Modeling of biogeochemical cycles and climate change on the Continental Shelf: An example from the Pacific coast of Canada

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Abstract

The development of a quantitative understanding of the interactions among physical, chemical and biological processes is critical for predicting the marine ecosystem response to climate change. This study presents results from a coupled plankton/circulation model (ROMS) developed to study factors influencing bloom dynamics on the continental shelf of southern Vancouver Island. Model results show the influence of the Juan de Fuca Eddy on the growth and retention of phytoplankton and the importance of different sources of nutrients (*i.e.*, wind-driven upwelling, topographically controlled upwelling, and the outflow from Juan de Fuca Strait) on primary production and biogeochemical cycles. The usefulness of this type of model to assess the potential responses of the marine ecosystem to climate change scenarios is discussed, as well as the limitations of present biogeochemical models, to predict future climate change.

Introduction

Ecosystem models are important tools to study biogeochemical cycles that are driven by complex interactions among physical, chemical and biological processes. In the open ocean, simple ecosystem models coupled to zero- or one-dimensional physical models have successfully contributed to the study of the importance of macro- and micronutrients on primary production, food-web interactions and physical–biological interactions (*e.g.*, Fasham *et al*., 1990; Doney *et al.*, 1996). However, the high temporal and spatial variability of coastal regions makes it often necessary to couple ecosystem models to high resolution circulation models. Plankton ecosystem models coupled to circulation models are increasingly being applied to a variety of regions in the ocean to improve our understanding of ecosystem dynamics and to generalize discrete observations (*e.g.*, Gruber *et al.*, 2006; Powell *et al.*, 2006). These ecosystem models also have the potential to help us understand and quantify the interactions between marine ecosystems and climate change and to predict plausible ecosystem changes.

The southwestern coast of Vancouver Island (Fig.1) is one of the most productive fishing regions along the west coast of Canada (Ware and McFarlane, 1989). This region is at the northern end of the California Current System and is influenced by summer coastal upwelling. It is also influenced by freshwater inputs from the Fraser River, producing an estuarine circulation and strong tidal currents (Crawford, 1991). All these processes contribute to the dynamics of nutrient supply and phytoplankton and ultimately to the high primary productivity

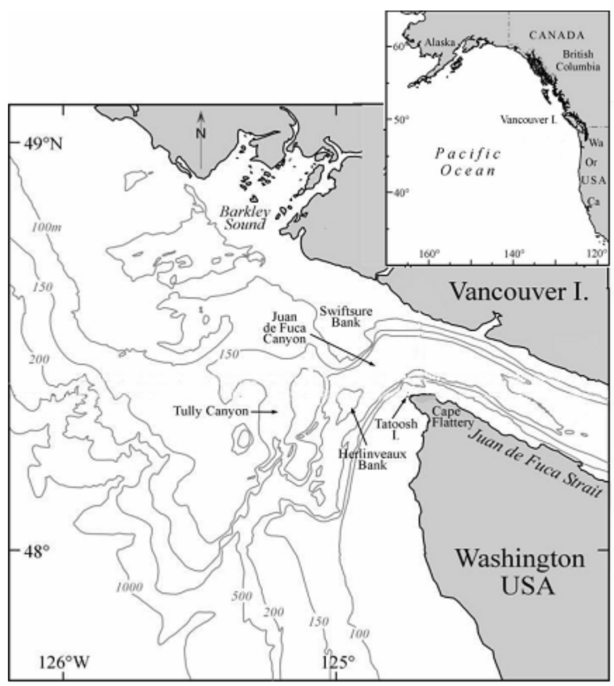

Fig. 1 Geography and bathymetry (m) of the southwestern coast of Vancouver Island in the Northeast Pacific.

observed in this region. In the summer, phytoplankton blooms are often found in this region associated with the Juan de Fuca Eddy, a seasonal cyclonic cold eddy located west of the entrance to Juan de Fuca Strait. This eddy is formed during periods of upwelling favorable winds, which in combination with the estuarine flow and tides, produce enhanced upwelling off Cape Flattery (Foreman *et al.*, 2008). Similarly, the Okhotsk Sea is one of the most biologically productive regions in the world with high fisheries production and high primary productivity, especially on the continental shelf (*e.g.*, Sorokin and Sorokin, 2002). In these dynamical regions, the coupling of an ecosystem model to a three-dimensional coastal ocean circulation model should yield new insight on the physical processes affecting the distribution of micronutrients in the region, and help understand the resulting impact on phytoplankton growth.

