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Distributions and Variability of Particulate Organic Matter in a Coastal Upwelling System

Lee Karp-Boss
University of Maine - Main, lee.karp-boss@maine.edu

P. A. Wheeler

B. Hales

P. Covert

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L. Karp-Boss
School of Marine Sciences, University of Maine, Orono, Maine, USA

P. A. Wheeler, B. Hales, and P. Covert
College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA

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[1] In this study we examined the spatial and temporal variability of particulate organic material (POM) off Oregon during the upwelling season. High-resolution vertical profiling of beam attenuation was conducted along two cross-shelf transects. One transect was located in a region where the shelf is relatively uniform and narrow (off Cascade Head (CH)); the second transect was located in a region where the shelf is shallow and wide (off Cape Perpetua (CP)). In addition, water samples were collected for direct analysis of chlorophyll, particulate organic carbon (POC), and particulate organic nitrogen (PON). Beam attenuation was highly correlated with POC and PON. Striking differences in distribution patterns and characteristics of POM were observed between CH and CP. Off CH, elevated concentrations of chlorophyll and POC were restricted to the inner shelf and were highly variable in time. The magnitude of the observed short-term temporal variability was of the same order as that of the seasonal variability reported in previous studies. Elevated concentrations of nondegraded chlorophyll and POM were observed near the bottom. Downwelling and rapid sinking are two mechanisms by which phytoplankton cells can be delivered to the bottom before being degraded. POM may be then transported across the shelf via the benthic nepheloid layer. Along the CP transect, concentrations of POM were generally higher than they were along the CH transect and extended farther across the shelf. Characteristics of surface POM, namely, C:N ratios and carbon:chlorophyll ratios, differed between the two sites. These differences can be attributed to differences in shelf circulation. *INDEX TERMS:* 4279 Oceanography: General: Upwelling and convergences; 4219 Oceanography: General: Continental shelf processes; 4805 Oceanography: Biological and Chemical: Biogeochemical cycles (1615); *KEYWORDS:* POM, upwelling, beam attenuation

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1. Introduction

[2] It is widely accepted that coastal upwelling systems contribute significantly to global ocean primary production, but their quantitative role in the global carbon cycle and as source regions of organic material to the adjacent open ocean is not well understood. Coastal upwelling is associated with rapid production and accumulation of organic material. A significant fraction of this organic material is in the particulate form [*Duval et al.*, 1997; *Hill and Wheeler*, 2002; *Wetz and Wheeler*, 2003]. It has long been recognized that variations in the distributions and characteristics of the particulate organic pool have pronounced effects on the fluxes of carbon, nutrients, and other elements. Particulate organic material (POM) is readily available for consumption by higher trophic levels and can be quickly removed from the euphotic zone via sinking. In spite of extensive studies on chemical and biological responses to coastal upwelling, there is a surprising lack of information on POM in such systems. Basic questions such as, how is POM distributed across the shelf, what are the processes affecting POM distributions, and what is the variability associated with POM distributions, have not been adequately answered. Such information is an essential prerequisite for better understanding the role of coastal upwelling systems in the cycling and export of organic carbon.

[3] Our current knowledge of the dynamics of POM, in response to coastal upwelling, is based on a limited number of studies in which broad spatial surveys and/or coarse temporal measurements (i.e., seasonal studies) have been conducted. The response of coastal waters to wind stress, however, is on temporal scales of a few days and spatial scales on the order of tens of kilometers [*Smith*, 1995]. Distributions of biogeochemical parameters in coastal water are strongly affected by horizontal and vertical transport processes and can vary greatly on timescales of a few weeks

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[*Gardner et al.*, 2001] to less than a day [*Barange et al.*, 1991]. Given the inherent variability of upwelling systems, high-resolution temporal and spatial measurements are required to better understand distribution patterns of POM and the mechanisms responsible for it.

[4] Direct chemical measurements of POM that are based on analysis of discrete water samples provide useful information on the characteristics of the organic material, but they are limited in their spatial and temporal coverage. In recent years several studies have demonstrated that optical properties such as beam attenuation and scattering can be used as bulk descriptors of suspended particles and particulate organic carbon (POC) in the open ocean [*Gardner et al.*, 1993; *Gundersen et al.*, 1998; *Bishop*, 1999; *Bishop et al.*, 1999; *Gardner et al.*, 2000; *Balch et al.*, 2001] and in coastal waters [*Gardner et al.*, 2001]. The use of in situ optical profilers can therefore dramatically enhance the spatial and temporal resolution at which biogeochemical fields can be measured. Single-wavelength optical measurements, however, respond to the bulk of the particulate material, and the relationship between beam attenuation or scattering and particle concentrations can vary from one environment to another, depending on the size, composition, and surface properties of the particles [*Zaneveld*, 1973]. Here we show that beam attenuation is highly correlated with POC and particulate organic nitrogen (PON) in a coastal upwelling system. We use this relationship to study spatial and temporal distributions of POC over the Oregon shelf during the upwelling season.

[5] Upwelling off Oregon is a seasonal phenomenon. Southward upwelling favorable winds prevail from April through September [*Smith*, 1974]. Periods of upwelling typically last 3–7 days, followed by a period of relaxation during which the wind direction is often reversed. Major hydrodynamics features of the Oregon upwelling region have been studied extensively and are described by *Halpern* [1976], *Huyer* [1983], and *Smith* [1995], among others. In general, during periods of upwelling favorable winds, the surface Ekman layer (roughly 20 m deep) is being transported offshore, and subsurface water upwells near the coast. The rise of isopycnals to the surface results in a formation of a front that marks the boundary between the recently upwelled cold, nutrient-rich water inshore and warmer, nutrient-poor oceanic surface water. The front typically forms near the shore and then moves offshore as wind forcing continues. Strong gradients in biological and optical properties are often associated with the front [*Zaneveld and Pak*, 1979; *Small and Menzies*, 1981]. During relaxation, when wind ceases or changes direction, the front retreats shoreward. The main features of the alongshore velocity field include an equatorward current (jet) at the surface and a slower poleward undercurrent along the bottom. Alongshore velocities are typically an order of magnitude larger than cross-shelf velocities.

[6] Organic particles in the coastal water of Oregon originate from two main sources: rivers, with the Columbia River as a major source, and in situ production. In situ production of particulate organic carbon and nitrogen is particularly significant during the upwelling season [*Hill and Wheeler*, 2002]. Information on distribution patterns and the characteristics of these particles is limited. *Small et al.* [1989] reported seasonal changes in distribution patterns of beam attenuation, total suspended particulate material (i.e., organic and inorganic particles), POC, and PON in response to seasonal changes in prevailing winds. A three-layered vertical structure of suspended particles was observed during spring and summer, with elevated concentrations of particles at the surface and near the bottom (the benthic nepheloid layer (BNL)). As the surface mixed layer became deeper during winter, more uniform distributions of particles were observed. As *Small et al.* [1989] pointed out, it is difficult to assess seasonal and interannual patterns in a highly patchy environment that is sampled sporadically, since large short-term variability can mask seasonal or interannual variability.

[7] The study by *Small et al.* [1989] focused on only one cross-shelf transect over the central Oregon shelf. Spatial variability, however, adds another dimension to the complexity of studying POM distribution patterns off Oregon. Variations in shelf topography largely affect coastal circulation and hence the distribution of chemical, biological, and optical properties. In northern Oregon the shelf is relatively uniform and narrow (~30 km wide). Shelf sediments, from the shore to the 120 m isobaths, are composed of sand [*Kulm*, 1977]. The shelf becomes wider off central Oregon, and its uniformity is broken by Heceta Bank (~60 km wide). Mesoscale distributions of POM in surface water off Oregon have been studied only recently, as part of the northeast Pacific Global Ocean Ecosystem Dynamics (GLOBEC) program [*Hill and Wheeler*, 2002]. Substantial alongshore and cross-shore variations in surface distributions of phytoplankton biomass and POM were observed, suggesting strong effects of shelf topography on POM distributions and cross-shelf transport [*Hill and Wheeler*, 2002].

[8] Here we show that short-term temporal variability in distributions of POM can be significant and should be taken into account in the design of long-term monitoring programs in the interpretation of seasonal and interannual patterns and in estimations of carbon fluxes from the shelf. We also show that despite the high temporal variability the three-layered vertical structure of POM observed by *Small et al.* [1989] is a persistent feature over the shelf, suggesting that the BNL may be an important route for the transport and transformation of organic material. Finally, we show that differences in shelf width can lead to different distribution patterns and characteristics of particles.

