

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

Fei Chai

School of Marine Sciences, 5706 Aubert Hall  
University of Maine  
Orono, Maine 04469

phone: (207) 581-4317 fax: (207) 581-4990 email: [fchai@maine.edu](mailto:fchai@maine.edu)

Emmanuel Boss

School of Marine Sciences, 5706 Aubert Hall  
University of Maine  
Orono, ME 04469

phone: (207) 581-4378 fax: (207) 581-4990 email: [emmanuel.boss@maine.edu](mailto:emmanuel.boss@maine.edu)

Award Number: N00014-08-1-0273

### **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 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 simulates and predicts the subsurface light field as well as the ocean optical measurements.

### **APPROACH**

To achieve the first objective, we have conducted a series of 3D physical-biological model simulations for the Pacific Ocean and California Current System to test the model performance. By collaborating

with the Dynamics of Coupled Processes Section (led by Dr. Igor Shulman) at NRL, we have incorporated the Carbon, Silicate, and Nitrogen Ecosystem (CoSiNE) model into both the Navy Coastal Ocean Model (NCOM) and Regional Ocean Model System (ROMS). The CoSiNE model (Chai et al., 2002; 2003; 2007; and 2009) was developed originally for the equatorial and Pacific Ocean. During the past several years, we have implemented the CoSiNE model for different regional studies and improved its performance. Now we have successfully transferred the updated CoSiNE model into a biogeochemical module, which could be easily incorporated into other numerical models.

To achieve the second and the fourth objectives, we incorporate spectrally-resolved inherent optical properties (IOPs) into the existing ROMS-CoSiNE model. To simulate IOPs realistically in the biological model, we have modified the CoSiNE model by incorporating phytoplankton carbon, nitrogen, and chlorophyll as separate state variables. Modeled phytoplankton chlorophyll can be compared with satellite derived chlorophyll and absorption coefficients, and phytoplankton carbon can be compared with satellite derived backscattering coefficients. Because CDOM plays an important role in absorption spectra in the ocean, we also include a microbial loop, including the color dissolved organic carbon (CDOC) in the modified CoSiNE model to mimic color dissolved organic matter (CDOM) dynamics in the ocean which was treated as a constant value in previous one-dimensional model (Fujii et al., 2007). The modeled CDOC concentration is converted to CDOM absorption coefficient through an empirical relationship (Bissett et al., 2004) and further compared with satellite data. By doing so, more model variables can be compared and constrained by the satellite data. With the modeled phytoplankton carbon, chlorophyll and CDOC concentration, spectrally-resolved IOPs such as phytoplankton absorption, CDOM absorption and particulate organic carbon concentration (POC) backscattering coefficients are then calculated with the prescribed specific spectra for absorption and backscattering. These IOPs are used as an optical feedback to drive the vertical distribution of underwater light field that can substantially affect phytoplankton photosynthesis and shortwave radiation near the surface. To achieve this, two radiative transfer schemes are used here. The first one is a simplified and empirical scheme that estimates underwater light attenuation from IOPs (Penta et al., 2008). This scheme is computationally cheap and easy to apply in large-scale physical-biogeochemical simulations. We also collaborate with Dr. Curt Mobley at Sequoia Scientific for the second scheme to implement the updated version of EcoLight into the ROMS-CoSiNE model. The updated EcoLight will simulate detailed and spectrally-resolved underwater light field instead of only light attenuation, which not only can simulate optical feedbacks to biological activities but also can simulate biological feedbacks to ocean temperatures.

To achieve the third objective, the performances of the coupled ROMS-CoSiNE-Optics model are evaluated by comparing the model results with SeaWiFS and MODIS satellite data and available in-situ measurements. 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. In-situ measurements including SeaWiFS Bio-optical Archive and Storage System (SeaBASS) dataset, CalCOFI measurements (<http://calcofi.org/>) and World Ocean Atlas 2005 (WOA05) are also used to evaluate model's performance.

## **WORK COMPLETED**

We have fully evaluated the original 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), ecosystem productivities (Liu and Chai, 2009a), biological responses to physical environment (Liu and Chai, 2009b), and meso-scale eddy activities (Xiu et al., 2010), as well as the biogeochemical responses to the meso-scale eddies (Xiu and Chai, 2011; Xiu et al., 2011; Xiu et al., 2012).

