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Connections between physical, optical and biogeochemical processes in the Pacific Ocean

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ABSTRACT

A new biogeochemical model has been developed and coupled to a three-dimensional physical model in the Pacific Ocean. With the explicitly represented dissolved organic pools, this new model is able to link key biogeochemical processes with optical processes. Model validation against satellite and in situ data indicates the model is robust in reproducing general biogeochemical and optical features. Colored dissolved organic matter (CDOM) has been suggested to play an important role in regulating underwater light field. With the coupled model, physical and biological regulations of CDOM in the euphotic zone are analyzed. Model results indicate seasonal variability of CDOM is mostly determined by biological processes, while the importance of physical regulation manifests in the annual mean terms. Without CDOM attenuating light, modeled depth-integrated primary production is about 10% higher than the control run when averaged over the entire basin, while this discrepancy is highly variable in space with magnitudes reaching higher than 100% in some locations. With CDOM dynamics integrated in physical-biological interactions, a new mechanism by which physical processes affect biological processes is suggested, namely, physical transport of CDOM changes water optical properties, which can further modify underwater light field and subsequently affect the distribution of phytoplankton chlorophyll. This mechanism tends to occur in the entire Pacific basin but with strong spatial variability, implying the importance of including optical processes in the coupled physical-biogeochemical model.

1. Introduction

Light distribution below the ocean surface has been treated as a control mechanism for autotrophic growth. Optical and biogeochemical processes are essentially connected via the interaction of light with particulate and/or dissolved matters in the ocean. Under a given oceanic environment with ample nutrients, photosynthetic organism biomass generally increases with increasing light. As the biomass grows and accumulates, light absorption and scattering become stronger, leading to less light penetration in the water, which in turn provides a negative feedback for the biological activities (Yentsch and Phinney, 1989; Bissett et al., 2001; Rothstein et al., 2006). The impacts of physical processes on biogeochemical processes have been primarily recognized as horizontal and/or vertical transports of nutrients and plankton biomass. Changes in optical properties through physical processes, which alter underwater light field and further change biological activities, however, are another linkage between physical and biogeochemical processes. Thus, it is important to relate these processes when assessing marine ecosystem.

Many marine ecosystem models, varying from simple nutrient, phytoplankton, zooplankton, and detritus (NPZD) models to complex models with 20 or more components (e.g., Chai et al., 2002; Moore et al., 2002; Anderson and Pondaven, 2003; Aumont et al., 2003; Fennel et al., 2003; Goebel et al., 2010) often use an approximation of integrated photosynthetically active radiation (PAR, 400–700 nm) that only attenuates with phytoplankton biomass (or chlorophyll) and seawater to control the assimilation of inorganic nutrients. Such a simplification in relationship between light attenuation and phytoplankton biomass is easy to implement for numerical calculation and biological consideration. However, considerable nonlinearity exists when considering phytoplankton sizes and their photo-adaptive states (Smith and Baker, 1978; Bricaud et al., 1983). In addition to phytoplankton, detritus and colored dissolved organic matter (CDOM) absorption and particulate backscattering, referred to as inherent optical properties that are often not represented in ecosystem models can affect underwater light field as well (e.g., Babin et al., 2003a;Boss et al., 2004).

Adding optics to an ecosystem model has been suggested to be more accurate in generating subsurface light field (Fujii et al., 2007). Directly comparing modeled optical properties with ocean color and in situ data also gives additional constraints on model parameters to reduce uncertainties in model simulations, as many satellite-derived products, such as chlorophyll concentration,

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carbon biomass, and primary production, are estimated based on empirical or semi-analytical algorithms linking with ocean optics (IOCCG, 2006). However, only few ecosystem models have considered the optical processes associated with underwater light field (e.g., Bissett et al., 1999a; Fujii et al., 2007). The one-dimensional (1-D) ecosystem model developed by Fujii et al. (2007) is able to simulate underwater light field and the feedbacks to biological processes. The CDOM that is not included in their model, however, may have an important role in regulating phytoplankton dynamics and nutrient cycling in the euphotic zone. The production and destruction mechanisms for CDOM include phytoplankton exudation, zooplankton messy feeding, detritus breakdown, bacterial production and consumption, and photolysis by ultraviolet (UV, 280–400 nm) light, which are fundamentally different and decoupled from those for phytoplankton, especially in coastal regions where terrestrial CDOM is introduced. To incorporate CDOM in an ecosystem model, one must consider the cycling of dissolved matter pool and the microbial loop in the ocean in addition to the classic NPZD processes.

The objective of this study is to develop an ecosystem model that explicitly describes wavelength-resolved optical properties (visible light, 400–700 nm), associated with multi-nutrient phytoplankton, zooplankton, and detritus. We also include the photo-acclimation process for phytoplankton in the model to better resolve the dynamic link between phytoplankton chlorophyll and carbon biomass. Carbonate system, including dynamics of total alkalinity, ocean calcification and the air-sea gas exchange of carbon dioxide, is explicitly represented as well. We couple this model to the Pacific Ocean (45°S to 65°N, 100°E to 70°W) with a three-dimensional (3-D) general circulation model. The model performance is examined by comparing model outputs with available satellite and in situ data. Numerical experiments are conducted to understand the dynamic connections between physical, optical and biogeochemical processes in the Pacific Ocean.