2. Methods

[9] Data presented here were collected as a component of the Coastal Ocean Advances in Shelf Transport (COAST) study. Information on the objectives, research components, and participants of COAST can be found at http://damp.oce.orst.edu/coast/. During May–June 2001 we conducted intense measurements of cross-shelf distributions of hydrographic, optical, and biogeochemical properties aboard R/V *Thomas G. Thompson*. In this paper we focus on data collected along two cross-shelf transects. The first is located off Cascade Head (hereafter CH) (Figure 1) where the shelf is relatively uniform and narrow. The second transect is centered on Heceta Bank (off Cape Perpetua, hereafter CP) (Figure 1), a shallow bank rising to within 50 m of the sea

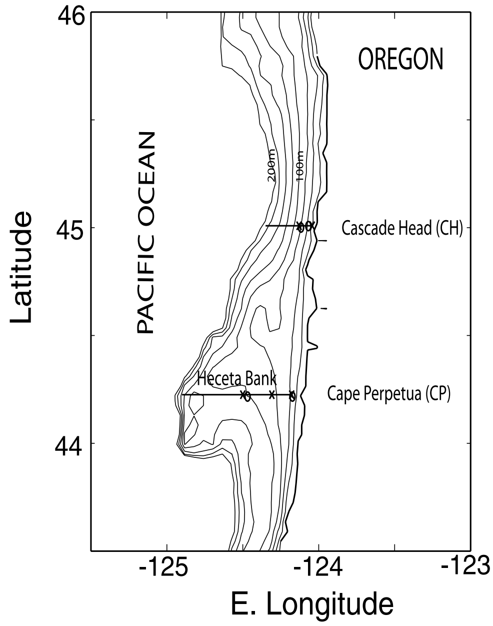

Figure 1. A map of the study area. Stations along Cascade Head (CH) and Cape Perpetua (CP) transects are marked with crosses. Mooring locations are marked with circles. Bottom contours are plotted every 25 m.

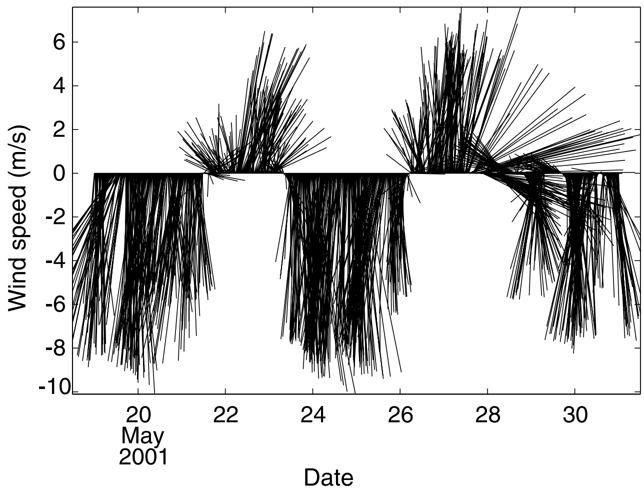

Figure 2. Wind speed (m s^{-1}) for the period of the study. Data were collected by the Oregon State University (OSU) mooring group (M. Levine, T. Boyd, and M. Kosro, (available at http://damp.coas.oregonstate.edu/coast/moorings.shtml)). Negative values indicate southward wind; positive values indicate northward wind.

surface and extending ~60 km off shore. To examine the short-term temporal variability in the distributions of optical and biochemical parameters, measurements along the CH transect were repeated daily during the week of 22–27 May 2001.

[10] Wind and current data were obtained from moorings located at the inner shelf and midshelf of the two transects (Figure 1). The data were provided by T. Boyd, M. Levine, and M. Kosro (Oregon State University (OSU), available at http://damp.coas.oregonstate.edu/coast/moorings.shtml).

[11] Hydrographic and optical properties were measured along the CH and CP transects using a pumped profiling system. Briefly, the system consisted of a towed vehicle whose depth in the water column was precisely controlled automatically and remotely by a computer-operated winch. The tow cable was paid out and recovered based on the vehicle's depth relative to a predetermined depth versus time target curve. The vehicle carried a SeaBird 9/11+ conductivity-temperature-depth system (www.seabird.com) and a suite of in situ sensors including temperature and conductivity (SeaBird), photosynthetically active radiation (PAR) (Biospherical QSP200L, www.biospherical.com), and beam attenuation (WET Labs C-star, 660 nm, 25-cm path length) sensors. The vehicle also carried a high-pressure positive-displacement pump. The pump delivered seawater samples back to the ship at a continuous rate of 8 L min^{-1}, for high-speed chemical analyses, following the design of *Hales and Takahashi* [2002]. These measurements were made at the same time as high-resolution measurements of turbulence were conducted (J. N. Moum et al., Ocean Mixing Group, OSU).

[12] Beam attenuation coefficients (c) were calculated from the continuous light transmission measurements, according to manufacturer (WET Labs), using the conversion $c = -(1/r)\ln(\mathrm{Tr})$, where r is the path length (25 cm) and Tr is the transmittance (i.e., the ratio of the signal output to the reference output). We used manufacturer reference values and conducted calibrations during the cruise (dark and deionized water) to assure that the instrument's readings

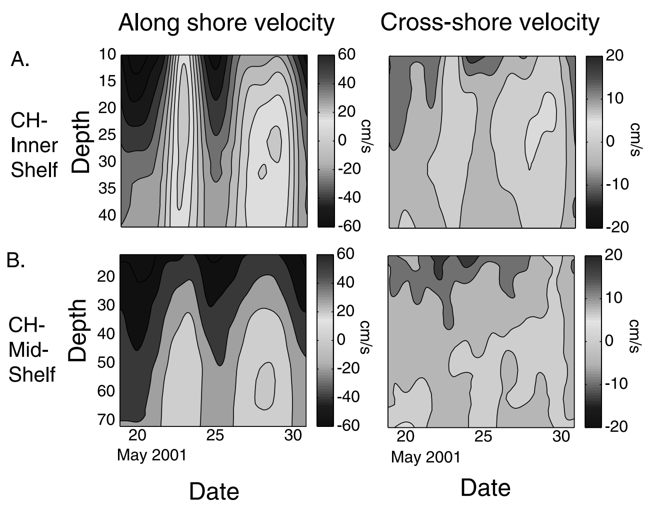

Figure 3. Alongshore and across-shore currents off CH. Data were collected by the OSU mooring group (M. Levine, T. Boyd and M. Kosro (available at http://damp.coas.oregonstate.edu/coast/moorings.shtml)) from two acoustic Doppler current profiler (ADCP) moorings located at the (a) inner (45°0.04′N, 124°4.102′W) and (b) middle (45°0.011′N, 124°6.995′W) shelf off CH. Velocity data were sampled every 120 s in 2-m bins over the water column depth. Negative alongshore velocities indicate southward flow; positive alongshore velocities indicate northward flow. Negative cross-shore velocities indicate an offshore flow; positive cross-shore velocities indicate an onshore flow. See color version of this figure at back of this issue.

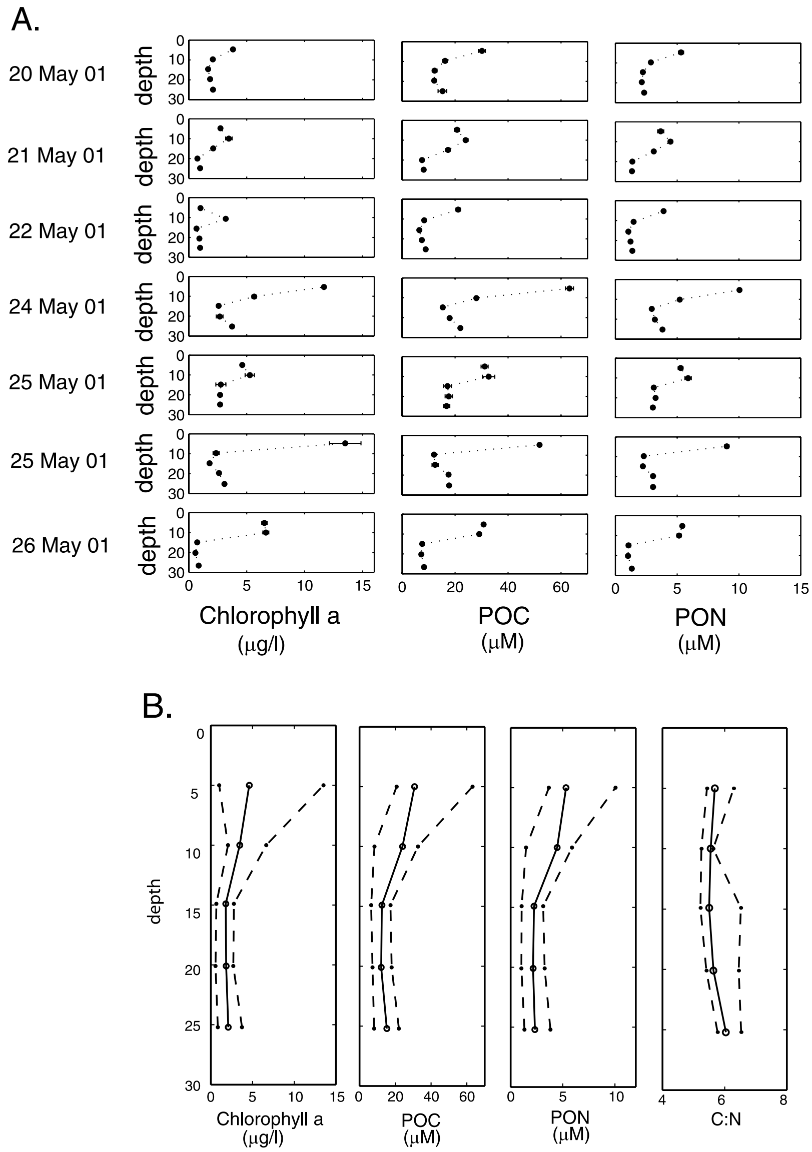

Figure 4. (a) Vertical distributions of chlorophyll, POC, and PON at station CH1 (inshore station). Values are the mean plus/minus standard deviation of triplicate samples. (Note that standard deviations are calculated and plotted for all data points. In several cases the dot representing the value is larger than the standard deviation.) (b) Median values (solid lines) for 20–26 May 2001 for the vertical distributions of chlorophyll, POC, PON, and C:N ratios. Dashed lines indicate the maximal and minimal values measured for each of these parameters.

remained stable during the cruise. The instrument's windows were cleaned daily.

