Ecosystem Modeling of the Oregon Shelf: Everything but the Kitchen Sink

Yvette H. SPITZ

*College of Oceanic and Atmospheric Sciences, Oregon State University,
Corvallis, OR 97331, U.S.A.*

Abstract—The Oregon coast has long been recognized as a region of strong summer upwelling and rich productivity. Over the last decade several observational programs have begun to unravel the underlying factors controlling observed patterns of primary and secondary production. Key discoveries include the finding that phosphorus availability can control phytoplankton production, despite the common misconception that nitrogen is the sole proximate limiting nutrient. Enhanced field efforts have also revealed frequent summertime episodes of hypoxic and even anoxic bottom waters during the last decade. The severity and duration of these low-oxygen events, as well as their spatial extent along the Oregon shelf vary on an annual basis. Finally, regular blooms of *Myrionecta rubra*, a "red-tide" forming mixotrophic ciliate, have been recorded within the Columbia River Estuary (CRE) over the last 15 years or so. Incongruously, these red waters persist for months while the residence time of the CRE is a few days. Simple ecosystem and active particle tracking models coupled to circulation models have complemented field experiments to help us better understand the dominant forcing (physical and biological) leading to hypoxic/anoxic events, the frequency of phosphorus stressed conditions, and the mechanisms for retention of *Myrionecta rubra* in the CRE.

Keywords: coastal ecosystem dynamics and model, oxygen dynamics and modeling, Oregon coast, phosphorus cycle

INTRODUCTION

As more observational resources are trained on our oceans, existing numerical and heuristic models can be adapted to incorporate new findings of key processes and players in the marine environment. This manuscript will describe a recent revolution of the current understanding of ecosystem dynamics in two complex biological and physical systems: the Oregon shelf and the Columbia River estuary (CRE). Specifically, enhanced monitoring has revealed the unexpected regulatory role of phosphorus, widespread hypoxic events, and enigmatic blooms of *Myrionecta rubra*.

Phosphorus has not routinely been considered to play a significant role in controlling phytoplankton production in upwelling-dominated coastal systems.

Thus, little attention was devoted to the role of phosphorus (P) off the Oregon Coast until the Coastal Ocean Advances in Shelf Transport (COAST) program in 2001–2003. During this project, Ruttenberg and Dyhrman (2005) and Dyhrman and Ruttenberg (2006) found that dissolved organic phosphorus (DOP) concentrations often exceed dissolved inorganic phosphorus (DIP) in the euphotic zone and found strong evidence that DOP is being utilized by phytoplankton in the upwelling-dominated Oregon coastal system. We have developed a coupled biochemical/circulation model to examine whether phytoplankton experience P stress and to examine the extent to which phytoplankton may utilize DOP as a nutritional resource.

Frequent summertime episodes of low dissolved oxygen (hypoxic; dissolved oxygen < 1.43 ml/l) bottom waters have been observed since 2002 on the Oregon shelf (Grantham et al., 2004; Chan et al., 2008). The severity and duration of these events as well as the spatial extent of the hypoxic water vary on an annual basis. Oxygen levels during August to September 2006 were so low that anoxic (absence of DO in the water) conditions were reached at some locations along the shelf, leading to the death of fish, crab and other benthic species. Low-oxygen conditions on the shelf are the cumulative, or synergistic, result of many processes; among the most important are (1) the amount of total primary production, (2) the residence time of water at a given location, and (3) the initial DO content of the source waters that upwell onto the shelf. We have developed a simple model to address the importance of these factors in driving hypoxic/anoxic events.

