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Thin phytoplankton layer formation at eddies, filaments, and fronts in a coastal upwelling zone

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On two cruises in August and September 2003 (hereafter cruises 2 and 3) during wind relaxations and transitions to upwelling conditions, thin layers of phytoplankton were observed in or a few meters below the stratified transition layer at the mixed layer base and in regions of sheared flow on the flanks of eddies, filaments, and fronts near Monterey Bay, California. On an earlier cruise in August (cruise 1), no thin layers were found after a prolonged wind relaxation. Chlorophyll concentrations and shear were both an order of magnitude less than on cruises 2 and 3. Our vertical profiles were made using a fluorometer mounted on a conductivity–temperature–depth package, which was lowered from the ship as slowly as $0.25\,\mathrm{m\,s^{-1}}$ every 10 km on five ~80-km cross-shore transects. Remotely sensed sea-surface temperature, chlorophyll, and currents are required to understand the temporal and spatial evolution of the circulation and to interpret the quasi-synoptic *in situ* data. Decorrelation scales are ~20 km from lagged temperature and salinity covariances. Objectively mapped sections of the *in situ* data indicate the waters containing thin layers were recently upwelled at either the Point Sur or Point Año Nuevo upwelling centers. Spatially limited distributions of phytoplankton at the coastal upwelling centers (~40 km alongshore, 20 km cross-shore, and 30 m thick) were transformed into thin layers by current shear and isolated from wind-driven vertical mixing by the stratification maximum of the transition layer. Vertically sheared horizontal currents on the flanks of the eddies, filaments, and fronts horizontally stretched and vertically thinned phytoplankton distributions. These thin, elongated structures were then observed as thin layers of phytoplankton in vertical fluorescence profiles at four stations on cruise 2 and eight stations on cruise 3. Light winds during relaxations did not mix away these thin layers. On cruise 2, thin layers were found at eddies at the inshore and offshore ends of a 100-km-long filament, while broader subsurface chlorophyll maxima were found along the filament. This result suggests that higher-resolution sampling along and across a filament may find thin layers forming and dissipating along its length. On cruise 3, thin layers were found at three adjacent stations across an upwelling front and may have extended continuously for >20 km, but neither species composition nor bio-optical data are available to confirm this conjecture. The thin layers were 1–5 m thick in the vertical at full width half maximum and had peak fluorescence values from $7-30\,\mathrm{mg\,m^{-3}}$. (Bottle chlorophyll samples showed fluorometer chlorophyll readings may have been $1.3-1.5\times$ too large, but the scatter in this relation was considerable especially at the larger fluorescence values detected in thin layers.) While sheared currents thinned an initially thick subsurface chlorophyll maximum into thin layers, the peak values in these thin layers exceeded concentrations in the upwelled source waters and were unexplained by our data.

1. Introduction

1.1. Autonomous Ocean Sampling Network II

The Autonomous Ocean Sampling Network II (AOSN-II) experiment combined ocean models with observations from autonomous platforms (gliders, autonomous underwater vehicles, drifters, profiling floats), *in situ* instruments (on ships, moorings, and towed bodies), and remote sensors (coastal radar, aircraft, and

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satellites) to observe and predict the physics and biology of a coastal upwelling zone (Ramp et al., 2008). We contributed broad surveys of currents, hydrography, and chlorophyll-related fluorescence on three cruises (2–6 August, 21–25 August, and 3–6 September 2003) in the Monterey Bay region (Fig. 1). Our ship-based vertical profiles provided a relatively rapid, quasi-synoptic assessment of the subsurface oceanic mesoscale within which spatially limited measurements were made by other slowly moving platforms.

1.2. Observations of thin layers

During cruises 2 and 3, we observed thin layers (<5-m thick in the vertical) of phytoplankton, which are difficult to resolve with typical shipboard measurements and are far below the vertical resolution of regional models. The physical and biological mechanisms forming and maintaining these thin layers in different locations and under different physical conditions is an active area of research. Here, we document thin layers associated with mesoscale flows in a coastal upwelling zone.