[13] Discrete water samples for chemical analysis of chlorophyll, POC, and PON were collected from fixed stations at inshore and midshelf locations along each of the transects (Figure 1). The pump was maintained at fixed depths while water was pumped into the laboratory aboard the ship and collected in acid-washed 20-L carboys. Each carboy was gently mixed, and triplicate samples were drawn for the analysis of chlorophyll *a*, POC, and PON. Note that our use of the pump to deliver seawater to the laboratory should not be confused with in situ large-volume filtration systems that have been developed as an alternative approach for POC measurements (see review by *Gardner et al.* [2003]). Depth of water samples was confirmed by comparing shipboard salinity measurements of the water at the end of the sampling stream to in situ salinity measurements.

[14] For chlorophyll analysis, triplicate 125-mL samples were filtered onto 25 mm GF/F filters. The filters were stored in glass vacutainers and kept frozen (−30°C), in the dark, until further processing on shore. Chlorophyll was extracted in 95% MeOH, in a dark freezer, for 24 hours. Chlorophyll concentrations were determined fluorometrically with a 10-AU Turner fluorometer. The fluorometer was calibrated with purified chlorophyll at least annually, and a solid secondary standard was used for daily runs.

[15] Samples for POC and PON analysis were prefiltered through a 200-μm mesh to remove large grazers. Triplicate 500- to 1000-mL samples were filtered onto precombusted GF/F filters. Filters were stored in precombusted glass

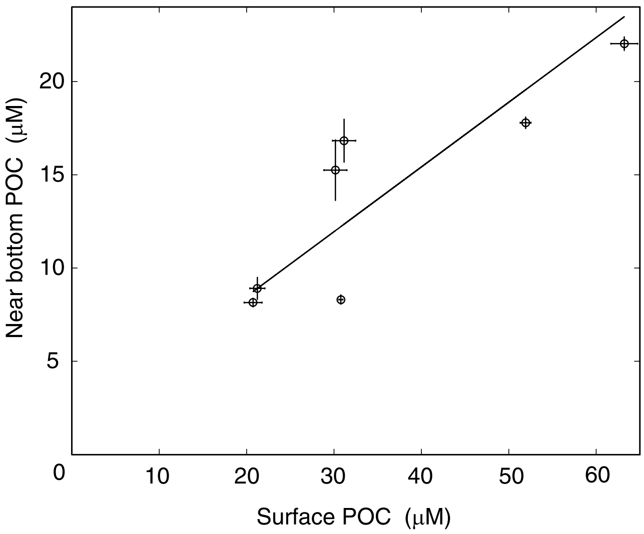

Figure 5. Near-bottom POC versus surface POC for station CH1. Values are the mean plus/minus standard deviation of triplicate samples. Regression line (level II, linear regression, least squares bisector) shows $[POC_{bottom}] = 0.35[POC_{surface}] + 1.54$; $r^2 = 0.86$; $n = 7$. Symmetrical uncertainty limits for the slope and intercept are 0.08 and 3.16, respectively.

vacutainers and kept frozen (−30°C) until further analysis. Prior to analysis, filters were fumed with hydrochloric acid to remove inorganic carbon. Dried filter samples were then sent to the analytical lab at University of California, Santa Barbara (http://www.msi.ucsb.edu/Analab/), where POC and PON were measured with a CEC 440XA Elemental Analyzer (Exeter Analytical, Inc.). Acetanilide was used as a standard. To obtain final carbon and nitrogen concentrations, we subtracted the average carbon and nitrogen values of filter blanks from each of the samples. For all the stations considered in this manuscript, carbon and nitrogen values of samples were at least 2.5 times larger than blank values.

[16] Regression analysis was used to examine the relationships between chemical (POC and PON) and optical (beam attenuation) measurements. Since both types of measurements are subjected to errors, we used model II linear regression (i.e., slope of line is determined by regressing Y on X and X on Y). There are several approaches for the model II linear regression; none appear to be without a bias [*Laws*, 1997]. Here we used the least squares bisector approach [*Sprent and Dolby*, 1980]; the slope of line is determined by bisecting the minor angle between the two regressions. We compared our results to the geometric mean approach, and no significant differences were found between the two methods.

3. Results

3.1. Northern Shelf of Oregon (CH): Distributions of Chlorophyll, POC, PON, and Beam Attenuation

[17] Repeated measurements of vertical distributions of chlorophyll, POC, and PON at the inner (CH1) and midshelf (CH3) stations off CH were conducted for 8 days (20–27 May). During this period, winds shifted from upwelling favorable (southward winds) to downwelling favorable (northward winds) and back to upwelling favorable (Figure 2). Alongshore surface currents were often an order of magnitude higher than cross-shelf velocities over both the inner and middle shelf (Figure 3). Changes in velocity fields, in response to changes in wind direction, were more rapid over the inner shelf compared to the midshelf (Figure 3). While alongshore surface currents (at 10 m) over the inner shelf changed direction between periods of upwelling favorable winds and relaxation, surface currents over the midshelf remained southward during 20–27 May.

[18] A time series of vertical distributions of chlorophyll, POC, and PON at the inshore station (CH1, 2.5 km off shore) are shown in Figure 4a. Concentrations of chlorophyll, POC, and PON varied considerably with time. Short-term temporal variability in chlorophyll and POM was most pronounced in the upper 10 m (Figure 4b), where changes in chlorophyll concentrations span an order of magnitude, ranging from 1.01 ± 0.01 μg L^{-1} to 13.5 ± 1.36 μg L^{-1} (Figure 4). POC concentrations near the surface showed a threefold range from 20.75 ± 1.02 μ*M* C to 63.22 ± 1.53 μ*M* C (Figure 4). Significant concentrations of chlorophyll and POC were measured near the bottom (0.84 ± 0.06 to 3.74 ± 0.14 μg chlorophyll L^{-1} and 8.15 ± 0.25 to 22.03 ± 0.38 μ*M* C), often exceeding those at middepth (Figure 4a). POC concentrations near the surface and near the bottom are well correlated (Figure 5). Vertical distributions of PON showed a similar pattern to that described for POC. Near-surface concentrations of PON ranged from 3.67 ± 0.25 to 10.05 ± 0.1 μ*M* N. PON concentrations near the bottom ranged from 1.3 ± 0.1 μ*M* N to 3.82 ± 0.04 μ*M* N. Carbon to nitrogen ratios were generally below the Redfield ratio of 6.7 (Figure 4b). On average, we did not observe a significant increase in the C:N ratio with increasing depth.

[19] The midshelf station (CH3, 9.3 km off shore) was visited three times during this study. Concentrations of chlorophyll, POC, and PON were significantly lower than those observed at the inshore station (Figure 6). Maximal concentrations of chlorophyll (1.68 ± 0.68 μg L^{-1}), POC (16.80 μ*M* C), and PON (3.04 ± 0.19 μ*M*, data not shown) were observed at a depth of 10 m. Concentrations of POC were slightly elevated near the bottom, compared to mid-depth concentrations (Figure 6). On average, C:N ratios of surface POM and near-bottom POM were lower than the Redfield ratio (Figure 6b) and increased between 60 and 80 m (Figure 6b). At both stations, POC was highly correlated with chlorophyll, even for samples collected near the bottom (Figure 7).