In this study, a simple plankton ecosystem model has been coupled to a circulation model (Regional Ocean Modeling System, ROMS) to study factors influencing summer bloom dynamics on the continental shelf off southwestern Vancouver Island. In the next section the model is described. Then, model results are presented and discussed, followed by a summary.

Model Description

Biological model

The model developed in this study is based upon the one-dimensional mixed layer/five-component NPZD (nutrient-phytoplankton-zooplankton-detritus) type model previously developed for the subarctic Pacific (Peña, 2003). The model was mainly modified to include the silicon cycle, separate compartments for NO_3 and NH_4, microzooplankton grazing on small and large phytoplankton, and differential re-mineralization of sinking silicon and nitrogen detritus. The increased complexity was necessary to represent conditions more characteristic of coastal regions. The modified ecosystem model has eight compartments: dissolved nutrients (NO_3, NH_4 and $Si(OH)_4$), diatoms that take up $Si(OH)_4$, a small size class of phytoplankton, microzooplankton, and two types of sinking detritus (nitrogen and silicon detritus). The food-web structure is shown schematically in Figure 2. All model compartments are expressed in terms of their nitrogen concentration (mmol-N m^{-3}). The processes incorporated in the model include growth of small phytoplankton and diatoms controlled by light, NO_3 and NH_4, and for diatoms also by $Si(OH)_4$. Uptake of nutrients by phytoplankton during the growth process is represented via a Michaelis-Menten formulation. Grazing by microzooplankton on small and large phytoplankton and nitrogen detritus is modeled by the Holling type-III formulation. Natural loss processes (*i.e.*, mortality and excretion) for both phytoplankton and zooplankton are linear. The differential remineralization of nitrogen and silicon detritus is linear as well. As in the previous model, the effect of top-down control by mesozooplankton in this model is formulated by imposing the grazing pressure of the observed biomass on diatoms and microzooplankton using a Holling type-III formulation. Also in the model, temperature affects all physiological parameters according to Q_{10} factors referenced to 10°C.

Biophysical model

The biological model is coupled to a three-dimensional coastal ocean circulation model. The circulation model is an implementation of the ROMS developed by Foreman *et al.* (2008). The model domain is bounded by approximately 45.5°N to 50.0°N and 123.5°W to 128.5°W, with 30 non-uniform vertical layers, with increased resolution near the surface and bottom boundary layers. A

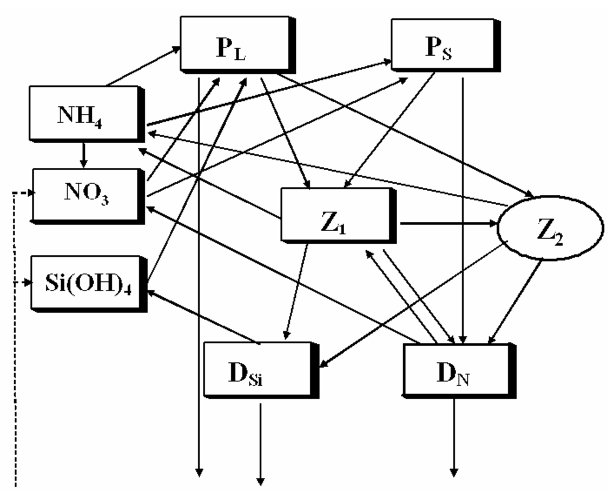

Fig. 2 Diagram of the food-web model: fluxes are shown with solid lines, external input of nutrients by dashed lines. Model compartments are represented by rectangles and the imposed biomass of mesozooplankton by an oval compartment. P_L represents diatoms, P_S small phyto-plankton, Z_1 microzooplankton, Z_2 mesozooplankton, D_N nitrogen detritus and D_{Si} silicon detritus.

