Research papers

Role of wind in regulating phytoplankton blooms on the Mid-Atlantic Bight

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ABSTRACT

Mixing has long been recognized as having an important role in influencing underwater light and nutrient budgets and thus regulating phytoplankton bloom. Mixing related to stratification and de-stratification is a key parameter of the physical environment that can control the timing and magnitude of blooms. Here we use a high-resolution three-dimensional biogeochemical model in the Mid-Atlantic Bight (MAB) to study phytoplankton bloom dynamics for the years 2004–2007. We present a simulated fall-winter bloom in the shelf region and spring bloom in the shelf-break front region. The ratio of light over mixed layer depth (MLD) was used to determine the trade-off effects of mixing (increase mixing will increase nutrients availability but decrease light availability). We find that the critical light value ($I'_{chl\ mas}$) is around 60 (W m^{-2}) for the shelf region and 150 (W m^{-2}) for the shelf-break front region. There is a predictable linear regression relationship between $I'_{chl\ mas}$ and depth. A sensitivity run with no wind forcing was used to test the role of wind-induced mixing on the balance between light and nutrient terms and its influence on timing and magnitude of the bloom. The phytoplankton dynamics in the shelf-break front region are found to be more sensitive to the wind-induced mixing.

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1. Introduction

Broad continental shelves are highly productive systems that are globally significant zones for the biogeochemical cycling of elements (Longhurst, 1998). This is especially true for the Mid-Atlantic Bight (MAB), which has an extremely productive ecosystem that is fueled by large seasonal phytoplankton blooms (O'Reilly and Busch, 1984; O'Reilly et al., 1987). This has motivated numerous observational studies on the physical forcing of phytoplankton blooms in the MAB. These studies have documented the spatial and temporal variability in phytoplankton biomass in the MAB and have hypothesized about the key physical processes that underlie the observed variability. The 12 yr (1977–1988) NOAA NMFS Marine Resource Monitoring and Prediction (MARMAP) survey of the Northeast of US continental shelf found the highest phytoplankton concentrations during the winter-spring (O'Reilly and Zetlin, 1998). This was consistent with previous results from the Coastal Zone Color Scanner (CZCS) and Sea-viewing Wide Field of view Sensor (SeaWiFS) imagery that showed a fall-winter maximum of chlorophyll concentration in the middle and outer shelf waters and a spring maximum in the shelf-break/slope waters (Ryan et al., 1999; Xu et al., 2011; Yoder et al., 2001). Despite these large data sets, the observational

studies did not have the spatial and temporal data required to link the environmental factors that underlie the phytoplankton dynamics. This has prompted the development of coupled ecosystem models to test hypotheses about the physical regulation of the MAB phytoplankton communities (Fennel et al., 2006).

Models describing phytoplankton dynamics must reconcile a phytoplankton's need for light and nutrients, both of which are related to the overall mixing in the water column. The limitation of light to support phytoplankton growth builds on the (Sverdrup, 1953) "critical depth" model which predicts the initiation of phytoplankton blooms only after cells reside at a the critical depth where photosynthesis is larger than respiration allowing for the build-up of biomass. The maximum depth suitable for phytoplankton photosynthesis is most often defined as the depth where photosynthetic available radiation (PAR) is 1% of its surface value. While the absolute lower limit of light capable of supporting photosynthesis is still a subject of debate (Dubinsky and Schofield, 2010), estimates of the compensation depth irradiance based on Sverdrup's theory suggest it is relatively uniform throughout many regions of the ocean (Siegel et al., 2002). If light is present in sufficient quantities, the magnitude and duration of the bloom is then a complex function of mixing, nutrient availability (Tilman, 1982) and grazing pressure (Fasham et al., 1990; Gentleman et al., 2003; Martin, 1965; Turner and Tester, 1997). The flux of nutrients to the euphotic zone is determined by mixing across the nutricline, which can happen with mixed layer depth (MLD) increase if it is associated with

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entrainment. MLD thus has been demonstrated to be a key factor in determining phytoplankton abundance (Behrenfeld et al., 2002; Field et al., 1998); however while vertical mixing in the upper-ocean boundary layer can increase productivity in the surface waters through enhanced nutrient supply from deep waters it can also decrease productivity due to mixing phytoplankton below the critical depth and therefore introducing the possibility of light limitation (Dutkiewicz et al., 2001). To parameterize the relative roles of mixing and light availability the ratio of Z_{mld} (mixing layer depth) to Z_{eu} (euphotic depth) has been used to describe the regulating primary production (Huisman et al., 1999; Irigoien and Castel, 1997); however, this ratio only reflects the relationship between surface light condition and MLD. Therefore, the ratio of integral of light in the euphotic zone and MLD ($\int_{-Z_{eu}}^{0} I(z)dz/z_{mld}$) might be a preferred value to compare the balance between light limitation and nutrient limitation.

We use time series of satellite chlorophyll and 3-D biophysical model simulations to investigate the relative importance of mixing rates and light availability for phytoplankton populations in the MAB.

2. Methods

For this project we utilized data collected by the Mid-Atlantic Regional Coastal Ocean Observing System (MARCOOS) that is part of the United States Integrated Ocean Observing System (IOOS) (Schofield et al., 2010). MARCOOS provided an extensive data set to validate biological model simulations. In this effort we used surface data provided by ocean color satellite imagery and in situ data collected by Webb Slocum gliders (Schofield et al., 2007).