For several decades, annually recurring blooms of the mixotrophic ciliate, *Myrionecta rubra*, have been observed in the Columbia River estuary in late summer and persist for several weeks to months. An effort to understand the dynamics of these blooms was conducted by Herfort et al. (2010) in three consecutive years (2007–2009). They found that *M. rubra* appear to harbor the same cryptophyte chloroplast in recurring blooms and their analyses suggest that the plastid is from *Teleaulax amphioxeia*. However, free-living cells of this species were practically absent from the bloom patches in the estuary. Continuous efforts to explain the formation of these blooms suggest that the cryptophytes are found in abundance in a small bay, Baker Bay, at the entrance of the Columbia River Estuary and could be the source of prey for the *M. rubra* that are then advected to the estuary main channels and retained in these regions for several weeks. The retention mechanisms are, however, poorly understood. Moreover retention is counterintuitive as the river flushing time is of the order of a few days. *M. rubra* is known to be an extremely effective swimmer capable of swim speeds in the range of 1 mm s^{-1} (Riisgård and Larsen, 2009). This swimming behavior may allow the organism to remain in the estuary, assuming the organism has an effective strategy of vertical movement to avoid the strongest outflowing currents. Particle tracking simulations have been performed with a variety of swimming strategies and biological behavior in order to determine the factors that are the most efficient in retaining *M. rubra* in the estuary.
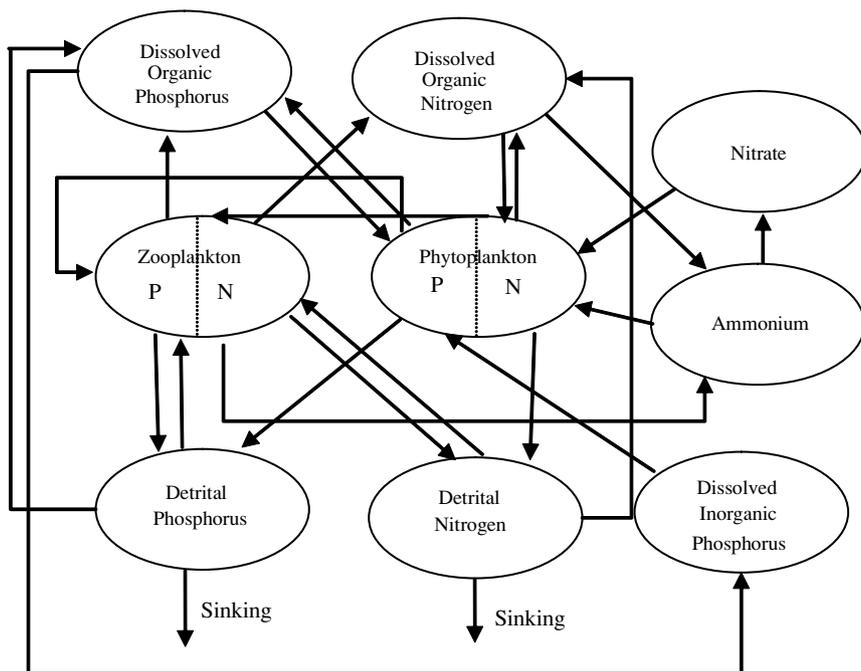
Fig. 1. Ecosystem model with nitrogen and phosphorus cycle.

METHODS

Two new ecosystem models (Figs. 1 and 2) were developed based on the Spitz *et al.* (2005) nitrogen cycle NPZD model (nitrate, ammonium, phytoplankton, zooplankton and detritus). In addition to the nitrogen cycle, the first model includes the phosphorus cycle and dissolved organic matter (Fig. 1). It is coupled to the Regional Ocean Model System (ROMS) circulation model (http://www.myroms.org/) and applied to the Oregon coast during summer 2001 in a setup similar to the one in Spitz *et al.* (2005).

In order to answer the question of patterns of low oxygen along the Oregon shelf, the second model is based on the Spitz *et al.* (2005) model with an additional oxygen component and is coupled to ROMS in the configuration described in Koch *et al.* (2010). Oxygen is calculated from respiration, regeneration and production processes using a constant O:N ratio. In addition, alteration of oxygen in the coastal ocean by air-sea exchange and ventilation processes is calculated using Wanninkhof (1992) equations, which are controlled by wind speed, gas solubility, and temperature and salinity dependence of the Schmidt number.

M. rubra particles are simulated using Lagrangian particle tracking simulations where the velocity fields are obtained from simulations with the
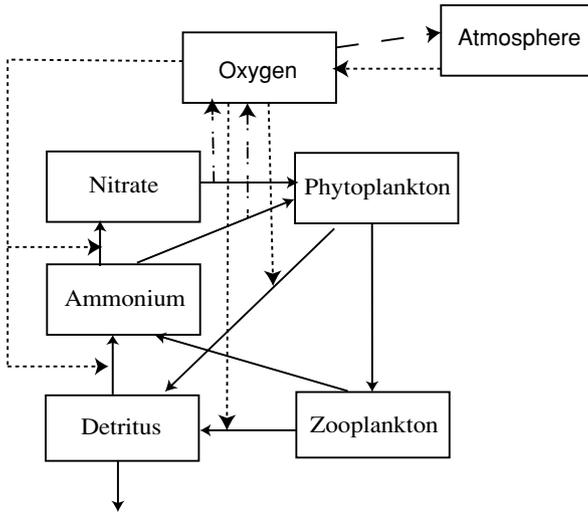
Fig. 2. Ecosystem model including oxygen. The solid lines represent the five-component nitrogen-based ecosystem model. The dotted and dashed lines represent the source and sink pathways for oxygen.

