



ELSEVIER

Contents lists available at ScienceDirect

## Progress in Oceanography

journal homepage: [www.elsevier.com/locate/pocean](http://www.elsevier.com/locate/pocean)

# Simulating the ocean's chlorophyll dynamic range from coastal upwelling to oligotrophy

N. Van Oostende<sup>a,\*</sup>, R. Dussin<sup>b</sup>, C.A. Stock<sup>c</sup>, A.D. Barton<sup>d</sup>, E. Curchitser<sup>b</sup>, J.P. Dunne<sup>c</sup>, B.B. Ward<sup>a</sup>

<sup>a</sup> Department of Geosciences, Princeton University, NJ, USA

<sup>b</sup> Department of Environmental Sciences, Rutgers University, NJ, USA

<sup>c</sup> Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton, NJ, USA

<sup>d</sup> Scripps Institution of Oceanography and Section of Ecology, Behavior and Evolution, University of California San Diego, USA

## ARTICLE INFO

## Keywords:

Chlorophyll  
Coastal upwelling  
Diatom  
Coastal hypoxia  
Phytoplankton community size-structure  
California Current

## ABSTRACT

The measured concentration of chlorophyll *a* in the surface ocean spans four orders of magnitude, from  $\sim 0.01 \text{ mg m}^{-3}$  in the oligotrophic gyres to  $> 10 \text{ mg m}^{-3}$  in coastal zones. Productive regions encompass only a small fraction of the global ocean area yet they contribute disproportionately to marine resources and biogeochemical processes, such as fish catch and coastal hypoxia. These regions and/or the full observed range of chlorophyll concentration, however, are often poorly represented in global earth system models (ESMs) used to project climate change impacts on marine ecosystems. Furthermore, recent high resolution ( $\sim 10 \text{ km}$ ) global earth system simulations suggest that this shortfall is not solely due to coarse resolution ( $\sim 100 \text{ km}$ ) of most global ESMs. By integrating a global biogeochemical model that includes two phytoplankton size classes (typical of many ESMs) into a regional simulation of the California Current System (CCS) we test the hypothesis that a combination of higher spatial resolution and enhanced resolution of phytoplankton size classes and grazer linkages may enable global ESMs to better capture the full range of observed chlorophyll. The CCS is notable for encompassing both oligotrophic ( $< 0.1 \text{ mg m}^{-3}$ ) and productive ( $> 10 \text{ mg m}^{-3}$ ) endpoints of the global chlorophyll distribution. As was the case for global high-resolution simulations, the regional high-resolution implementation with two size classes fails to capture the productive endpoint. The addition of a third phytoplankton size class representing a chain-forming coastal diatom enables such models to capture the full range of chlorophyll concentration along a nutrient supply gradient, from highly productive coastal upwelling systems to oligotrophic gyres. Weaker 'top-down' control on coastal diatoms results in stronger trophic decoupling and increased phytoplankton biomass, following the introduction of new nutrients to the photic zone. The enhanced representation of near-shore chlorophyll maxima allows the model to better capture coastal hypoxia along the continental shelf of the North American west coast and may improve the representation of living marine resources.

## 1. Introduction

The distribution of phytoplankton exhibits both intricate fine-scale structure and large-scale patterns that shape marine resource distributions and biogeochemical cycles across spatial scales ranging from hundreds of meters to ocean basins (Longhurst, 2007; Lévy et al., 2012; Stukel et al., 2017). The measured distribution of chlorophyll, a proxy for phytoplankton biomass, in the open oceans spans four orders of magnitude, ranging from as low as  $\sim 0.01 \text{ mg m}^{-3}$  in the oligotrophic gyres to  $> 10 \text{ mg m}^{-3}$  in a few highly productive coastal zones. Oligotrophic subtropical gyres account for the majority of ocean surface area (Longhurst et al., 1995). In contrast, regions with an annual mean

chlorophyll concentration  $> 3 \text{ mg m}^{-3}$ , primarily in coastal zones, account for only  $\sim 1\%$  of the global ocean (SeaWiFS Level-3 Mapped Chlorophyll Data Version, 2014), yet have a disproportionate impact on marine resources and biogeochemical processes. Fish catch, for example, is strongly skewed toward high chlorophyll coastal regions (Ryther, 1969; Friedland et al., 2012; Stock et al., 2017). The biological pump is also intensified (Eppley and Peterson, 1979; Dunne et al., 2005) and decomposition of sinking organic matter depletes oxygen in zones underlying high productivity. Such regions often harbor unique biogeochemical transformations, such as denitrification (Christensen et al., 1987; DeVries et al., 2012), or hypoxia detrimental to demersal fish and benthic invertebrates (Grantham et al., 2004; Chan et al., 2008;

\* Corresponding author at: 158 Guyot Hall, Princeton University, Princeton, NJ 08544, USA.