[20] Beam attenuation coefficients, measured at the same fixed depths from which samples were taken for chemical analysis of POM (at stations CH1 and CH3), are linearly correlated with POC and PON concentrations (Figure 8). Thus we use beam attenuation to infer POC distributions. High-resolution, cross-shelf measurements of beam attenuation were repeated for 7 days (Figure 9). On average, during this period, high surface concentrations of POC were limited to a narrow band near the shore. Over the middle and outer shelf, relatively elevated concentrations of particles are found below the surface (20–30 m). The presence of a benthic nepheloid layer across the shelf (i.e., a layer of relatively elevated concentrations of particles near the bottom) is also evident. This time series of cross-shelf beam attenuation measurements shows high variability over a

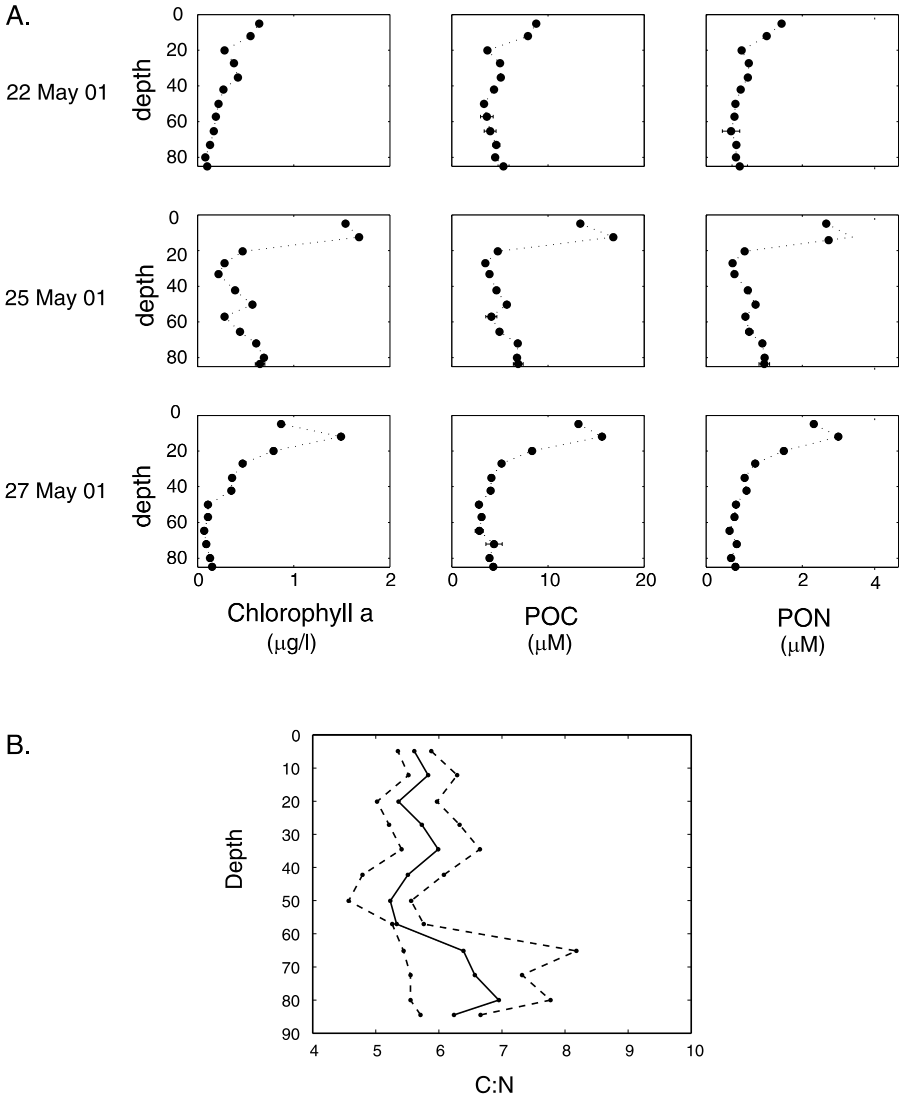

Figure 6. (a) Vertical distributions of chlorophyll, POC, and PON at station CH3. Values are the mean plus/minus standard deviation of triplicate samples. (Note standard deviations are calculated and plotted for all data points. In several cases the dot representing the value is larger than the standard deviation.) (b) Mean values of C:N ratios for 22–27 May 2001 (solid line). Dashed lines indicate the maximal and minimal values measured.

short period of time. The variability is most pronounced at the inner shelf, where the magnitude of the variability in the concentrations of surface chlorophyll and POC and in beam attenuation coefficients is of the same order as the signal itself (Figures 4b and 9).

3.2. Central Shelf of Oregon (CP): Distributions of Chlorophyll, POC, PON, and Beam Attenuation

[21] One cross-shelf transect was conducted off CP, beginning on 28 May and ending on 30 May. During this time, winds had transitioned from downwelling favorable to upwelling favorable (Figure 2). Alongshore currents were predominantly southward or weakly northward, over the inner shelf and were southward at the surface over the midshelf (Figure 10). In general, velocities of alongshore surface currents along the CP transect are smaller compared to currents along the CH transect. Vertical distributions of chlorophyll, POC, PON, and C:N ratios at three stations across the bank (5.1 km at CP1, 15.4 km at CP3, and 30.4 km at CP4 off shore) are shown in Figure 11. High surface concentrations of chlorophyll were observed at all three stations, with the highest concentrations observed at CP3 (9.52 ± 0.85 μg L^{-1}). Concentrations of POC at the surface were typically higher than those measured off CH, ranging from 66.11 ± 5.4 μ*M* POC at CP4 to 96.90 ± 4.04 μ*M* POC at CP3. Surface concentrations of PON over midshelf were also higher compared to those measured over the midshelf off CH, ranging from 7.51 ± 0.14 μ*M* POC at CP4 to 12.19 ± 0.42 μ*M* POC at CP3. Concentrations of chlorophyll, POC, and PON near the bottom were slightly elevated compared to middepth at all three stations. POC and chlorophyll over the bank are highly correlated, but the carbon to chlorophyll ratio is higher

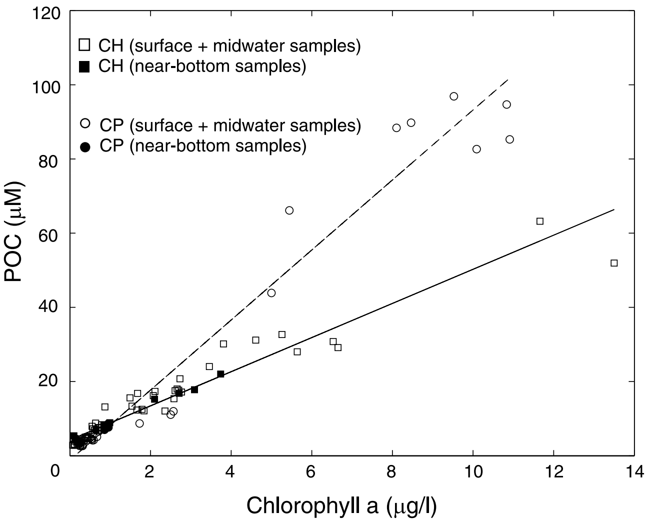

Figure 7. POC versus chlorophyll for samples collected off CH (CH1 plus CH3, open squares are samples from surface and midwater depths; solid squares are samples collected 5 m above the bottom) and off CP (CP1 plus CP3 plus CP4, open circles are samples from surface and midwater depths; solid circles are samples collected 5 m above the bottom). Regression line for CH (solid line, level II, linear regression, least squares bisector) shows [POC] (μ*M*) = 4.60[Chl] (μg L^{-1}) + 4.24; n = 59; r^2 = 0.95. Symmetrical uncertainty limits for the slope and intercept are 0.17 and 0.52, respectively. Regression line for CP (dashed line, level II, linear regression, least squares bisector) shows [POC] (μ*M*) = 9.44[Chl] (μg L^{-1}) −1.18; n = 29; r^2 = 0.98. Symmetrical uncertainty limits for the slope and intercept are 0.36 and 1.69, respectively.

over the bank compared to the northern site (Figure 7). At all three stations, significantly higher C:N ratios were measured in POM from surface samples compared to samples taken from deeper depths (Figure 11) and compared to samples from the CH transect (Figure 4b).

[22] Beam attenuation coefficients along the CP transect are also highly correlated with POC and PON (Figure 8), suggesting that the observed particles are largely of organic origin. High-resolution measurements of beam attenuation coefficients show a surface layer (∼10−15 m thick) of elevated concentrations of particles that extends over the bank (Figure 12). Overall, concentrations of particles over the bank are higher compared to concentrations of particles over the northern shelf. A region of relatively elevated concentrations of particles near the bottom is restricted to the midshelf (Figure 12).

4. Discussion

[23] During the upwelling season the Oregon shelf is a region of significant production and accumulation of POM. Surface concentrations of POC and PON measured during the period of this study often exceeded concentrations reported for other shelf regions [*Hill and Wheeler*, 2002, and references therein]. Distributions of POM, however, are highly variable in space and time. Overall, POC was well correlated with chlorophyll, suggesting