stretched coordinate rectangular grid with horizontal resolution as coarse as 5 km adjacent to the western boundary and as fine as 1 km near the entrance of Juan de Fuca Strait is employed to obtain an accurate representation of topographic and coastal features of the region. The model is forced with tides, average summer upwelling-favorable winds, temperature and salinity monthly climatologies, and buoyancy boundary conditions that maintain an estuarine flow in Juan de Fuca Strait. The initial and boundary conditions of the model for nitrate and silicate are derived from three-dimensional summer climatology generated from a combination of data from the Institute of Ocean Sciences and the World Ocean Database 2001. For lack of better information, all other compartments are initialized with a constant value. Given the prescribed forcing, the model simulates summer conditions of temperature, salinity and currents that are in reasonable agreement with observations (Foreman *et al.*, 2008).

Results and Discussion

The model was run for 60 days and the results from the last 15 days are presented here. The modeled surface distribution of phytoplankton (diatoms and small phytoplankton) and nitrate concentration (Fig. 3) show the influence of the Juan de Fuca Eddy, located west of Juan de Fuca Strait, on the growth and retention of phytoplankton. Phytoplankton concentrations are higher around the eddy region and along the Washington upwelling coast. Similarly, nitrate is abundant (>15 mmol m^{-3}) nearshore and in the estuarine outflow from Juan de Fuca Strait that curls around the eddy in a counterclockwise manner. Nutrient concentrations decrease seaward such that no detectable nitrate was observed in the upper 10 m west of the continental shelf.

The modeled phytoplankton distribution patterns are in agreement with remotely-sensed observations of ocean color during the summer, as illustrated in Figure 4. In particular, the model captures the increased phytoplankton abundance in the continental shelf and eddy region, and lower concentrations offshore, but tends to over-predict phytoplankton biomass in Juan de Fuca Strait.

To determine the importance of different sources of nutrients (*i.e.*, wind-driven upwelling, topographically controlled upwelling, and the outflow from Juan de Fuca Strait) on phytoplankton biomass and primary production, the model was run with and without tidal forcing and wind forcing. Results from these experiments indicate that estuarine outflow from Juan de Fuca Strait is essential for nutrient enrichment and bloom generation. The strong influence of tidal mixing on nitrate fluxes from the estuarine outflow is illustrated in Figure 5, which shows that fluxes are significantly reduced in the simulation without tidal forcing compared to those from the simulation without winds but with tides. In the model, the eddy is formed

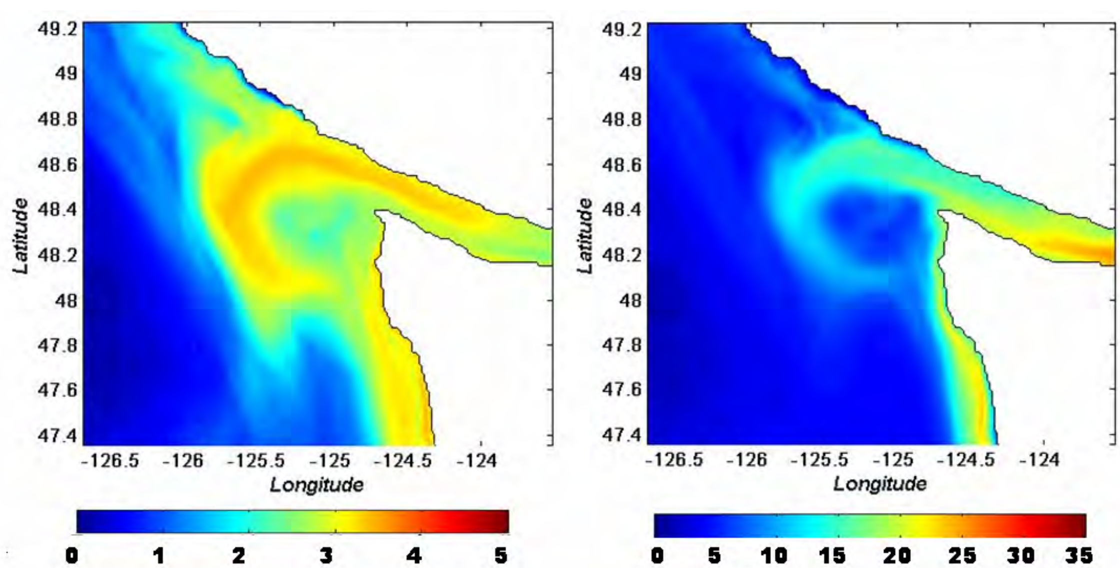

Fig. 3 Model surface phytoplankton (left panel, $P_S + P_L$) and nitrate concentration (right panel) average over days 46–60 of the 60-day simulation.