E-mail address: [oostende@princeton.edu](mailto:oostende@princeton.edu) (N. Van Oostende).

<https://doi.org/10.1016/j.pocean.2018.10.009>

Received 8 August 2017; Received in revised form 20 July 2018; Accepted 9 October 2018

Available online 10 October 2018

0079-6611/ © 2018 Elsevier Ltd. All rights reserved.

Keller et al., 2015).

The biomass of large phytoplankton (> 20  $\mu\text{m}$ ), including many species of diatoms, characteristically makes up an important fraction of high biomass phytoplankton blooms (Chisholm, 1992; Raimbault et al., 1988; Chavez, 1989; Irigoien et al., 2004; Goericke, 2011). Moreover, because large phytoplankton dominate at high chlorophyll concentrations, variability in their biomass explains most of the absolute variability in chlorophyll concentration globally (Claustre, 1994; Venrick, 2002; Uitz et al., 2010). The explanation for this relationship between chlorophyll concentration and contribution of large phytoplankton cells hinges upon the balance of phytoplankton growth and losses to predation. At least two non-mutually exclusive mechanisms have been proposed to explain these observations. The first mechanism is the size-dependent ‘sequential invasion’ of phytoplankton groups along a resource gradient (cf. Armstrong, 1994; Ward et al., 2012). In the steady state case, phytoplankton species of incrementally larger cell size are added sequentially along a gradient of increasing flux of limiting resources (i.e., nutrients), supporting higher autotrophic biomass (Chisholm, 1992; Moloney and Field, 1989; Irwin et al., 2006; Barber and Hiscock, 2006). The smallest phytoplankton cells thrive in low nutrient conditions due to nutrient scavenging advantages afforded by high surface area to volume ratios, and their lower minimal cellular nutrient requirement. As the level of the limiting nutrient increases the abundance of the smallest cells (i.e., picoplankton such as *Prochlorococcus*) is constrained by a grazer-imposed threshold ( $\sim 0.5 \text{ mg chlorophyll m}^{-3}$ ), above which the total community biomass is supplemented by increasing contributions of sequentially larger phytoplankton size groups until the next size-group threshold is reached.

The second mechanism is transient decoupling of phytoplankton biomass accumulation from grazing (Thingstad, 1998; Irigoien et al., 2005; Romagnan et al., 2015). This mechanism is often associated with changes from unfavorable to favorable phytoplankton growth conditions, such as spring bloom initiation or the surfacing of upwelled, high nutrient water masses. Microzooplankton growth rates are generally comparable to those of their phytoplankton prey, which allows them to respond rapidly to increases in phytoplankton growth. The high microzooplankton turnover rate can quickly re-establish top-down control on small phytoplankton by cropping a significant portion (averaging 60–75%) of the daily phytoplankton production across a spectrum of ocean and coastal systems (Landry and Calbet, 2004). Mesozooplankton, however, grow more slowly and in many cases have longer and more complex life cycles (Hansen et al., 1997), such that their larger phytoplankton prey can temporarily outpace grazer control (Franks, 2001; Fuchs and Franks, 2010). Because the phytoplankton species dominating at high biomass are typically large, and often mechanically or chemically protected (e.g., dinoflagellates such as *Karenia* sp., *Phaeocystis* spp. colonies, chain-forming diatoms such as *Chaetoceros* spp. and *Thalassiosira* spp.) they are less susceptible to microzooplankton grazing and most vulnerable to larger grazers (Irigoien et al., 2004; Slaughter et al., 2006). This trade-off between lower resource competition of larger phytoplankton and increased grazing resistance against smaller grazers has often been used in ecological models to allow bloom formation of large phytoplankton (Kretzschmar et al., 1993; Ingrid et al., 1996; Leibold, 1996; Terseleer et al., 2014). Chlorophyll concentration in the ocean, therefore, results from interlinking environmental conditions, plankton community size-structure and food webs.