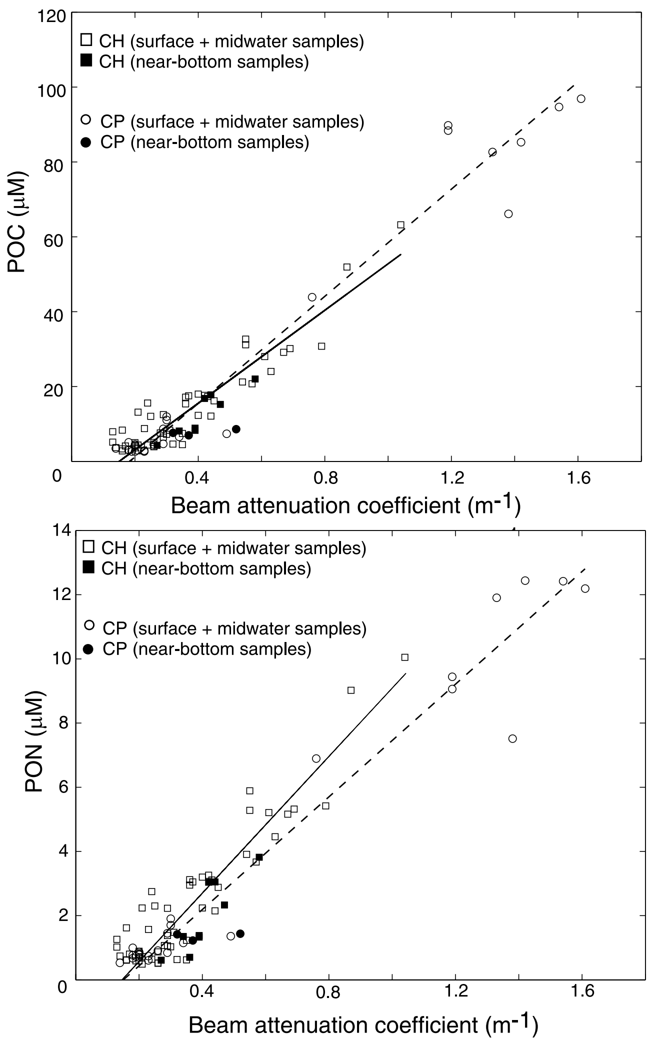

Figure 8. (a) POC (μ*M*) versus beam attenuation coefficient (m^{-1}) for samples collected off CH (CH1 plus CH3, open squares are samples from surface and midwater depths; closed squares are samples collected 5 m above the bottom) and off CP (CP1 plus CP3 plus CP4, open circles are samples from surface and midwater depths; closed circles are samples collected 5 m above the bottom). Regression line for CH (solid line, level II, linear regression, least squares bisector): [POC] (μ*M*) = 62.1[beam c] (m^{-1}) −9.3; n = 59; r^2 = 0.92. Symmetrical uncertainty limits for the slope and intercept are 3.3 and 1.4, respectively. Regression line for CP (dashed line, level II, linear regression) shows [POC] (μ*M*) = 71.5[beam c] (m^{-1}) − 13.1; n = 29; r^2 = 0.98. Symmetrical uncertainty limits for the slope and intercept are 3.0 and 2.2, respectively. (b) PON (μ*M*) versus beam attenuation coefficient (m^{-1}). Regression line for CH (solid line, level II, linear regression) shows [PON] (μ*M*) = 10.65[beam c](m^{-1}) − 1.56; n = 59; r^2 = 0.91. Symmetrical uncertainty limits for the slope and intercept are 0.6 and 0.25, respectively. Regression line for CP (dashed line, level II, linear regression) shows [PON] (μ*M*) = 8.78[beam c] (m^{-1}) −1.29; n = 29; r^2 = 0.97. Symmetrical uncertainty limits for the slope and intercept are 0.38 and 0.28, respectively.

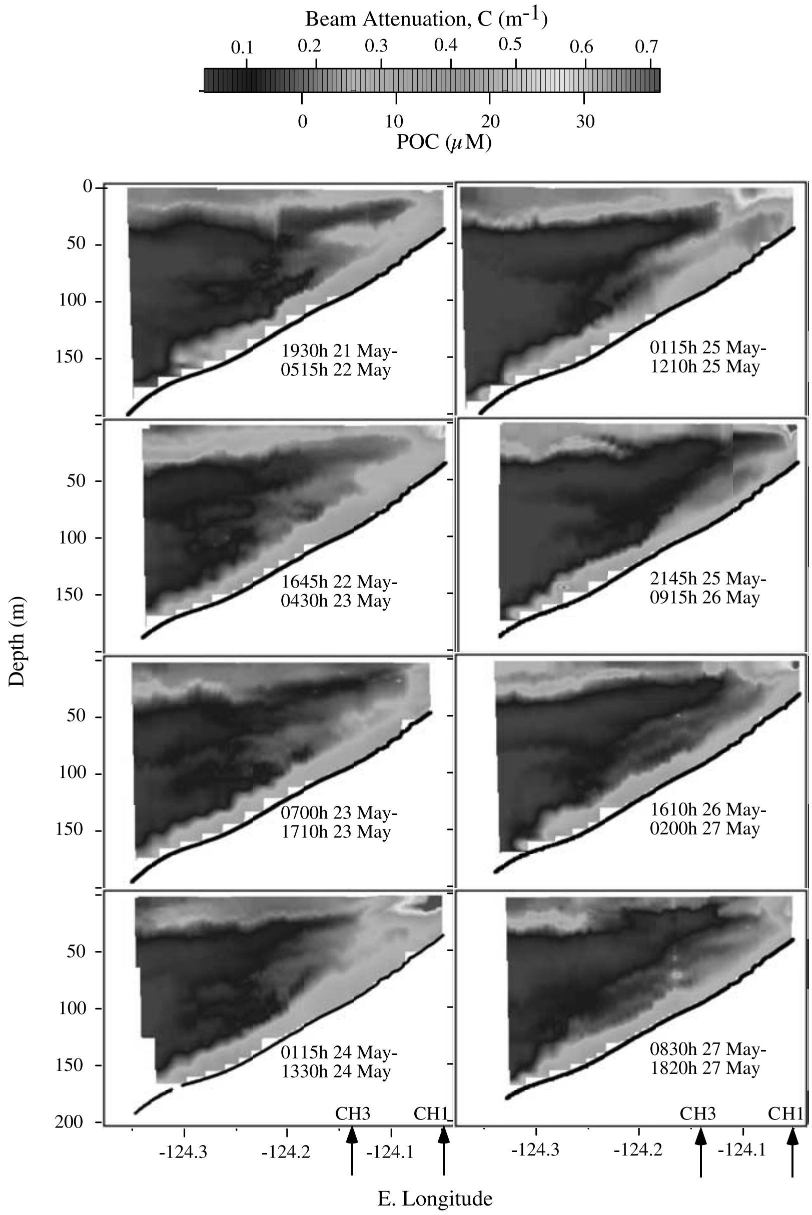

Figure 9. A time series of cross-shelf beam attenuation coefficients off CH. POC concentrations (μ*M*) are estimated from the regression in Figure 8a. See color version of this figure at back of this issue.

that it is largely marine-derived and associated with phytoplankton production. The relationship between the two, however, can vary between locations (i.e., CH versus CP).

[24] Beam attenuation coefficients were highly correlated with POC and PON, suggesting that the spatial and temporal variability in optical properties observed in this study was primarily due to the variability in the distributions of organic particles. Beam attenuation by particles depends on the concentration, size distribution, index of refraction, and shape of the particles [*Zaneveld*, 1973]. Thus the relationship between POC (or PON) and beam attenuation found in this study may vary with time and between locations within the Oregon upwelling system and between the Oregon upwelling system and other coastal environments. Small but significant differences in the slopes were found between CH and CP, suggesting that the properties of particles differed between these two locations. In coastal environments, river input and resuspension events can greatly affect the relationship and degree of correlation between POC and beam attenuation. For example, over the New England shelf the relationship between POC and beam attenuation during spring and summer was highly variable and often weak [*Gardner et al.*, 2001]; particles at surface water were distinctly different from particles near the bottom, largely because of resuspension of sediments [*Gardner et al.*, 2001]. In this study the slopes of the regressions between POC and beam attenuation were not significantly different between surface (at 5 m, 63.8 ± 9.5, r^2 = 0.92) and bottom samples (5 m above bottom, 70.7 ± 11.7, r^2 = 0.9) off CH, suggesting a more homogeneous composition of

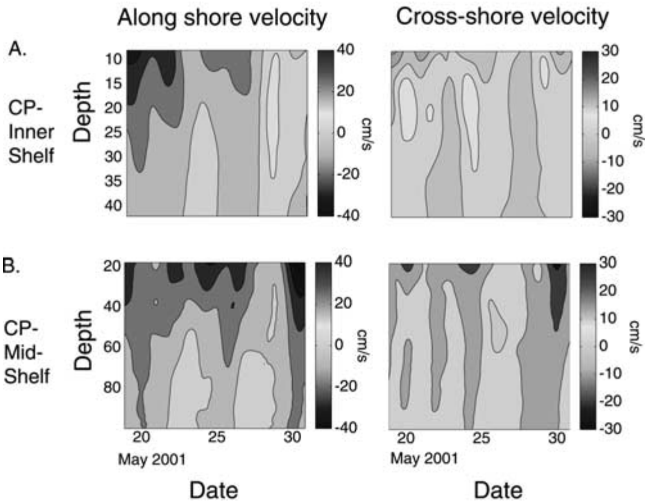

Figure 10. Alongshore and across-shore currents off CP. Data were collected by the OSU mooring group (M. Levine, T. Boyd and M. Kosro; available at http://damp.coas.oregonstate.edu/coast/moorings.shtml)) from two ADCP moorings located at the (a) inner and (b) middle shelf off CP. Velocity data were sampled every 120 s in 2-m bins over the water column depth. Negative alongshore velocities indicate southward flow; positive alongshore velocities indicate northward flow. Negative cross-shore velocities indicate an offshore flow; positive cross-shore velocities indicate an onshore flow. See color version of this figure at back of this issue.

particles (for CP the number of surface and bottom samples is too small to allow similar comparison).

[25] Results from this study highlight three important features associated with the distributions of POM off Oregon during the early upwelling season: (1) the existence of a significant short-term variability, (2) the presence of relatively elevated concentrations of nondegraded chlorophyll and POM in the benthic boundary layer, in particular over the northern inner shelf, and (3) alongshore variations in the distributions and characteristics of POM that are associated with shelf topography. These features, the potential processes involved, and the implications for POM transport from the shelf are discussed in sections 4.1–4.3.