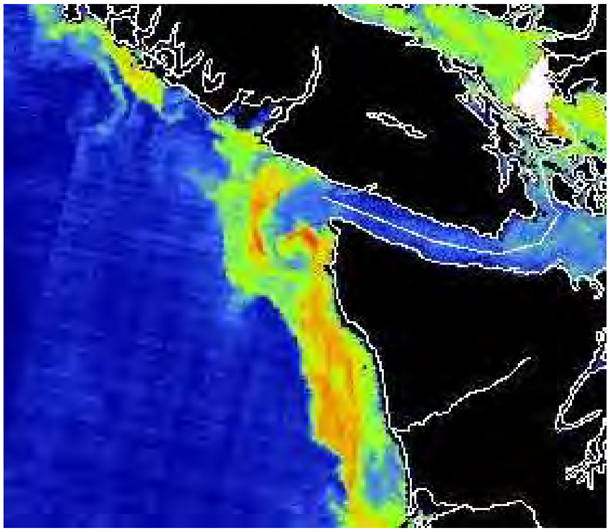

Fig. 4 MERIS satellite fluorescence for June 3, 2003 (courtesy of the European Space Agency and provided by J. Gower and S. King, IOS, Fisheries and Oceans Canada).

when either wind or tidal forcing is applied. A stronger bloom in the eddy region is obtained when the model is forced with estuarine flow and tides instead of with estuarine flow and winds.

In summary, our results indicate that phytoplankton production is influenced by nutrient fluxes, stratification, and temperature, all of which are likely to be affected by climate change. Impacts on phytoplankton will lead to cascading effects throughout the marine ecosystem. In coastal regions, the high temporal and spatial variability makes it challenging to detect ecosystem changes based on observations only. Thus, there is a need to develop three-dimensional circulation models that can point to plausible changes. To work towards this aim, the model was used to explore ecosystem responses to changes that might accompany climate change. Figure 6 shows preliminary results from a warming simulation where a constant offset of 3°C is applied to the initial temperature field. For the warming simulation, model phytoplankton biomass is of similar magnitude and distribution pattern to that of the standard run. In contrast, the model exhibits a more pronounced effect on primary production, resulting in higher productivity in the warming simulation. Since phytoplankton biomass is the result of growth and grazing, the results suggest that zooplankton grazing also increases with warming. It should be noted that in this simple warming simulation, the temperature offset applied to the model has no effect on the mixed-layer evolution and only explores the response of the ecosystem model to warming, separated from the response that might result from changes in the physical model.

Additional interpretation of these results is not warranted, since although the model can reproduce observations reasonably well, it has little 'predictive' power. The model currently lacks the complexity (species or functional groups, parameters that 'adapt/change' in response to changing ocean conditions/forcing, *etc.*) for the ecosystem to behave differently under different oceanic or climatic regimes. However, adding complexity (and realism) to models does not necessarily improve their predictive power, especially if the information