We incorporated a bio-optical module and the original CoSiNE code into the Navy Coastal Ocean Model (NCOM) for the California Current System, and have been coordinating effort to improve the CoSiNE performance in the NCOM.

We modified the CoSiNE code by incorporating optical variables and feedbacks in the ecosystem model and coupled it in the ROMS-CoSiNE-Optics model for the Pacific domain. This coupled model reproduced satellite observed phytoplankton carbon and chlorophyll variability in different temporal and spatial scales (Xiu and Chai, 2012, in press).

We evaluated the ROMS-CoSiNE-Optics model results with remote sensing derived IOPs and other biological parameters for the Pacific Ocean and CaLCOFI region (Xiu and Chai, in prepare).

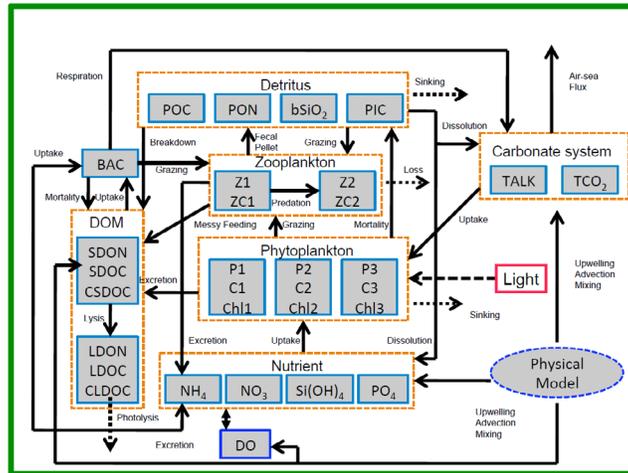
We have collaborated with Dr. Curt Mobley to incorporate EcoLight into an idealized ROMS-CoSiNE model for an upwelling system. EcoLight was completely rewritten from scratch in Fortran 95 by Dr. Curt Mobley to bring it up to the standards of the ROMS-CoSiNE code. Some results have been reported as an invited talk at the Gordon Research Conference in June 2011 by Dr. Chai, and at the IOCCG course in July 2012 by Dr. Mobley.

## **RESULTS**

We have conducted a series of the ROMS-CoSiNE model, without the optical component, for the Pacific Ocean for the period of 1990 to 2008. For doing so, we can evaluate the ROMS-CoSiNE model results with available observations, and then improve the CoSiNE model performance (Liu and Chai, 2009a; Liu and Chai, 2009b; Bidigare et al., 2009; Chai et al., 2009; Xiu et al., 2010; Palacz et al., 2011; Xiu and Chai, 2011; Xiu et al., 2011; Xiu et al., 2012). Since these ROMS-CoSiNE model results have been published in the peer-reviewed journals, we are not including these results in this report.

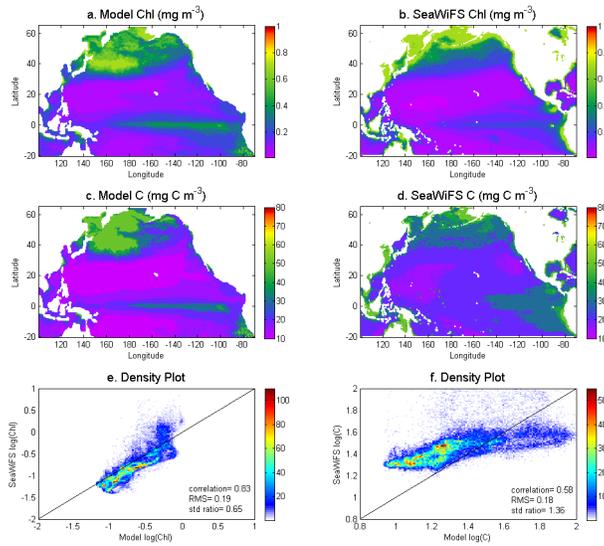
The original 10-component CoSiNE model from Chai et al. (2002) was modified to include 31 state variables (Figure 1). With these new variables, the model can simulate photosynthesis, inorganic nitrogen assimilation, and pigment synthesis processes separately associated with dynamic carbon-to-chlorophyll and carbon-to-nitrogen ratios. This separation allows the decoupling between modeled phytoplankton carbon and chlorophyll, and corresponding optical absorption and backscattering, respectively, which was observed from satellite studies (e.g., Behrenfeld et al., 2005). The carbon and nitrogen cycling system was also realistically improved by adding the dissolved pool and bacterial dynamics in the model. CDOC modeled as a colored byproduct of dissolved organic carbon (DOC) is split into labile (LDOC) and semi-labile (SDOC) pools according to their turnover rates. In the model,