4.1. Short-Term Variability in Distributions of POM

[26] Distributions of POM and beam attenuation coefficients off Cascade Head show significant short-term variability, in particular over the inner shelf. Such variability is not surprising considering the advective nature of the system, both horizontally and vertically, and that the amplitude of fluctuations of the currents is highest inshore and decreases with distance from shore [*Huyer et al.*, 1978]. During the period of this study, currents shifted directions and magnitude in less than a day. At times, southward, alongshore surface currents reached velocities of 60 cm s^{-1}. While it has long been known that considerable temporal variability in hydrographic conditions occurs on short timescales during the upwelling season off the Oregon coast, concurrent short-term variability in chlorophyll and POM distributions has not been documented prior to this study. The short-term variability we observed in POM is of the same magnitude as the seasonal variability reported by *Hill*

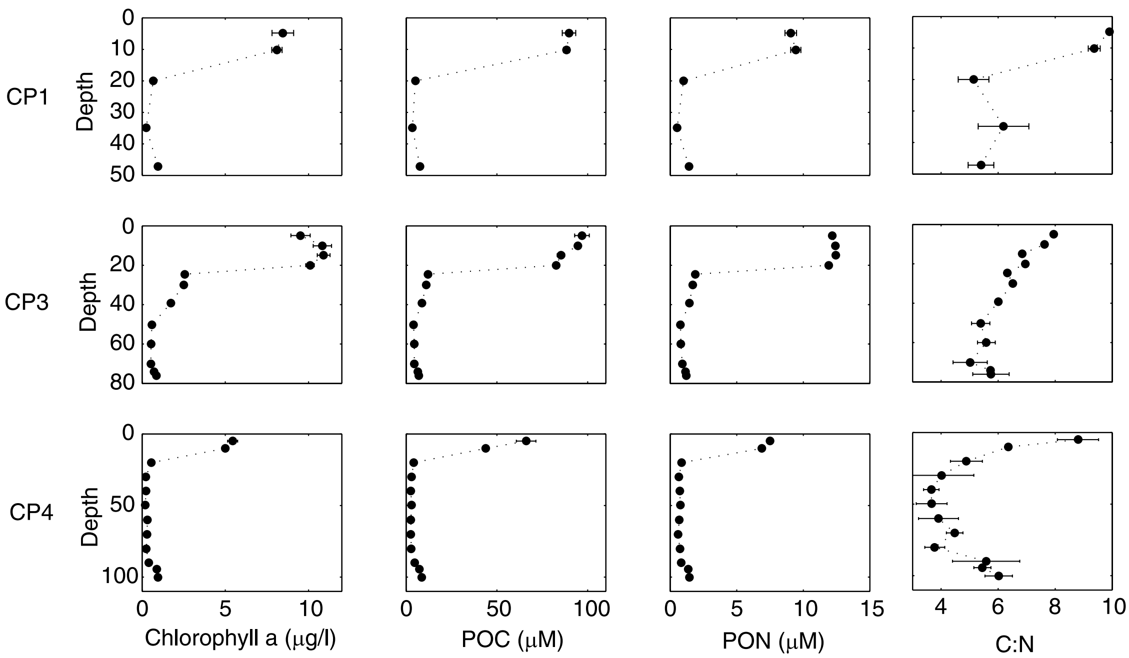

Figure 11. Vertical distributions of chlorophyll, POC, PON, and carbon to nitrogen ratios off CP: (top) CP1, (middle) CP3, and (bottom) CP4. Values are the mean plus/minus standard deviation of triplicate samples. (Note that standard deviations are calculated and plotted for all data points. In several cases the dot representing the value is larger than the standard deviation.)

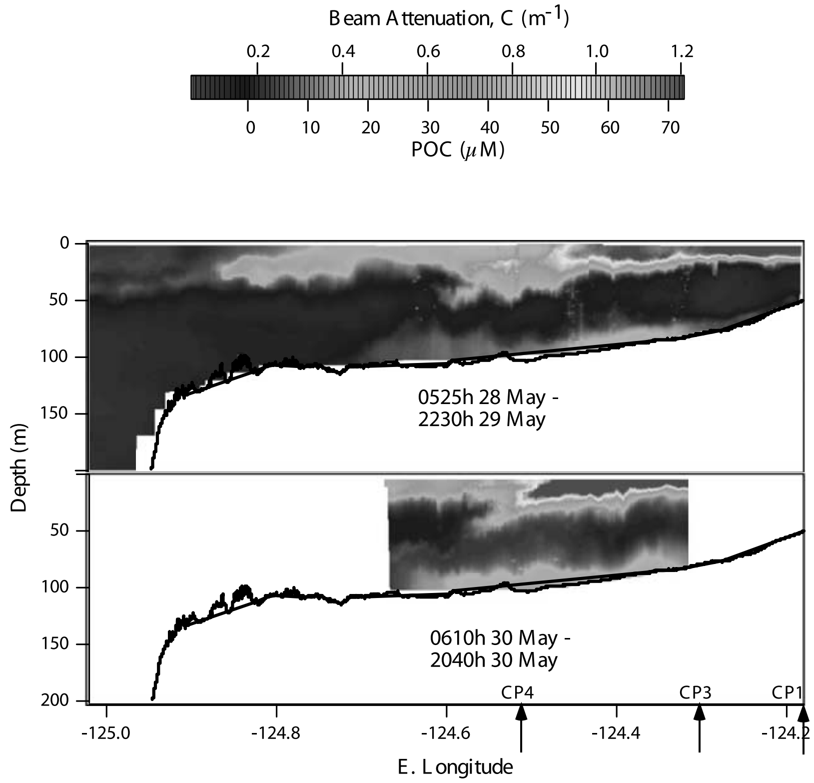

Figure 12. Cross-shelf transect of beam attenuation coefficient off Cape Perpetua over Heceta Bank (CP line). POC values (μM) are estimated from the regression in Figure 8a. See color version of this figure at back of this issue.

and Wheeler [2002] for this region. This implies that data from long-term monitoring programs (e.g., GLOBEC), during which samples are collected sporadically, should be interpreted carefully. What may appear as annual or interannual differences may simply be the result of short-term variability.

4.2. Vertical Distributions and the Role of the Benthic Boundary Layer

[27] A three-layer pattern in the vertical distributions of chlorophyll, POC, and beam attenuation was often observed during this study. This pattern consists of elevated concentrations near the surface, a middepth layer of relatively lower concentrations, and relatively elevated concentrations near the bottom (i.e., the BNL). Such a distribution pattern has been previously observed for beam attenuation and POM over the Oregon shelf during spring and summer [*Pak and Zaneveld*, 1977; *Small et al.*, 1989] and in other coastal environments [*Azetsu-Scott and Johnson*, 1994; *Gardner et al.*, 2001]. Previous observations, however, described the BNL over the Oregon shelf as nonchlorophyllus, high in biogenic silica, and almost always with C:N ratios exceeding 10 [*Small et al.*, 1989]. Our observations clearly show the presence of nondegraded chlorophyll near the bottom (5 m above the bottom) at the shallow inshore station off CH (CH1, station depth 30 m). Elevated concentrations of chlorophyll and POM in surface waters are most likely the result of the response of phytoplankton to upwelled nutrient-rich water. The presence of nondegraded, chlorophyll-containing particles near the bottom at CH1 is more surprising. We exclude resuspension of benthic algae as a significant source for the elevated chlorophyll for two main reasons: First, measured light levels (PAR) at ~5 m above bottom ranged between 2 and 15 microeinstein m^{-2} s^{-1}, too low to support significant production of benthic algae [*Cahoon*, 1999]; second, friction velocities near the bottom, along the CH line, did not exceed 1.04 cm s^{-1} (A. Perlin et al., Response of the bottom boundary layer over a sloping self to variations in alongshore winds, submitted to *Journal of Geophysical Research*, 2004, hereinafter referred to as Perlin et al., submitted manuscript, 2004). Off the Oregon coast, sediments are sandy up to the 100-m isobaths. These friction velocities are not sufficient to resuspend sandy sediments and the benthic microalgae within them [*Middleton and Southard*, 1984] but are sufficient to resuspend phytoplankton aggregates and organic "fluff" that have settled on the bottom. We therefore conclude that the source of chlorophyll near the bottom is phytoplankton from the euphotic zone that has recently been transferred to depth. The presence of viable phytoplankton cells in the BNL has been reported in other studies from this region [*Small et al.*, 1989; *Wetz et al.*, 2004]. There was no significant difference in the C:N ratios between POM collected from the surface (5.7 ± 0.3) and POM collected from the bottom (6.1 ± 0.3). These data suggest that chlorophyll-containing POM near the bottom is associated with phytoplankton from the surface and that it has not been near the bottom long enough for physiological or degradation processes to occur and significantly affect these ratios. Future studies would require microscopic

analysis of water samples to examine the composition of the particles near the bottom.