2.1. The biogeochemical model

In this study we used the Regional Ocean Modeling System (ROMS, http://www.myroms.org) (Haidvogel and Beckmann, 1999; Wilkin et al., 2005) which was configured to the continental shelf of the Middle Atlantic Bight (MAB) (the model domain is shown in Fig. 1). The model has a horizontal grid resolution of approximately 5 km, and uses 36 vertical layers in a terrain-following s-coordinate system. The biogeochemical model was developed and described in Fennel et al. (2006). The model here assumes nitrogen is the major limiting nutrient, which is a reasonable assumption as nutrient budgets indicate nitrogen limitation is frequently observed in the MAB (Ryther and Dunstan, 1971; Sharp and Church, 1981). Also nitrogen availability in the MAB is found the key nutrient to accurately simulating primary production (Fennel et al., 2006). The basic structure of this model follows a classical Fasham model (Fasham et al., 1990) and is constructed using seven state variables: phytoplankton, zooplankton, nitrate, ammonium, small and large detritus, and chlorophyll. The time rate change of phytoplankton is influenced by the growth rate of phytoplankton, grazing by zooplankton, mortality, aggregation of phytoplankton to small and large detritus, and vertical sinking of the aggregates. This model drives phytoplankton growth (μ) through variations in temperature (T) (Eppley, 1972), incident light intensity (I) (Evans and Parslow, 1985), and the availability of nutrients (Parker, 1993), following:

$$\mu = \mu_{max} f(I)(L_{NO_3} + L_{NH_4}) \tag{1}$$

μ_{max} is the maximum growth rate which depends on temperature. I is the photosynthetically available radiation and decreases with water depth due to absorption by seawater (assumed constant) and the time and spatially varying chlorophyll computed by the model.

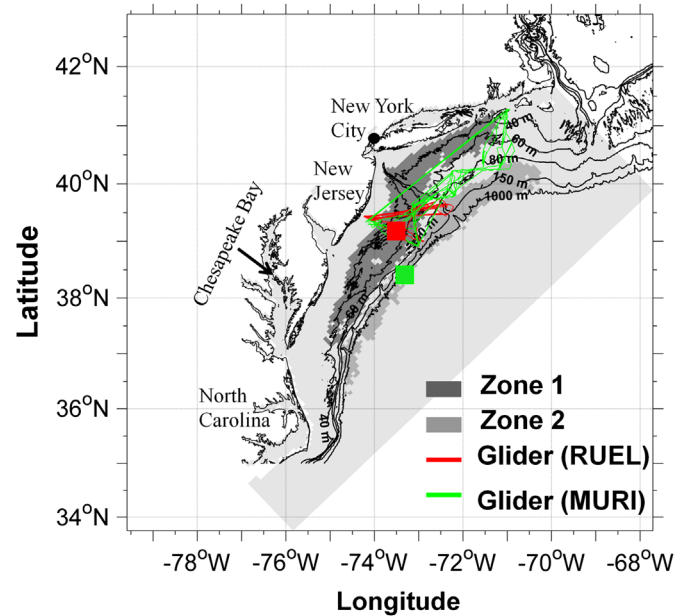$$I = I(z) = I_0 par \exp\{-z(K_w + K_{chl} \int_z^0 Chl(\zeta)d\zeta)\} \tag{2}$$

Fig. 1. Model domain (light gray). Dark gray and gray highlight the Zone 1 and Zone 2 region identified by Xu et al. (2011). Red and green lines show the glider transects. Red and green square symbols represent the grid point used for calculation in Zone 1 and Zone 2. The black lines with number show the bathymetry. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where I_0 is the surface incoming light and is the shortwave radiation flux from NCEP reanalysis data, *par* is the fraction of light that is available for photosynthesis and equals 0.43. K_w and K_{chl} are the light attenuation coefficients for water and chlorophyll, and are set to 0.04 m^{-1} and $0.025 \text{ (mg Chl)}^{-1} \text{ m}^{-2}$ respectively (Fennel et al., 2006). The $f(I)$ represents the photosynthesis-light (P–I) relationship. The parameter α is the initial slope of the P–I curve. The terms L_{NO_3} and L_{NH_4} represents the nutrients limitation.

$$f(I) = \frac{\alpha I}{\sqrt{\mu_{max}^2 + \alpha^2 I^2}}, \tag{3}$$

$$L_{NO_3} = \frac{NO_3}{K_{NO_3} + NO_3} \frac{1}{1 + NH_4/K_{NH_4}}, \tag{4}$$

$$L_{NH_4} = \frac{NH_4}{K_{NH_4} + NH_4} \tag{5}$$

The rate of grazing by zooplankton is represented by a Holling type s-shaped curve (Gentleman et al., 2003). The mortality loss term has linear relationship with phytoplankton. The aggregation rate is assumed to scale with the square of small particle abundance for more details see Fennel et al., 2006. The model was driven by atmospheric forcing provided by the North American R (NAM) forecast regional Reanalysis (NARR) from the National Centers for Environmental Prediction (NCEP). We used a 3-hourly re-analysis of surface air temperature, pressure, relative humidity, 10 m vector winds, precipitation, downward long-wave radiation, and net shortwave radiation to specify the surface fluxes of momentum and buoyancy using bulk formulae (Fairall et al., 2003). In the open boundary, we specified temperature, salinity, nitrate (NO_3), total inorganic carbon (TIC), alkalinity, and oxygen. Because the focus of this study is the influence of wind forcing on phytoplankton dynamics, the open boundary inputs are specified by the climatology input based on the Fennel ROMS model simulation of the Northeast North American (NENA) shelf (Fennel et al., 2006). We included the inputs of seven rivers