CDOC is produced by phytoplankton mortality, zooplankton messy feeding and mortality, and detritus breakdown. It is consumed by bacteria through the whole water column, and photobleached by UV light in the upper water layer. The subsequent bacterial respiration and photobleached CDOC both can contribute to the budget of total CO<sub>2</sub> (TCO<sub>2</sub>) and further affect carbon cycling in the ocean.



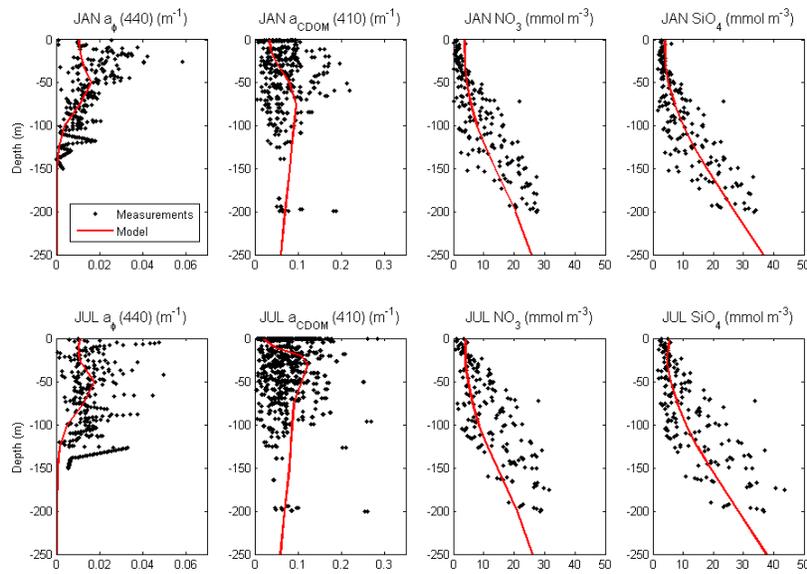
**Figure 1: The flow-chart of modified CoSiNE model.**

Performances of the coupled ROMS-CoSINE-Optics model are evaluated by comparing the model results with SeaWiFS satellite data. Figure 2 shows a comparison of modeled climatological phytoplankton chlorophyll and carbon with SeaWiFS data. The modeled chlorophyll and carbon show a generally similar spatial pattern with SeaWiFS data: high values are found in the equatorial and subpolar regions, and relatively low values are found in the subtropics. Since nutrient supply from rivers is not included in the model, high chlorophyll and carbon conditions observed in some coastal regions are not reproduced. On the other hand, SeaWiFS data in the nearshore region is known for its inability to distinguish between turbidity and chlorophyll. Therefore, the high influx of sediments along the coast is likely to lead to an overestimation of chlorophyll or carbon concentration in SeaWiFS data. Away from the coastal region, the model tends to overestimate chlorophyll concentrations in the Gulf of Alaska and eastern and central equatorial Pacific. This discrepancy is expected because these two regions have been characterized as HNLC regions limited by low supplies of iron. Without iron limitation on phytoplankton growth rates, the coupled model is unable to reproduce the biological activities accurately in these regions.



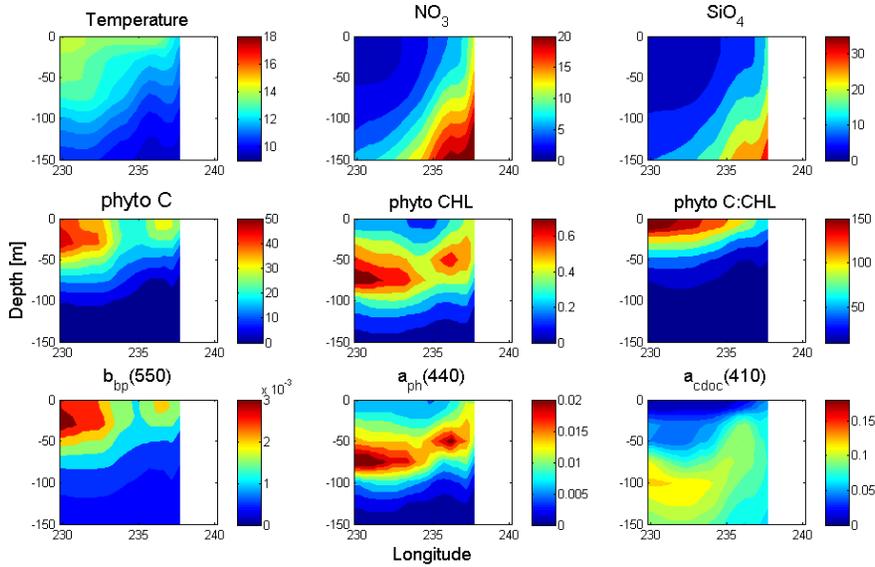
***Figure 2: Comparison of spatial distributions of surface chlorophyll and carbon between modeled annual-mean climatology and SeaWiFS observations during the 1997-2007 period.***