2. Model and data

2.1. Biogeochemical processes

The ecosystem model is primarily based on the Carbon, Silicon, Nitrogen Ecosystem (CoSINE) model (Chai et al., 2002). We follow previous approaches to simulate phytoplanktonic photo-acclimation and the dynamic chlorophyll-to-carbon ratio under different growth conditions (Geider et al., 1998; Moore et al., 2002; Fujii et al., 2007). The ecosystem consists of 31 state variables describing three phytoplankton functional groups in three different biomass forms, picoplankton nitrogen, carbon and chlorophyll (P1, C1, Chl1), diatoms nitrogen, carbon and chlorophyll (P2, C2, Chl2), and coccolithophorids nitrogen, carbon and chlorophyll (P3, C3, Chl3); two size classes of zooplankton, microzooplankton nitrogen (Z1), mesozooplankton nitrogen (Z2), and their carbon terms (ZC1, ZC2); detritus in terms of particulate organic nitrogen (PON), particulate organic carbon (POC), particulate inorganic carbon (PIC) and biogenic silica ($bSiO_2$); silicate ($Si(OH)_4$); phosphate (PO_4); dissolved oxygen (DO); total alkalinity (TALK); total CO_2 (TCO_2); two forms of dissolved inorganic nitrogen, nitrate (NO_3) and ammonium (NH_4); bacteria nitrogen (BAC); as well as dissolved organic matter, labile dissolved organic nitrogen (LDON), labile dissolved organic carbon (LDOC), colored labile dissolved organic carbon (CLDOC), semi-labile dissolved organic nitrogen (SDON), semi-labile dissolved organic carbon (SDOC), and colored semi-labile dissolved organic carbon (CSDOC) (Fig. 1). The governing equations and formulations of biogeochemical processes are denoted in Appendix A, and a list of parameters used in the model is provided in Table 1.

Nutrient uptake and photosynthetic rate are modeled as functions of environmental factors and cellular composition (C:Chl and C:N). The model includes down-regulation of pigment content at high irradiance or when growth rate is limited by nutrients and temperature, and feedback between nitrogen and carbon metabolism (Geider et al., 1998). Phytoplankton ratios (C:Chl and C:N) vary dynamically between maximum and minimum cell quotas according to the changes in light and nutrient levels (Xiu and Chai, 2012). The maximum and minimum cell quotas for different phytoplankton functional groups are chosen based on Moore et al. (2002) and Fujii et al. (2007).

All phytoplankton take up NO_3, NH_4, PO_4 and TCO_2 for photosynthesis. Diatoms also take up $Si(OH)_4$ for the silicification process, and coccolithophorids utilize TALK and TCO_2 for the calcification process (Fujii and Chai, 2007). The microzooplankton graze on picoplankton and bacteria. The mesozooplankton feed on diatoms, coccolithophorids, microzooplankton, and detritus. The remineralization of organic nitrogen, silicon and carbon, both inside and below the euphotic zone, is a critical process for nutrient recycling efficiency. It depends on a number of factors, including water temperature, nutrient condition, particle sizes and zooplankton grazing (Ragueneau et al., 2000; Ward, 2000). The remineralization of organic nitrogen is primarily biological with a rapid production of NH_4 and TCO_2 through zooplankton grazing in the euphotic zone and bacteria decomposition of organic matter below the euphotic zone. Below the euphotic zone, sinking particulate organic matter (POM) is converted to inorganic nutrients and dissolved organic matter (DOM) by a regeneration process. Through the dissolution process, a majority of the POM is converted to inorganic nutrients (90%), and the rest goes into the DOM pool.

The DOM pool consists of dissolved organic carbon and nitrogen. There are a number of processes that can produce and utilize or remineralize DOM, and most of these processes are poorly understood (Christian and Anderson, 2002). To the first-order approximation, DOM processes are modeled as consumption by bacteria and productions by phytoplankton exudation, zooplankton messy feeding, and detrital breakdown, as adopted in many studies (e.g., Anderson and Williams, 1998; Walsh et al., 1999; Tian et al., 2000; Christian and Anderson, 2002; Anderson and Pondaven, 2003). Phytoplankton exudation representing an active release by phytoplankton is modeled as a fraction of primary production. This fraction is highly variable in different studies, with magnitudes ranging from 2% to 56.4% (Christian and Anderson, 2002). Grazer-related DOM production is modeled as zooplankton messy feeding, which is a fixed fraction of grazed materials. Among previous studies, this fraction also varies significantly with a range of 2.5–50% (Christian and Anderson, 2002). From lab experiments, Strom et al. (1997) estimated that about 16–37% of algal carbon was released during an ingestion event. Particle dissolution into the DOM pool with the first-order rate process is used in our model. This approach is a simplified simulation of the underlying mechanism and has been widely used (e.g., Anderson and Williams, 1998; Levy et al., 1998; Vallino, 2000; Yamanaka et al., 2004), although other environmental factors such as temperature, turbulence, and bacteria can modify this process.

The primary mechanism for DOM loss is uptake by heterotrophic bacteria. According to different turnover rates, the DOM is further divided into labile and semi-labile pools. Labile pool can be consumed directly by bacteria, while semi-labile pool includes molecules that require ectoenzyme hydrolysis to be converted to labile matter. Bacteria utilization of the DOM is modeled by a hyperbolic function that is similar to Michaelis–Menton kinetics (Anderson and Williams, 1998; Anderson and Pondaven, 2003). Bacteria production and remineralization are modeled following Anderson and Williams (1998) and Walsh et al. (1999). Colored