[28] One mechanism by which phytoplankton can quickly reach the BNL is via subduction of surface water during periods of wind reversal. The upwelling season off Oregon is characterized by periods in which upwelling favorable winds dominate, followed by periods of relaxation. During relaxation, winds shift direction, and the mean surface cross-shelf flow becomes shoreward. This can lead to the accumulation of phytoplankton and other particles near the shore and to subduction of the water containing the phytoplankton and other particles to depth over the inner shelf. During this study, downwelling favorable winds prevailed on 22 and 23 May. Elevated concentrations of chlorophyll and POC were observed on 24 May 2001 at the surface and bottom of the inner shelf (Figure 4).

[29] Mass sedimentation of phytoplankton aggregates is another mechanism by which chlorophyll is delivered to the bottom before being degraded [*Smetacek*, 1985]. Sinking velocities of diatom aggregates in the ocean may exceed 50 m d^{-1} [*Alldredge and Silver*, 1988]. In shallow locations, such as CH1, phytoplankton could potentially reach the bottom in about 1 day. Rapid sinking is often associated with depletion of nutrients. During this study, however, surface water at CH1 and CH3 was always nutrient-replete.

[30] Off CP a three-layer pattern in beam attenuation was also evident, especially over the midshelf. Unfortunately, data on friction velocities along the CP line were not been available to us at the time of preparing this manuscript. Low concentrations of chlorophyll (<1 μg L^{-1}) were present in all the samples that were collected near the bottom. C:N ratios of POM from surface samples were significantly different from C:N ratios of POM collected near the bottom (Figure 11). This information suggests a decoupling between surface and bottom processes that affects distributions and characteristics of POM. Differences in the coupling/decoupling of surface and bottom processes between CH and CP may be a result of the relative importance of two-dimensional versus three-dimensional transport processes at each of these locations. Differences in the circulation between these two sites are discussed in section 4.3.

[31] The presence of relatively elevated concentrations of POM near the bottom in the inner shelf has been repeatedly observed in other inner shelf locations during this study and during GLOBEC cruises (unpublished data, 1998–2003). These observations suggest that bottom boundary currents may be an important route of POM transport. During upwelling, Ekman transport in the bottom is directed onshore [*Smith*, 1995] and may result in accumulation of material on the shelf rather than export. During downwelling favorable conditions the Ekman transport is directed offshore near the bottom [*Smith*, 1995] and could result in export of POM from the shelf. It is not yet possible, however, to assess the role of transport in the bottom boundary layer as so few measurements have been done [*Smith*, 1995; Perlin et al., submitted manuscript, 2004]. It is also unknown how efficient the benthic community is in utilizing the POM that reaches the bottom and how much remains available for export. Nevertheless, estimates of export of primary production from upwelling regions must consider transport of suspended material via bottom boundary layers, a process that is difficult to account for when using sediment traps.

[32] In addition to its potential role in POM transport the BNL appears to be an important source of phytoplankton seed stock. The presence of nondegraded chlorophyll at the BNL suggests that upwelled waters from the BNL may contain viable cells capable of growth. This idea is supported by incubation experiments of water samples from the BNL that did result in phytoplankton growth [*Small et al.*, 1989; *Wetz et al.*, 2004].

4.3. Effects of Shelf Topography on Cross-Shelf Distributions and Transport

[33] Striking differences in cross-shelf distributions, concentrations, and characteristics of the organic material were observed between the two transects. High concentrations of POM along the CH transect were restricted to the inner shelf (<9 km off shore), dropping significantly toward the middle and outer shelf. Conversely, along the CP transect, high concentrations of POM extended at least 30 km off shore. Surface POM off CH was enriched in nitrogen (mean C:N = 5.8 ± 0.2 and 5.6 ± 0.2 at CH1 and CH3, respectively) compared to surface POM off CP (C:N values of 9.9 ± 0.1, 7.95 ± 0.1, and 8.8 ± 0.7 at CP1, CP3, and CP4, respectively). Surface carbon to chlorophyll ratios were also higher off CP compared to off CH (Figure 7). While concentrations of nitrate and silicate at the surface were always above detection limit at CH1 and CH3 (ranging from 1.73 to 24.75 μ*M* for NO_3^-, from 4.83 to 42.5 μ*M* for $Si(OH)_4$, and from 0.50 to 2.16 μ*M* for PO_4^{-3}), surface concentrations of nitrate and silicate measured at CP1, CP3, and CP4 were below detection limit. Off CP, carbon-enriched POM from surface water could be due to decoupling between nitrogen and carbon dynamics, as a result of nitrate depletion [*Engel et al.*, 2002; *Wetz and Wheeler*, 2003].

[34] The observed differences between the two sites can be attributed to differences in shelf topography and circulation. Between CH and CP the continental shelf broadens by >40 km. As a result the circulation over the shelf varies dramatically between the two locations. While circulation over the northern shelf, where CH is located, has been extensively studied, circulation over Heceta Bank, where CP is centered, is less well understood. Recent model simulations of shelf circulation in response to upwelling illuminate some of the key differences in the wind-driven circulation between the two locations [*Oke et al.*, 2002]. First, the upwelled waters off CH and CP originate from different sources and thus may differ in their chemical characteristics, the phytoplankton community composition, and the resultant food web structure [*Oke et al.*, 2002]. The model points out that while the upwelling circulation off CH is quantitatively consistent with the two-dimensional conceptual model of wind-driven upwelling (i.e., offshore Ekman transport at the surface and onshore flow through the benthic boundary layer), the circulation over Heceta Bank (across the CP transect) is more complex and highly three-dimensional. Off CH the core of the upwelling jet is located onshore during upwelling and moves offshore upon relaxation [*Oke et al.*, 2002]. In contrast, off Heceta Bank, isopycnals are lifted over the midshelf and over a broader

region. The model also indicates a formation of a cyclonic eddy over the bank.

[35] Our observations of the distributions of chlorophyll, POM, and beam attenuation off CH and CP are consistent with the circulation pattern described by the model. Off CH the upwelling jet restricts surface distributions of phytoplankton and other particles to the inner shelf. Over CP, high surface concentrations of chlorophyll and other particles were found over a broader region of the shelf, with highest concentrations of chlorophyll and POM at CP3. Similarities in the characteristics of POM from surface and bottom samples, at CH1, are more consistent with a two-dimensional upwelling/downwelling circulation model, while the differences in the characteristics of POM from surface and bottom samples, off CP, are likely to result from complex, three-dimensional transport processes. The circulation model implies that the exchange rate of water varies greatly between CP and CH [*Oke et al.*, 2002]. Off the CH region, mean velocities of alongshore, southward currents can approach 45 cm s^{-1} (Figure 3) [*Halpern*, 1976]. Thus surface POM will be rapidly transported along the shelf. Amplitude of fluctuations in the alongshore component of the currents is higher inshore and decreases with increasing distance from shore [*Huyer et al.*, 1978]. This is evident in the higher variability observed in CH1 compared to CH3. While the mean alongshore current over the shelf is baroclinic (i.e., top and bottom layer move separately), dominant fluctuations in the alongshore currents near the coast are nearly barotropic. This may explain why surface and bottom POC are highly correlated. Our data do not indicate the presence of a significant cross-shelf transport of POM off CH, at least during the period when we occupied this line.

[36] Off Cape Perpetua (CP transect), alongshore velocities were generally slower compared to velocities off CH. Furthermore, the formation of a cyclonic eddy over the bank, as predicted by the model, implies slower water exchange rate off Cape Perpetua. We do not have the data to assess the temporal variability off CP, but higher C:N and chlorophyll/carbon ratios in surface water off CP compared to CH and differences in the degree to which nutrients were utilized between the two sites are consistent with this prediction.

5. Summary

[37] In order to assess the contribution of upwelling zones to carbon fluxes, POM standing stocks and variability must be assessed and constrained. Results from this study clearly show that magnitudes and distributions of POM during the upwelling season off Oregon are subjected to considerable variability in space and time. Differences in the characteristics and extent to which POM is distributed over the shelf are attributed to changes in shelf topography. Off CH, high concentrations of POM were mostly restricted to the inner shelf and dropped dramatically with increasing distance from shore, while off CP a plume of elevated POM concentrations extended beyond the midshelf. Short-term temporal variability in POM, as observed particularly over the inner shelf off CH, is of the same order of magnitude as that reported for seasonal variability in this region. This variability is attributed to large fluctuations in the magnitude and direction of the alongshore currents and the biological response to upwelling/relaxation events. It is thus imperative for future assessment of the role of the Oregon shelf to adjust the sampling strategy to constrain the small-scale variability in space and time. This type of sampling is not achievable with traditional ship-based discrete bottle-sampling station surveys; it requires a local observing system, such as recently implemented along the east coast of the United States, and a commitment to rapid, high-spatial resolution sampling. We observed a large concentration of chlorophyll-containing particles near the bottom, suggesting that vertical transport processes such as downwelling and rapid settling of phytoplankton cells may play an important role in removing POM from the surface. Off-shelf transport of that material may then occur via benthic boundary layer processes. Future studies should include measurement as close as possible to the bottom to constrain the magnitude of lateral bottom fluxes.