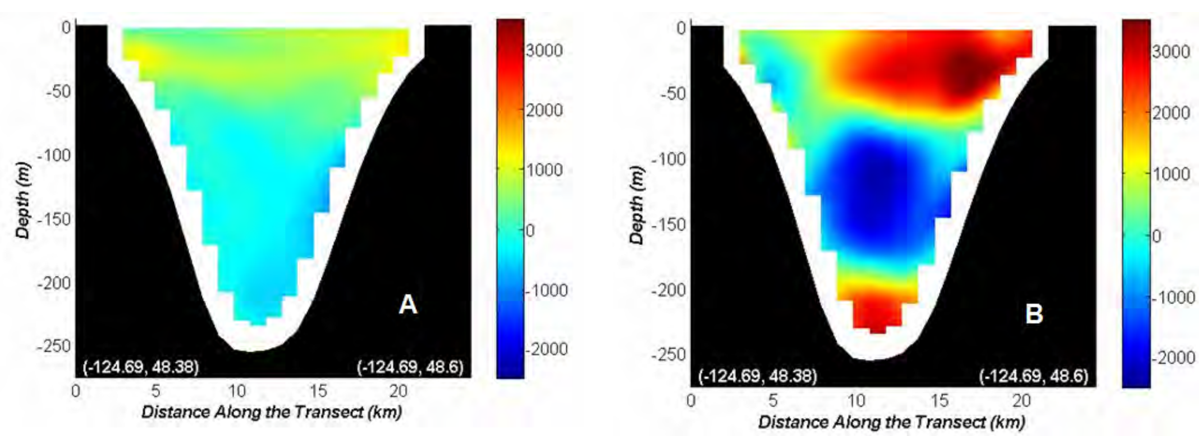

Fig. 5 Contours of the model fluxes of nitrate (mmol m^{-3} s^{-1}) along a transect at longitude 124.69°W across Juan de Fuca Strait, averaged over days 46–60 for (A) simulation with upwelling winds but no tides, and (B) simulation with tides but no wind.

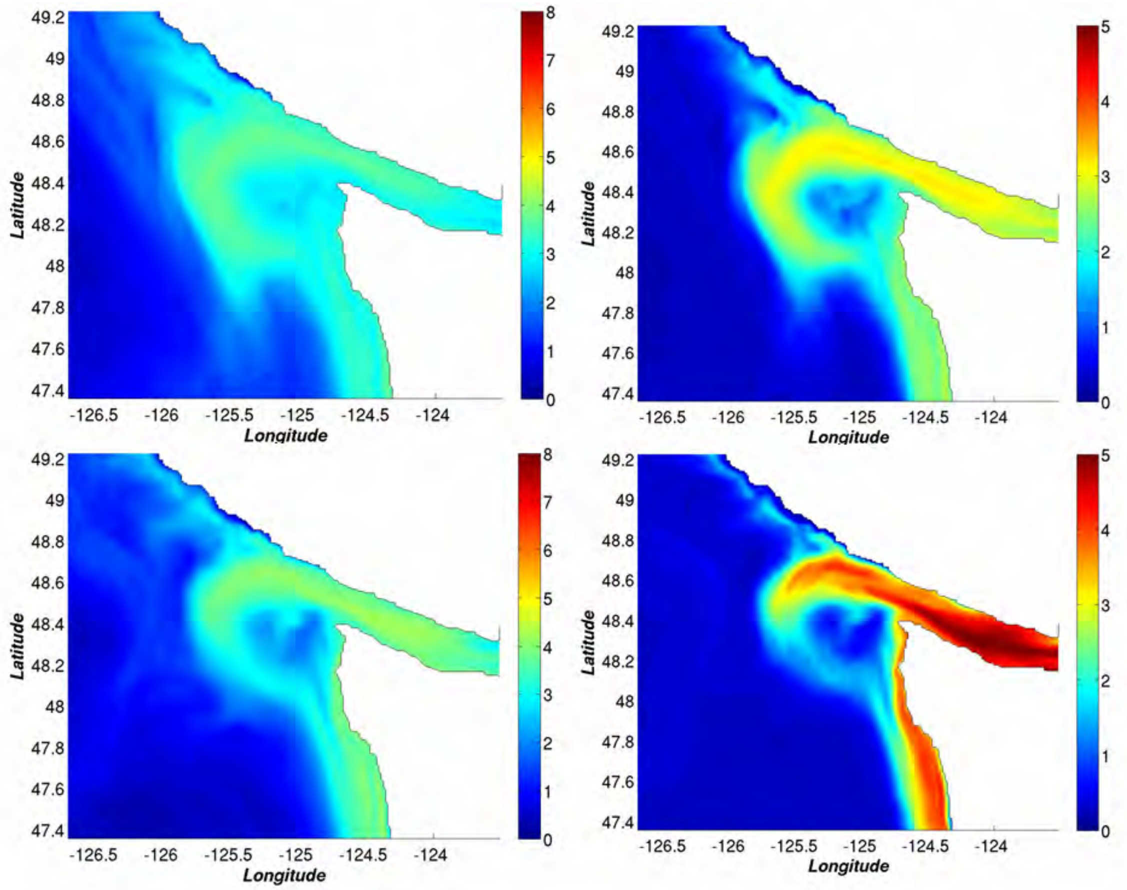

Fig. 6 Model surface phytoplankton (mmol-N m^{-3}, left panels) and primary production (mmol-N m^{-3} d^{-1}, right panels) average over days 46–60 of the 60-day simulation for the standard run (top panels) and for the warming simulation (bottom panels).