Chlorophyll observations often serve to constrain large-scale biogeochemical models used to elucidate the dynamics of marine ecosystems and productivity across trophic levels, and project ecosystem changes that might result from global environmental change. These models, however, generally fail to capture the entirety of observed chlorophyll range and frequency distribution (Fig. 1A) (Hashioka et al., 2013). Global biogeochemical models are adept at reproducing the very low chlorophyll observed in the oligotrophic regions but are often not able to match much higher values (3–10  $\text{mg chlorophyll m}^{-3}$ ) in

intensely productive coastal regions, or vice versa. This shortcoming is apparent when comparing the range of chlorophyll concentration from remote sensing observations with the output of a selection of models used in the fifth Coupled Model Intercomparison Project (CMIP5) (Fig. 1A). Even regional models covering areas of broad ecological gradients, such as the California Current System (CCS), apparently lack the ability to simulate the frequency distribution and/or the full range of very low surface chlorophyll concentrations offshore to high coastal chlorophyll concentrations observed in situ (Fig. 1B) (Gruber et al., 2006; Goebel et al., 2010; Gruber et al., 2011; Chenillat et al., 2013; Guo et al., 2014; Chenillat et al., 2015; Renault et al., 2016).

It has been hypothesized that the lack of very high chlorophyll conditions in most global earth system simulations arises primarily from under-representation of the intense circulation and mixing processes in coastal regions that often feature the highest chlorophyll values (Stock et al., 2011), even in highly size-structured models (Ward et al., 2012). This is particularly true for eastern boundary upwelling systems where global models exhibit some of their largest biases. However, prototype high-resolution earth system simulations, featuring  $1/10^\circ$  horizontal ocean resolution (Stock et al., 2017), and some eddy resolving regional simulations with  $\sim 5$  to 15 km horizontal resolution (Gruber et al., 2006; Goebel et al., 2010; Gruber et al., 2011; Chenillat et al., 2013; Guo et al., 2014; Chenillat et al., 2015; Renault et al., 2016) are also challenged in representing the full observed chlorophyll dynamical range or its spatial distribution. While submesoscale dynamics requiring  $\sim 1$  km resolution (e.g., fronts) can also facilitate phytoplankton blooms and associated export production by injecting nutrients into surface waters (Omand et al., 2015; Stukel et al., 2017), simulations to date suggest that refined spatial resolution alone may not be sufficient to capture high coastal chlorophyll.

In this study, our goal is to test whether improved resolution of the phytoplankton-grazer interactions can enable models to capture the dynamic range of chlorophyll concentration across an ecological gradient from productive to oligotrophic ecosystems, representative of the global oceans. The well-studied CCS, which features intensely productive and oligotrophic regions in close proximity, is used as a test region. We hypothesize that simulating the observed range of chlorophyll requires both high spatial resolution of circulation and improved representation of the ‘sequential invasion’ and ‘grazer decoupling’ mechanisms described above. A planktonic ecosystem model with a canonical two size-class phytoplankton structure, the Carbon, Ocean Biogeochemistry and Lower Trophics (COBALT) model (Stock et al., 2014), is amended to include an additional large coastal diatom group to test this hypothesis. Briefly, the new coastal diatom group has a larger individual cell size than the current large phytoplankton group in the COBALT model and implicit chain-forming is assumed to further protect it from grazing by smaller zooplankton groups. Furthermore, rapid diatom growth rates relative to similarly sized phytoplankton from other taxonomic groups (Edwards et al., 2012 their Fig. 3) minimizes allometric penalties associated with large size, increasing the potential for trophic decoupling. After assessing the ability of our coastal diatom addition to improve the range of chlorophyll concentration, we explore implications for the simulation of coastal hypoxia.

## 2. Methods

### 2.1. Model study domain, physical forcing and configuration

The full study domain spans the zonal extent of the CCS, from Vancouver Island ( $50^\circ\text{N}$ ) to southern Baja California Peninsula ( $20^\circ\text{N}$ ), extending up to 1200 km offshore parallel to the coast. This study focuses on the central part of the CCS as a quintessential example of the CCS coastal upwelling system with a narrow continental shelf and a sharp offshore to near-shore ecosystem gradient, spanning chlorophyll concentrations from  $\sim 0.03$  to  $> 10 \text{ mg m}^{-3}$  over an average summer

Download English Version:

<https://daneshyari.com/en/article/11263490>

Download Persian Version:

<https://daneshyari.com/article/11263490>

[Daneshyari.com](https://daneshyari.com)