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P. Covert, B. Hales, and P. A. Wheeler, College of Oceanic and Atmospheric Sciences, Oregon State University, 104 COAS Administration Bldg., Corvallis, OR 97331-5503, USA. (pcovert@coas.oregonstate.edu; bhales@coas.oregonstate.edu; pwheeler@coas.oregonstate.edu)

L. Karp-Boss, School of Marine Sciences, University of Maine, 5706 Aubert Hall Orono, ME 04469-5741, USA. (lee.karp-boss@maine.edu)

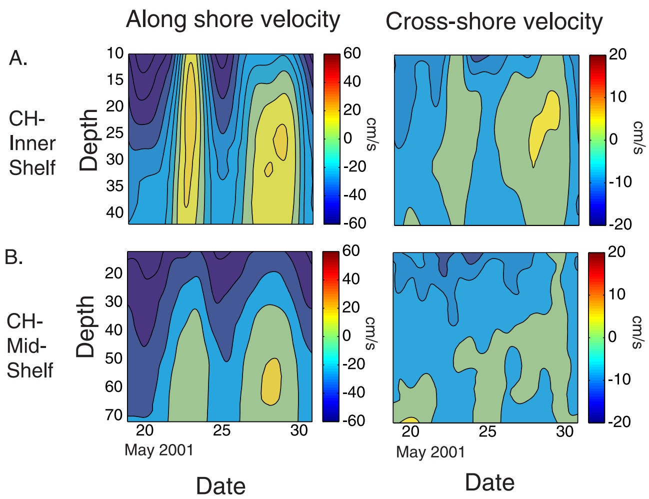

Figure 3. Alongshore and across-shore currents off CH. Data were collected by the OSU mooring group (M. Levine, T. Boyd and M. Kosro (available at http://damp.coas.oregonstate.edu/coast/moorings.shtml)) from two acoustic Doppler current profiler (ADCP) moorings located at the (a) inner (45°0.04′N, 124°4.102′W) and (b) middle (45°0.011′N, 124°6.995′W) shelf off CH. Velocity data were sampled every 120 s in 2-m bins over the water column depth. Negative alongshore velocities indicate southward flow; positive alongshore velocities indicate northward flow. Negative cross-shore velocities indicate an offshore flow; positive cross-shore velocities indicate an onshore flow.

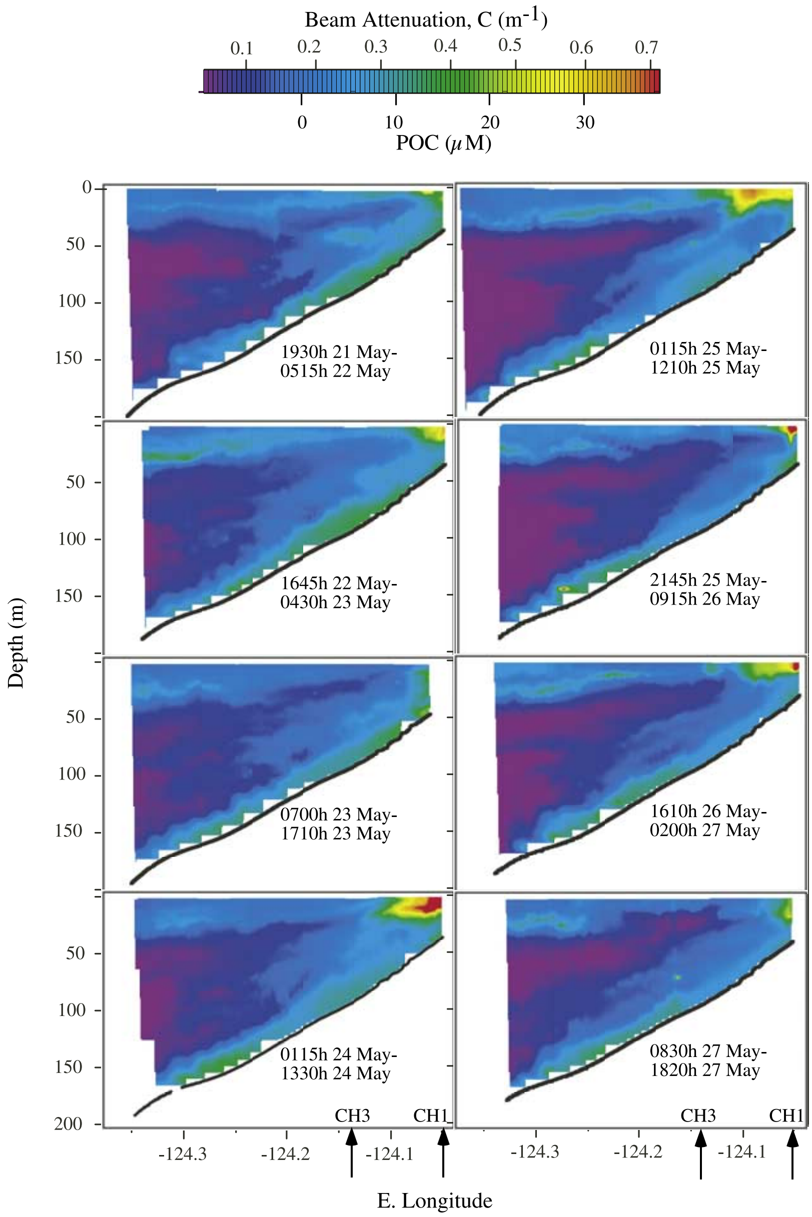

Figure 9. A time series of cross-shelf beam attenuation coefficients off CH. POC concentrations (μM) are estimated from the regression in Figure 8a.

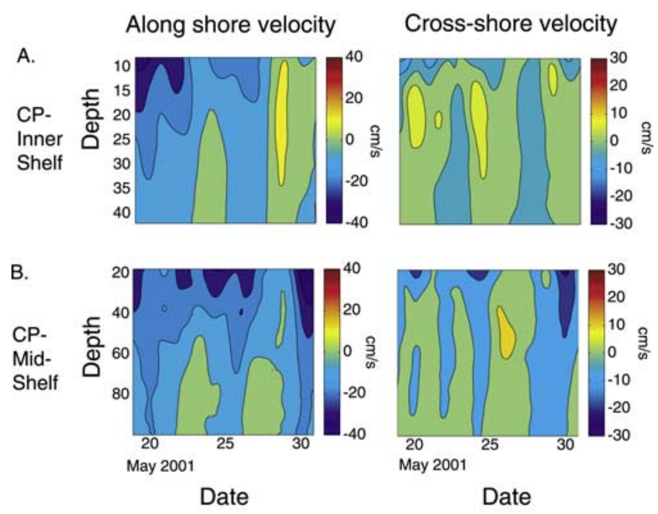

Figure 10. Alongshore and across-shore currents off CP. Data were collected by the OSU mooring group (M. Levine, T. Boyd and M. Kosro; available at http://damp.coas.oregonstate.edu/coast/moorings.shtml)) from two ADCP moorings located at the (a) inner and (b) middle shelf off CP. Velocity data were sampled every 120 s in 2-m bins over the water column depth. Negative alongshore velocities indicate southward flow; positive alongshore velocities indicate northward flow. Negative cross-shore velocities indicate an offshore flow; positive cross-shore velocities indicate an onshore flow.

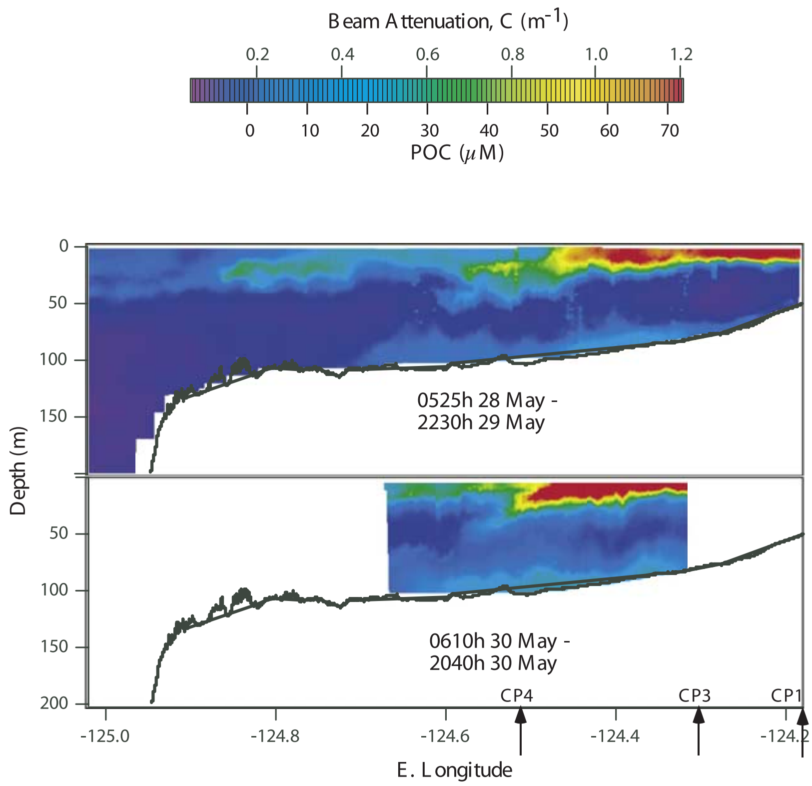

Figure 12. Cross-shelf transect of beam attenuation coefficient off Cape Perpetua over Heceta Bank (CP line). POC values (μM) are estimated from the regression in Figure 8a.