needed to construct and/or evaluate the more complex models is not available. Much work is necessary to improve confidence in climate-change prediction based on this type of ecosystem model.

Summary

Overall, this study provides an example of the utility of a coupled ecosystem/circulation model to the study of coastal ecosystems. In particular, the model was able to provide useful information on the importance of different sources of nutrients to phytoplankton growth and distribution, and to the transport of phytoplankton to the coast. The relatively simple ecosystem model developed here can be coupled to circulation models of other coastal regions, such as the Sea of Okhotsk, and can be used to address many ecosystem problems. In summary:

- The model is able to simulate the major biological features of the Vancouver Island shelf, higher surface nutrient and phytoplankton biomass in the Juan de Fuca Eddy, lower concentrations in Juan de Fuca Strait, and coastal upwelling off Washington State.
- The model indicates that the phytoplankton bloom in the Juan de Fuca Eddy region is the result of estuarine outflow from Juan de Fuca Strait and enhanced upwelling off Cape Flattery. The upwelling is generated by both the winds and the tides. A stronger bloom is generated in the eddy when the model is forced with estuarine flow and tides compared to the run forced by estuarine flow and winds.
- Preliminary results of the warming simulation suggest a strong response in the physiological rates of phytoplankton, with higher primary production and greater recycling rates but little change in concentrations.

References

Crawford, W.R. 1991. Tidal mixing and nutrient flux in the waters of southwest British Columbia. pp. 855–869 *in* Tidal Hydrodynamics *edited by* B.B. Parker, John Wiley and Sons, Inc.

Doney, S.C., Glover, D.M. and Najjar, R.G. 1996. A new coupled, one-dimensional biological-physical model for the upper ocean: Applications to the JGOFS Bermuda Atlantic Time-series Study (BATS) site *Deep-Sea Res. II* **43**: 591–624.

Fasham, M.J.R., Ducklow, H.W. and McKelvie, S.M. 1990. A nitrogen-based model of plankton dynamics in the oceanic mixed layer. *J. Mar. Res.* **48**: 591–639.

Foreman, M.G.G., Callendar, W., MacFadyen, A., Hickey, B.M., Thomson, R.E. and Di Lorenzo, E. 2008. Modeling the generation of the Juan de Fuca Eddy. *J. Geophys. Res.* **113**: doi:10.1029/2006JC 004082.

Gruber, N., Frenzel, H., Doney, S.C., Marchesiello, P., McWilliams, J.C., Moisan, J.R., Oram, J.J., Plattner, G.-K. and Stolzenbach, K.D. 2006. Eddy-resolving simulation of plankton ecosystem dynamics in the California Current System. *Deep-Sea Res. I* **53**: 1483–1516.

Peña, M.A. 2003. Modelling the response of the planktonic food web to iron fertilization and warming in the NE subarctic Pacific. *Progr. Oceanogr.* **57**: 453–479.

Powell, T.M., Lewis, C.V.W., Curchitser, E.N., Haidvogel, D.B., Hermann, A.J. and Dobbins, E.L. 2006. Results from a three-dimensional, nested biological-physical model of the California Current system and comparison with statistics from satellite imagery. *J. Geophys. Res.* **111**: doi:10.1029/2004JC 002506.

Sorokin, Y.I. and Sorokin, P.Y. 2002. Microplankton and primary production in the Sea of Okhotsk in summer 1994. *J. Plankton Res.* **24**: 453–470.

Ware, D.M. and McFarlane, G.A. 1989. Fisheries production domains in the Northeast Pacific Ocean. *In* Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models *edited by* G.A. McFarlane, *Can. Spec. Publ. Fish. Aquat. Sci*. **108**: 359–379.