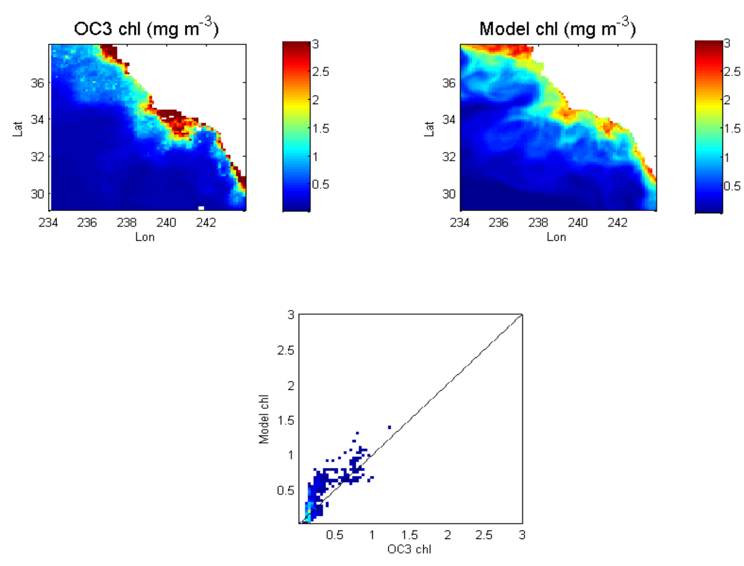

Figure 3: Spring (Mar, Apr, May 2006) averaged comparison between the modeled (12.5 km resolution) and satellite derived chlorophyll concentration. The model results are from 12.5 km high resolution Pacific ROMS-CoSiNE model.

Beside the development of ROMS-CoSiNE-Optics model for the Pacific Ocean, we have been collaborating with Sergio Derada at NRL to implement our CoSiNE model into the Navy Coastal Ocean Model (NCOM) for the Indian Ocean. The coupled physical and biological model is forced with high quality atmospheric wind, heat and freshwater fluxes for 10 years, which allows the model to reach a quasi steady state. We analyze the seasonal cycle first, and Figure 4 shows a snap shot (one day average) of the modeled surface phytoplankton biomass, which then we will run the NCOM-CoSiNE with interannual forcing from 1990 up to the present conditions. By doing so, it will allow us to investigate the impact of climate change in the physical and biological processes in the Indian Ocean. Currently, the optical module is being implemented into the NCOM-CoSiNE model for the Indian Ocean.

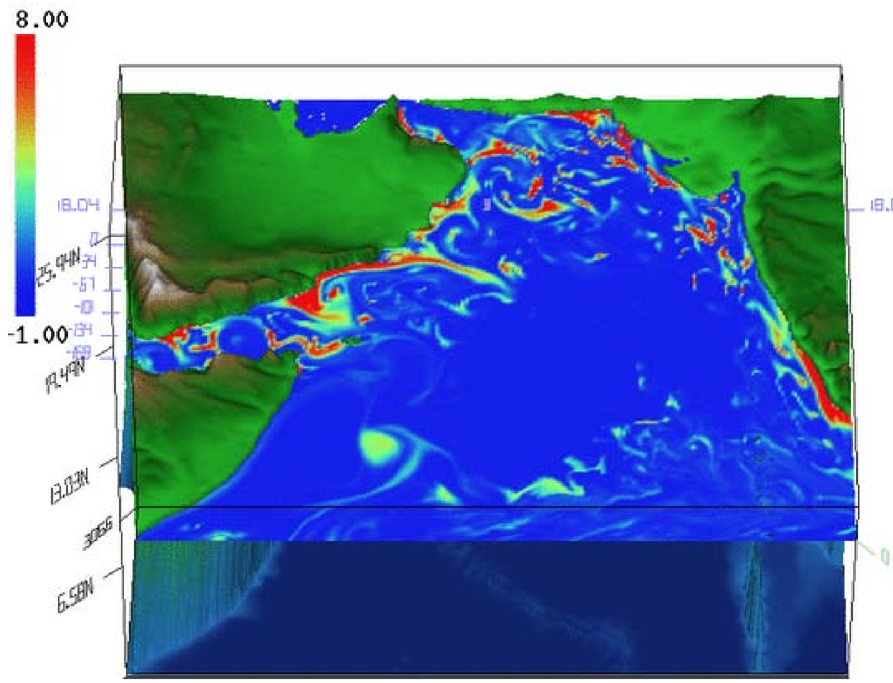

Figure 4: A snapshot of the modeled surface chlorophyll in mid July. The NCOM-CoSiNE clearly shows the upwelling signature along the coast of Oman, which in response to the Southwest Monsoon. The diatom is the dominated phytoplankton species along the coastal region. The modeled surface chlorophyll tends to match with the remote sensing observations very closely.

IMPACT/APPLICATIONS

Incorporating ocean optical processes into coupled physical-biological models will enable us to simulate and forecast optical properties in coastal waters. With demonstration of some initial successes of developing physical-biological-optical modeling and data assimilation capability for the Pacific Ocean, California Current System, and Indian Ocean, we should be able to start the development of an end-to-end ocean forecasting system. Such modeling system would be a powerful tool to design the adaptive sampling strategy and would be an essential component of future field experiments in any area of interests.

RELATED PROJECTS

This project has strong collaboration with other ONR supported projects. Besides working closely with the modeling group at the NRL and their BioSpace project, we are collaborating with Dr. Curtis Mobley of Sequoia Scientific on improving the link between the radiative transfer model (EcoLight) within the ROMS-CoSiNE-Optics. We are also collaborating with scientists at the Monterey Bay Aquarium Research Institute (MBARI) to use the observational data for the region. Dr. Yi Chao at JPL has been collaborating with us about implementing the CoSiNE into the ROMS for the Pacific Ocean and the CCS.

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