finite element unstructured grid circulation model SELFE (http://www.ccalmr.ogi.edu/CORIE/modeling/selfe/). 2000 particles are released with random horizontal and vertical position within Baker Bay where the *M. rubra* preys have been observed. They are vertically mixed using a random walk based on the vertical mixing coefficient obtained from SELFE.

<center>RESULTS—DISCUSSION</center>

Phosphorus cycle

Modeled dissolved organic phosphorus (DOP) and nitrogen (DON) in the surface water at 45°N (Fig. 3) agree well with *in situ* measurements during COAST May 2001 cruise only when DOP is taken up by phytoplankton. Observed DON/DOP ratio ($\mu M/\mu M$) varies between 20.7 and 87.5 with a mean of 45.24. Modeled DON/DOP ratio ranges between 37.3 and 66.7 when DOP is taken up and between 21.6 and 37.7 when DOP is not taken up.

We found that DOP uptake can support over 40% of primary production during relaxation/downwelling events while this percentage is relatively low during sustained upwelling. By comparison, Mather *et al*. (2008) show that the DOP pool can support 20% (range of 12–30%) of production in the NASG (North Atlantic Subtropical Gyre), while Lomas *et al*. (2010) show that DOP can support up to 60% of production at the Bermuda Atlantic Time Series station. In regions of the Oregon coast with a wider shelf (e.g., Cape Perpetua), DOP uptake accounts for a larger percentage of primary production. This is consistent with the
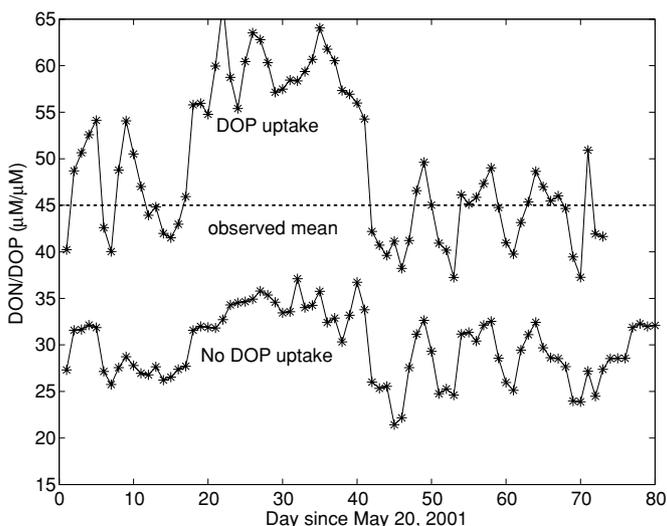
Fig. 3. Modeled DON/DOP ratio with and without DOP uptake at 45°N in the surface water 15 miles offshore at 45°N. The dotted line represents the mean DON/DOP ratio from observations during the May 2001 COAST cruise.

positive correlation observed between field alkaline phosphatase activity and DIP data for the Cape Perpetua region (Ruttenberg and Dyhrman, 2005), which lends confidence that our model indeed is representative of natural processes.

Hypoxic events

The modeled hypoxic conditions (dissolved oxygen less than 1.4 ml/l) on the Oregon shelf (Fig. 4) display significant differences in timing and extend between 2002 and 2006. In 2002, because of offshore low oxygen conditions at the start of the upwelling blooms in late April (not shown), the first hypoxic events on the shelf appear early in the upwelling season, i.e., late May. In contrast, in 2006 offshore oxygen levels were close to climatological values and much higher than in 2002. Consequently, hypoxic conditions were delayed by about a month compared to 2002.

