Interannual variability in phytoplankton blooms and plankton productivity over the Nova Scotian Shelf and in the Gulf of Maine

Hongjun Song[1,2], Rubao Ji[2,3,*], Charles Stock[4], Kelly Kearney[5], Zongling Wang[1]

[1]Key Lab of Science and Engineering for Marine Ecological Environment, The First Institute of Oceanography, SOA, Qingdao 266061, PR China

[2]Department of Biology, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA

[3]Marine Ecosystem and Environment Laboratory, Shanghai Ocean University, College of Marine Sciences, Institutes for Marine Sciences, Shanghai 201306, PR China

[4]NOAA Geophysical Fluid Dynamics Laboratory, Princeton University Forrestal Campus, Princeton, New Jersey 08540, USA

[5]Department of Geosciences, Princeton University, Princeton, New Jersey 08540, USA

*Corresponding author. Email: rji@whoi.edu

Marine Ecology Progress Series 426: 105–118 (2011)

Supplement 1. Comparison of the mixed layer depth (MLD) assessment, correlation between salinity and spring phytoplankton bloom (SPB) timing and the net primary production (NPP) variation extent among different salinity relaxation time settings. The forcings and other parameters of the Gulf of Maine (GoM) case were used here. MLD_{mod} and MLD_{obs} are the modeled and observed MLD, respectively. T_{SPB} is the SPB timing

Time scale	MLD_{mod} and MLD_{obs}		Correlations of salinity difference (0–50 m) & T_{SPB}	NPP variation (g C m^{-2} yr^{-1})	
	Correlation	Bias (m)		Mean	SD
10 d	R^2 = 0.583, p < 0.01	–7.84	r = 0.734, p < 0.01	137.3	5.8
5 d	R^2 = 0.621, p < 0.01	–6.25	r = 0.750, p < 0.01	138.2	6.5
1 d	R^2 = 0.634, p < 0.01	–4.66	r = 0.688, p < 0.01	139.9	7.1

Supplement 2. 1D ecosystem model.

The mixed layer code used for this paper is Matlab-based and was developed by K.K. and C.S. It simulates the evolution of water column properties under specified forcing by wind, heat, and salinity forcing. Allowance is also made for currents forced via a depth-independent pressure acceleration. There are 6 physical state variables in the physical model formulation: U and V are the east to west and south to north current velocities, q^2 is a turbulent quantity equal to 2× the turbulent kinetic energy, ℓ is a turbulent length scale, and T and S are the temperature and salinity. The momentum equations are standard 1D formulations:

$$\frac{\partial U}{\partial t} - fV = -\frac{1}{\rho_o}\frac{\partial p}{\partial x} + \frac{\partial}{\partial z} K_M \frac{\partial U}{\partial z} - \varepsilon U \quad (1)$$

$$\frac{\partial V}{\partial t} + fU = -\frac{1}{\rho_o}\frac{\partial p}{\partial y} + \frac{\partial}{\partial z} K_M \frac{\partial V}{\partial z} - \varepsilon V \quad (2)$$

where f is the Coriolis parameter, ρ is the density, K_M is the viscosity, $\frac{\partial p}{\partial x}$ is a specified pressure gradient (to impose a mean current), and ε is a momentum dissipation term. The dissipation term serves as a surrogate for horizontal momentum divergence. It removes energy from past storm events over a specified time scale as though energy were being transferred to more quiescent surrounding waters. Energy tends to accumulate unrealistically in 1D water columns without this effect (Mellor 2001). The value of ε was tuned such that the energy in the modeled currents is consistent with that observed. Values comparable to the time scales of storm events (1/3 d^{-1}) yielded reasonable results. The equations are solved using a semi-implicit Crank-Nicolson scheme.

The Mellor-Yamada turbulence closure scheme (Mellor & Yamada 1982) is used to calculate mixing coefficients. The reader is referred to this reference and Mellor (2004) for the governing equations and other details of this formulation. A k-epsilon formulation (see review by Umlauf & Burchard 2005) was also tested and yielded similar results to those presented herein. The top and bottom boundary conditions for Eqs. (1) and (2) are provided by the wind stress formulation of Large & Pond (1981) and a quadratic bottom drag law, respectively. Mixing at the surface was augmented by wave breaking scheme of Mellor & Blumberg (2004).