Comparisons of vertical distribution patterns between model and in-situ data in the CalCOFI region are shown in Figure 3. Due to the scarce of in-situ measurements, we cannot provide a point-to-point comparison. Figure 3 shows the comparison between the model and all the available historical datasets in the CalCOFI region. Overall, the model can reproduce the variations of biogeochemical and optical properties in both magnitudes and distribution patterns. The model suggests the low-nutrient and high-nutrient conditions in the surface and deep waters, respectively. Strong subsurface maximums both in chlorophyll and phytoplankton absorption are clear throughout the year. CDOM absorption, differs slightly, showing strong and shallow subsurface maximum in summer months, probably produced due to the intense photobleaching by UV light. Note that all the available in-situ measurements are plotted in this figure, but we only show the domain averaged data from the model. Thus, the good performance of the model is on a mean basis.



**Figure 3: In-situ measurements from the CalCOFI domain. Red curves are the averaged model results during 1992-2009.  $\text{NO}_3(\text{mmol m}^{-3})$ ,  $\text{SiO}_4(\text{mmol m}^{-3})$  and chl ( $\text{mg m}^{-3}$ ) data come from the CalCOFI website (<http://www.calcofi.org/>).  $a_\phi$  and  $a_{c\text{dom}}$  data come from the SeaBASS (<http://seabass.gsfc.nasa.gov/>).**

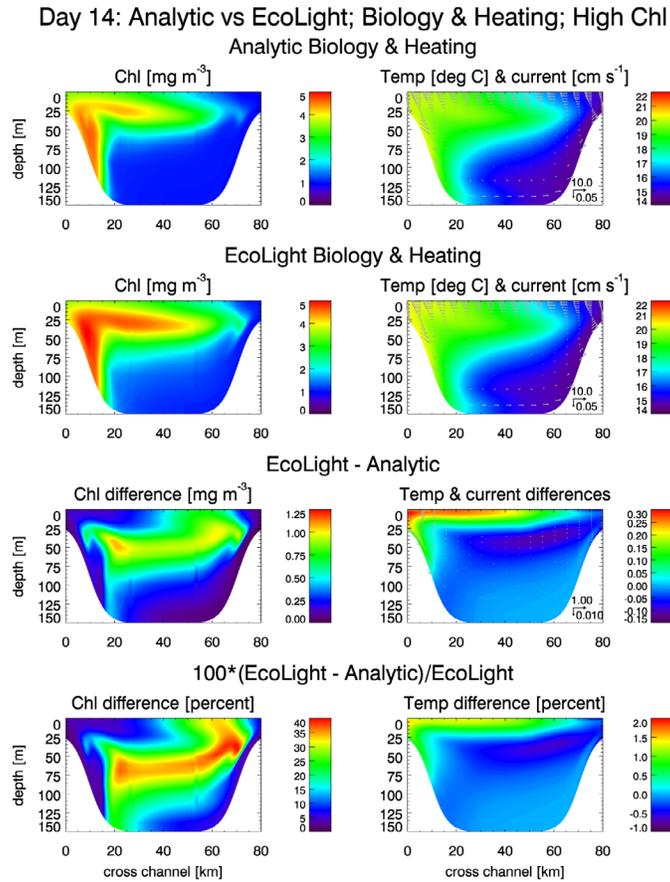
Although the model is configured for the Pacific basin with a horizontal resolution of 50 km and some meso- or small- scale structures cannot be resolved, our model is still robust to produce typical coastal features such as the upwelling event. Figure 4 shows a cross section of modeled variables in April. In this period, the coast is dominated by the strong upwelling due to the increased equatorward wind. As shown in Figure 4, cool and nutrient-rich deep waters are brought into the upper layers. Phytoplankton carbon mainly accumulates in the surface layer in response to the photosynthesis. Phytoplankton chlorophyll regulated by both light and nutrients, on the other hand, shows strong subsurface chlorophyll maximum (SCM), and the depth of SCM tends to increase when moving close to the coast as a result of the elevated nutrient condition due to upwelling. Particulate backscattering and phytoplankton absorption show similar patterns to phytoplankton carbon and chlorophyll, respectively. CDOM absorption seems to be influenced by the coastal upwelling stronger than other optical variables. The depth of subsurface CDOM maximum is about 100 m at  $230^\circ\text{E}$ , and it is raised to above 50 m when near the coast.