The region with the most days of hypoxic condition extends farther south in 2002 than in 2006. By the end of the upwelling season, very low oxygen levels extended to more than 50% of the Oregon shelf. Preliminary results indicate that several regions on the shelf were under severe hypoxic even anoxic conditions in 2006 but not in 2002. Very low oxygen levels were found higher in the water column in 2006 than in 2002. In addition, it appears that the region north of 47°N (boundary condition for our model) plays a larger role in leading to hypoxia on the Oregon shelf in 2006 than in 2002. The effect of the offshore and the Washington shelf oxygen level on hypoxia along the Oregon coast is currently
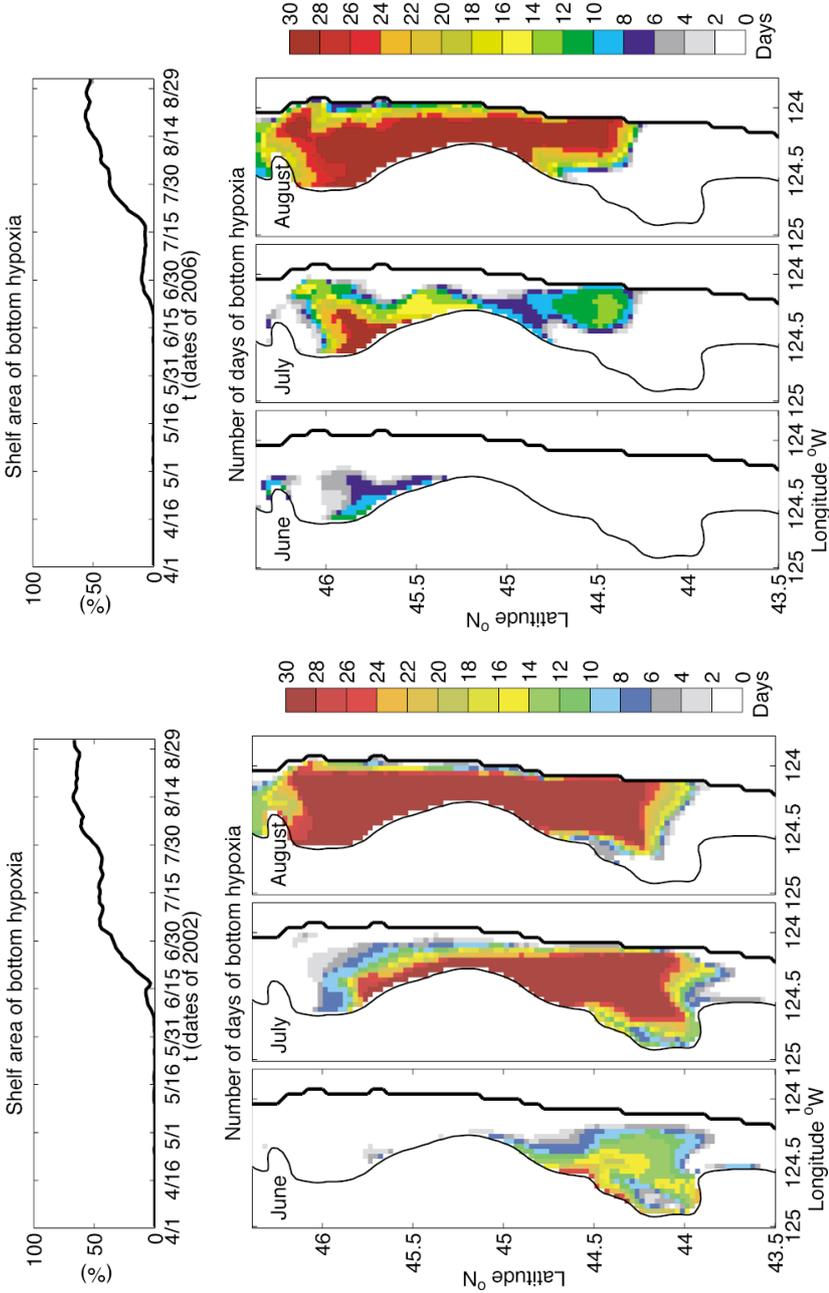
Fig. 4. Percentage of the shelf area and number of days in June, July and August with bottom oxygen less than 1.4 ml/l. The left panels represent the conditions in 2002 and the right panels are for 2006.
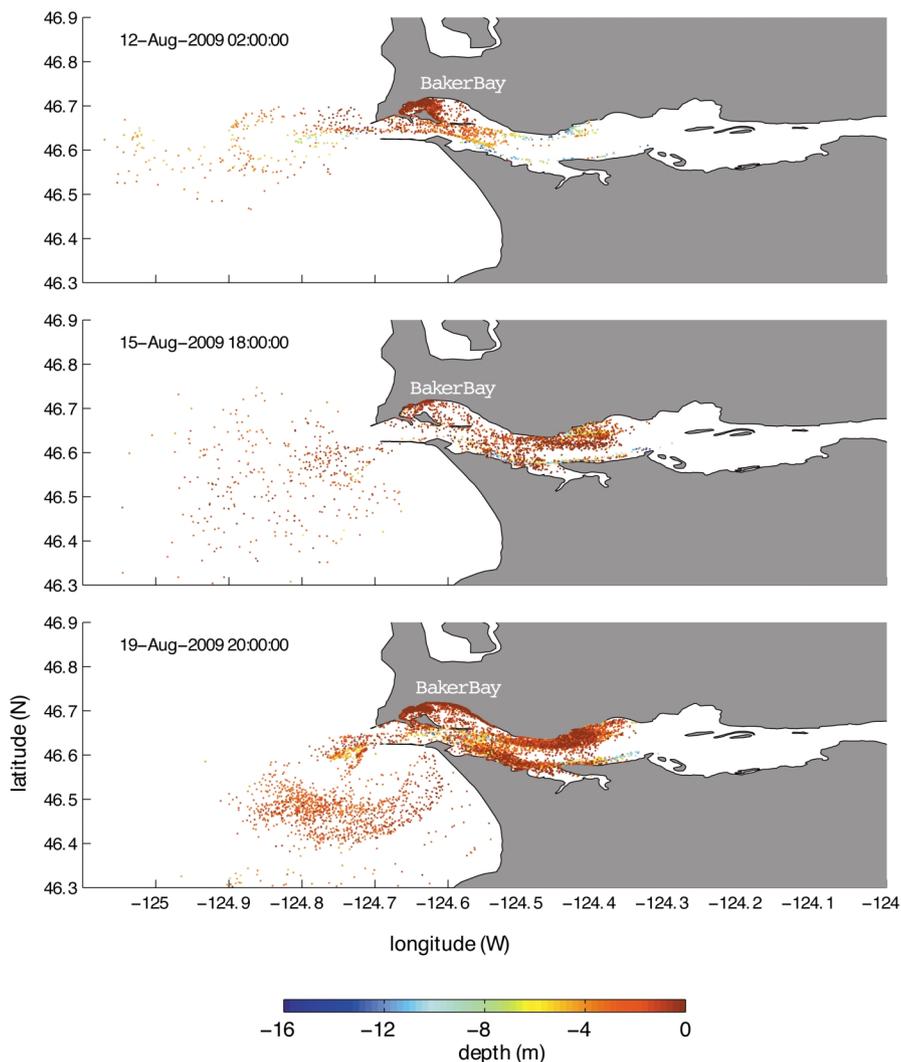
Fig. 5. *Myrionecta rubra* distribution at three times following a release at 1800 hrs on August 9th, 2009. The tidal circulation in the estuary is at slack water following flood tide. This 7 day period corresponds to a neap tidal period. The color of the particles indicates their location in water column.