The temperature and salinity equations are given by:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z} K_V \frac{\partial T}{\partial z} + s/s \quad (3)$$

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial z} K_V \frac{\partial S}{\partial z} + s/s \quad (4)$$

where K_v is the vertical turbulent diffusion coefficient, and *s/s* is used to indicate sources and sinks. The temperature source term (shortwave heat flux) and boundary condition (longwave heat flux, sensible and latent heating and cooling) are described in the "Model description" section of the main paper. The salinity is relaxed to observations as described in the "Model description."

The biological model functional groups and interactions are summarized in Fig. 2 in the main text, and the equations can be found in Stock & Dunne (2010). Note that the small detritus pools in this model are functionally equivalent to what some models refer to as the dissolved organic pools. However, several adjustments were made to enhance the model and adapt it to the 1D mixed layer. First, the Geider et al. (1997) photosynthesis-light dependence was incorporated into the model. This formulation allows for dynamic C:chl, and the values used for the small and large phytoplankton in this study are given in Table S1.

Second, a temperature-dependent linear phytoplankton mortality term was introduced. This term is meant to represent basal/maintenance metabolic costs of the phytoplankton and was found to play an important role in reducing phytoplankton populations in the winter months. The values used were 0.15 d^{-1} at 20°C for fast-growing large phytoplankton, and 0.10 d^{-1} for small phytoplankton. A Q_{10} value of 2 was used for the temperature dependence of this term. Note that a linear cell death term (sensu Bidle & Falkowski 2004) would produce a similar effect.

Third, the mesozooplankton population was divided into 2 groups. MZ represents a small to medium-bodied copepod and is parameterized in the same manner that LZ is specified in Stock & Dunne (2010). LZ is a large copepod/euphausid group. The rates are obtained by extrapolating the allometric relationship of Hansen et al. (1997). Specifically, the maximum ingestion rate at 20°C is 0.8 d^{-1}, the half-saturation constant is 1.0 mmol N m^{-3}, and the basal respiration at 20°C is 0.008 d^{-1}. The use of low basal metabolic rates for LZ yielded the best fit with observed mesozooplankton values, and the rationale for this choice is discussed by Stock & Dunne (2010).

Table S1. Parameters used for small phytoplankton (SP) and large phytoplankton (LP) within the Geider et al. (1997) formulation

Symbol	Definition	Units	SP	LP
P^C_{max}	Maximum photosynthesis rate at 20°C	d^{-1}	3.0	3.5
α^{chl}	Chl *a*-specific initial slope of the photosynthesis-irradiance curve	g carbon (g chl)$^{-1}$ m^2 Watt^{-1}	3.0×10^{-5}	2.0×10^{-5}
θ_{max}	Maximum chl *a* to carbon ratio	g chl *a* (g carbon)$^{-1}$	0.05	0.05
ζ	Cost of biosynthesis	Dimensionless	0.1	0.1

LITERATURE CITED

Bidle KD, Falkowski PG (2004) Cell death in planktonic, photosynthetic microorganisms. Nat Rev Microbiol 2:643–655

Geider RJ, MacIntyre HL, Kana TM (1997) Dynamic model of phytoplankton growth and acclimation: responses of the balanced growth rate and chlorophyll *a*: carbon ratio to light, nutrient-limitation and temperature. Mar Ecol Prog Ser 148:187–200

Hansen PJ, Bjørnsen PK, Hansen BW (1997) Zooplankton grazing and growth: scaling within the 2–2000-µm body size range. Limnol Oceanogr 42:687–704

Large WG, Pond S (1981) Open ocean momentum flux measurements in moderate to strong winds. J Phys Oceanogr 11:324–336

Mellor GL (2001) One-dimensional, ocean surface layer modeling: a problem and a solution. J Phys Oceanogr 31:790–809

Mellor GL (2004) Users guide for a three-dimensional, primitive equation, numerical ocean model (POM). Princeton University, Princeton, NJ

Mellor GL, Blumberg AF (2004) Wave breaking and ocean surface layer thermal response. J Phys Oceanogr 34:693–698

Mellor GL, Yamada T (1982) Development of a turbulence closure model for geophysical fluid problems. Rev Geophys 20:851–875

Stock CA, Dunne JP (2010) Controls on the ratio of mesozooplankton production to primary production in marine ecosystems. Deep-Sea Res I 57:95–112

Umlauf L, Burchard H (2005) Second-order turbulence closure models for geophysical boundary layers. A review of recent work. Cont Shelf Res 25:795–827

Supplement 3. Temporal coverage of the monthly salinity data in the Gulf of Maine (GoM) and on the Nova Scotian Shelf (NSS) from 1980 to 2008