**Figure 4: Cross sections of modeled physical, biogeochemical, and optical properties along 36.5N in April averaged during 1992-2009.**

Currently available ocean ecosystem models typically use very sophisticated treatments of the hydrodynamics (e.g., primitive equation solutions in terrain-following coordinate systems to obtain the advection and upper-ocean thermodynamics and mixing), fairly sophisticated biology (e.g., primary production, nutrient utilization, and grazing in multi-component food webs with several phytoplankton functional groups), but use grossly oversimplified treatments of the optics. Models used for global-scale predictions relevant to climate-change studies and understanding of the global ocean-atmosphere system are often driven by daily-averaged above-surface irradiances and very simple analytical formulations of light penetration through the water column. Recently such models have begun to include feedbacks between biology and hydrodynamics, but often with assumptions such as chlorophyll concentrations that are constant with depth. Recent models do recognize the importance of proper inclusion of two-way feedbacks between biology and hydrodynamics, but still rely on very simple treatments of the optics. During the past several months, Dr. Curt Mobley came to UMaine three times (April, July 2011, and Jun 2012) to work with us on incorporating EcoLight into the ROMS-CoSiNE-Optics model for an idealized upwelling system. We are glad to report that the integrated model system is finally working properly, and producing some really interesting results. Figure 5 shows a comparison between the analytic light treatment and Ecolight. The lower panels show the difference between these two runs. With Ecolight simulation (everything else are the same as the analytic model runs - physics and biology), during the upwelling period (about three weeks), the Ecolight simulation produce more chlorophyll, by about 1.2 mg/m<sup>3</sup> comparing to the analytic light treatment, which is about 24% of the highest value. Interestingly enough that this chlorophyll differences feed back to physical processes, mainly shortwave radiation redistribution near the surface. The Ecolight simulations calculate these processes, but the analytic light treatment does not. In the EcoLight upwelling region, the temperatures are reduced at depths of 20-70 m compared to the ROMS analytic values because of increased near-surface absorption by the higher chlorophyll values. Surface

water temperatures are as much at 0.3 deg higher in the downwelling area because of greater absorption near the surface during the time that the wind blows the surface water from right to left in the figures. The EcoLight run thus has greater water stratification in the upper 50 m.



**Figure 5: Comparison of modeled chlorophyll and temperature between the analytic light treatment and EcoLight calculated light. The difference between these two light calculations are shown in the lower panels.**

## IMPACT/APPLICATIONS

Incorporating ocean optical processes into coupled physical-biological models enables us to simulate and forecast optical properties in the ocean. To our knowledge, it is the first application of coupled physical, biological, and optical processes to the large-scale simulations. Coupling explicit optics to an ecosystem model provides advantages in generating a more accurate subsurface light field and additional constraints on model parameters that help to reduce model uncertainties. With demonstration of some initial successes of developing physical-biological-optical modeling and data assimilation capability for the Pacific Ocean and California Current System, we should be able to develop 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.

## 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. We are also collaborating with scientists (Dr. Francisco Chavez) 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 model into the ROMS for the Pacific Ocean and the CCS.