under investigation. Careful comparisons between modeled and measured oxygen from glider deployment for different years are presently being analyzed.

Myrionecta rubra

Several experiments were performed by giving four different behaviors to

the particles: 1) passive particles with no swimming nor biological division, 2) particles with vertical swimming (jumping) behavior, 3) particles with biological division and mortality and 4) particles with vertical swimming behavior (jumps of 1 mm s^{-1}) avoiding westward currents larger than 0.5 m s^{-1} and with one doubling per day and 0.1 d^{-1} mortality. The last scenario seems to be the most satisfactory (Fig. 5). It allows for retention of a large number of particles in the estuary and formation of *M. rubra* blooms similar in magnitude and location in the estuary, as well as in the water column, as the ones that have been observed over the last decade (Herfort *et al.*, 2010). In that scenario, *M. rubra* cell numbers increase during spring tides and the population is retained in the estuary during neap tides. The center of mass of the distribution shifts from east to west from spring to neap tide periods.

While there is a wealth of literature related to *M. rubra* in estuaries, lagoons and coastal regions around the world, it appears that the factors that control their vertical migration and allow persistent retention remain somewhat unclear. Much of this uncertainty is related to an ongoing debate as to whether light, turbulence or both induce *M. rubra* vertical motions and jumps. Another common uncertainty is related to their ingestion and photosynthetic rates. Additional scenarios with various cell division rates and jumping speeds are under investigation. However, in order for the current model to better represent the observed blooms, field campaigns in the Columbia River estuary during late summer and early fall will need to determine vertical distribution of *M. rubra* during several tidal and day-night cycles, which could lead to better understanding of the factors influencing their movements in the water column. In addition, while it will be a difficult task, laboratory experiments will need to be performed in order to prescribe accurate cell division rates.

<center>CONCLUSION</center>

This manuscript only reflects a small sample of the observational and modeling studies that have been and are currently undertaken to understand the biogeochemistry, ecology and physics of the Oregon coast. These activities will most likely continue for the next decades as a coastal observatory along the Newport Line (44°39′ N, 125°W to coast) and the Grays Harbor Line (47°0′ N, 125°W to coast) is being deployed as part of the as Ocean Observatories Initiative (OOI) (http://www.oceanobservatories.org/) sponsored by the National Science Foundation.

REFERENCES

Chan, F., J. A. Barth, J. Lubchenco, A. Kirincich, H. Weeks, W. T. Peterson and B. A. Menge (2008): Emergence of anoxia in the California Current Large Marine Ecosystem. *Science*, **319**, 920.

Dyhrman, S. T. and K. C. Ruttenberg (2006): Presence and regulation of alkaline phosphatase activity in eukaryotic phytoplankton from the coastal ocean: implications for dissolved organic phosphorus remineralization. *Limnol. Oceanogr.*, **51**, 1381–1390.

Grantham, B. A., F. Chan, K. J. Nielsen, D. S. Fox, J. A. Barth, A. Huyer, J. Lubchenco and B. A. Menge (2004): Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific. *Nature*, **429**, 749–754.

Herfort, L, T. D. Peterson, L. A. McCue, B. C. Crump, F. G. Prahl, A. M. Baptista, V. Campbell, R. Warnick, M. Selby, G. Roegner and P. Zuber (2010): *Myrionecta rubra* population genetic diversity and its cryptophyte chloroplast specificity in recurrent red tides in the Columbia River estuary. *Aquat. Microb. Ecol.*, doi:10.3354/ame01460.

Koch, A. O., A. L. Kurapov and J. S. Allen (2010): Modeling analysis of a separated jet in the Coastal Transition Zone off Oregon. *J. Geophys. Res.*, **115**, C08020, doi:10.1029/2009JC005704.

Lomas, M. W., A. L. Burke, D. A. Lomas, D. W. Bell, C. Shen, S. T. Dyhrman and J. W. Ammerman (2010): Sargasso Sea phosphorus biogeochemistry: an important role for dissolved organic phosphorus (DOP). *Biogeosciences*, **7**, 695–710.

Mather, R. L., S. E. Reynolds, G. A. Wolff, R. G. Williams, S. Torres-Valdes, E. M. S. Woodward, A. Landolfi, X. Pan, R. Sanders and E. P. Achterberg (2008): Phosphorus cycling in the North and South Atlantic Ocean subtropical gyres. *Nat. Geosci.*, **1**, 439–443.

Riisgård, H. U. and P. S. Larsen (2009): Ciliary-propelling mechanism, effect of temperature and viscosity on swimming speed, and adaptive significance of the 'jumping' ciliate *Mesodinium rubrum*. *Mar. Biol. Res.*, **5**, 585–595.

Ruttenberg, K. C. and S. T. Dyhrman (2005): Temporal and spatial variability of dissolved organic and inorganic phosphorus, and metrics of phosphorus bioavailability in an upwelling-dominated coastal system. *JGR-Oceans*, **110**, C10S13, doi:10.1029/2004JC002837.

Spitz, Y. H., J. S. Allen and J. Gan (2005): Modeling of ecosystem processes on the Oregon shelf during the 2001 summer upwelling. *J. Geophys. Res.*, **110**, C10S17, doi:10.1029/2005JC002870.

Wanninkhof, R. (1992): Relationship between wind speed and gas exchange over the ocean. *J. Geophys. Res.*, **97**, 7373–7382.

Y. H. Spitz (e-mail: yvette@coas.oregonstate.edu)