## REFERENCES

- Behrenfeld, B., E. Boss, D.A. Siegel, and D.M. Shea (2005): Carbon-based ocean productivity and phytoplankton physiology from space. *Global Biogeochemical Cycles* 19, doi:10.1029/2004GB002299.
- Bidigare, R.R., F. Chai, M. R. Landry, R. Lukas, C. Hannides, S. J. Christensen, D.M. Karl, L. Shi and Y. Chao (2009): Subtropical ocean ecosystem structure changes forced by North Pacific climate variations. *Journal of Plankton Research*, 31, 1131-1139.
- Bissett, W.P., DeBra, S., Dye, D., 2004. Ecological Simulation (EcoSim) 2.0 Technical Description. Florida Environmental Research Institute, Tampa.
- Chai, F., R. C. Dugdale, T-H Peng, F. P. Wilkerson, and R. T. Barber (2002): One Dimensional Ecosystem Model of the Equatorial Pacific Upwelling System, Part I: Model Development and Silicon and Nitrogen Cycle. *Deep-Sea Res. II*, Vol. 49, No. 13-14, 2713-2745.
- Chai, F., M. Jiang, R.T. Barber, R.C. Dugdale, and Y. Chao (2003): Interdecadal Variation of the Transition Zone Chlorophyll Front, A Physical-Biological Model Simulation between 1960 and 1990. *Journal of Oceanography*, Vol. 59, 461-475.
- Chai, F., M-S Jiang, Y. Chao, R.C. Dugdale, F. Chavez, and R.T. Barber (2007): Modeling Responses of Diatom Productivity and Biogenic Silica Export to Iron Enrichment in the Equatorial Pacific Ocean. *Global Biogeochemical Cycle*, Vol. 21, GB3S90, doi:10.1029/2006GB002804.
- Chai, F. G. Liu, H. Xue, L. Shi, Y. Chao, C-T Tseng, W-C Chou, and K-K Liu (2009): Seasonal and Interannual Variability of Carbon Cycle in South China Sea: a Three-Dimensional Physical-Biogeochemical Modeling Study. *Journal of Oceanography*, Vol. 65, pp. 703 to 720.
- Fujii, M., E. Boss, and F. Chai (2007): The value of adding optics to ecosystem models: a case study. *Biogeosciences* 4, 1585-1631.
- Lee, Z., K. L. Carder, and R. A. Arnone (2002): Deriving inherent optical properties from water color: a multiband quasi-analytical algorithm for optically deep waters. *Applied Optics*. 41, 5755-5772.
- Liu, G. and F. Chai (2009a): Seasonal and interannual variability of primary and export production in the South China Sea: A three-dimensional physical-biogeochemical model study. *ICES Journal of Marine Science*, 66, 420-431.

- Liu, G. and F. Chai (2009b): Seasonal and interannual variation of physical and biological processes during 1994-2001 in the Sea of Japan/East Sea: a three-dimensional physical-biogeochemical modeling study. *Journal of Marine Systems*, Vol. 78, 265-277.
- Palacz, A.P., F. Chai, R.C. Dugdale, and C.I. Measures (2010): Estimating iron and aluminum removal rates in the eastern equatorial Pacific Ocean using a box model approach. *Deep Sea Research II.*, 58, 311-324.
- Penta, B., Z. Lee, R.M. Kudela, S.L. Palacios, D.J. Gray, J.K. Lolliff, and I.G. Shulman (2008): An underwater light attenuation scheme for marine ecosystem models. *Optics Express*, Vol. 16, No. 21, 16581-16591.
- Xiu, P., F. Chai, L. Shi, H. Xue, and Y. Chao (2010): A census of eddy activities in the South China Sea during 1993-2007. *Journal of Geophysical Research*, 115, C03012, doi:10.1029/2009JC005657 .
- Xiu, P., A.P. Palacz, F. Chai, E.G. Roy, and M. L. Wells (2011): Iron flux induced by Haida eddies in the Gulf of Alaska. *Geophysical Research Letters*, 38, L13607, doi:10.1029/2011GL047946.
- Xiu, P., and F. Chai (2011): Modeled biogeochemical responses to mesoscale eddies in the South China Sea. *J. Geophys. Res.*, doi:10.1029/2010JC006800.
- Xiu, P., F. Chai, H. Xue, L. Shi, and Y. Chao (2012), Modeling the mesoscale eddy field in the Gulf of Alaska, *Deep Sea Research I*, 63, 102-117.
- Xiu, P., and F. Chai (2012), Spatial and temporal variability in phytoplankton carbon, chlorophyll, and nitrogen in the North Pacific, *Journal of Geophysical Research*, doi:10.1029/2012JC008067, in press.