Within the last decade, novel optical, acoustical, and water sampling instrumentation have produced centimeter- or meter-scale descriptions of plankton distributions (Cowles et al., 1993; Franks and Jaffe, 2001; Wolk et al., 2002; Holliday et al., 2003; Maar et al., 2003; Lunven et al., 2005; Sutor et al., 2005). Planktonic thin layers may extend horizontally for kilometers and persist for days (Dekshenieks et al., 2001; Rines et al., 2002; Holliday et al., 2003; McManus et al., 2003, 2005; Churnside, 2007). A thin layer is defined operationally as <5 m in vertical extent at full width half maximum, with a peak concentration >3× the ambient background, and reproducible in subsequent profiles (Dekshenieks et al., 2001). However, in the observations presented here, we usually have only single casts at each station. In-layer planktonic densities can be orders of magnitude greater than those just above or below the structure (e.g., Donaghay et al., 1992). Frequently, multiple thin layers occur in a single vertical profile, each with a distinct plankton assemblage (Rines et al., 2002; Lunven et al., 2005). Traditional sampling methods, usually performed with bottles mounted on conductivity–temperature–depth (CTD) profilers may not detect features with vertical spatial scales less than several meters. Careful data interpretation is needed because fluorescence patchiness may also be due to species variability and physiological variability within a single species caused by historical light exposure and nutrient availability (Eisner and Cowles, 2005; Sutor et al., 2005).

The vertical distribution of plankton in layers with large vertical gradients has potentially significant ecological consequences, including increased nutrient fluxes, unique species composition, increased predator/prey encounter, increased export from the upper ocean due to increased aggregation and sinking, and enhanced water column productivity (Cowles et al., 1993; McManus et al., 2003; Ryan et al., 2005; Sutor et al., 2005). Thin phytoplankton layer depth was closely associated with the depth and strength of the pycnocline (Dekshenieks et al., 2001; Rines et al., 2002; Sutor et al., 2005). Thin layers can be composed of taxa whose distribution is restricted to these single layers (Rines et al., 2002) or are present throughout the water column in weaker concentrations (McManus et al., 2003). At present there is an operational distinction between a thin layer and subsurface chlorophyll maximum, but it is uncertain whether the high plankton concentration in a thin layer is a result of successful occupation of an ecological niche or simply a consequence of the physics.

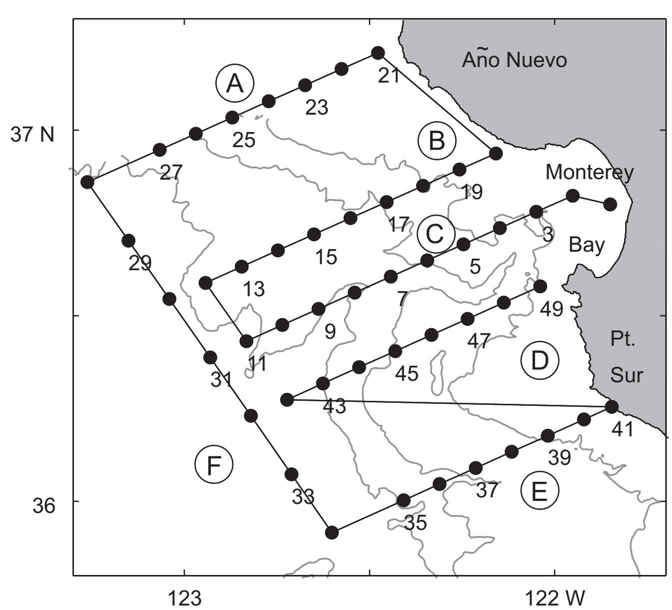

Fig. 1. The cruise track for all three cruises. Cross-shore transects are labeled A–E from north to south and the alongshore transect is F. Transect C is along CalCOFI line 67. Hydrographic stations are numbered in order of occupation and have a spacing of 10 and 20 km on the cross-shore and alongshore transects. Stations 1, 3, and 6 are located near MBARI moorings C1, M1, and M2. Stations 11, 12, and 42 were omitted on cruise 3 in the interest of time. Bathymetry is contoured at 1000, 2000, 3000, and 4000 m.

1.3. Current shear, stratification, and thin layers

The transition layer between the surface mixed layer and the weakly stratified interior is typically a 10–30-m thick, moderately turbulent region defined by maxima below the mixed layer in thermohaline variance, stratification, current shear, and potential vorticity (Johnston and Rudnick, 2008). Mixed-layer depth is a proxy for energy recently input to vertical mixing. Thinner phytoplankton and transition layers were found at the base of shallower mixed layers, where vertical mixing was weaker and stratification was stronger (Dekshenieks et al., 2001; Johnston and Rudnick, 2008). This suggests that the thickness and depth of thin layers are related to the thickness and depth of the transition layer.

The stratification maximum and moderate turbulence in the transition layer can increase phytoplankton concentrations in two ways. Firstly, sinking of large aggregations of phytoplankton may be slowed by changes in stratification at density steps and this convergence may lead to elevated concentrations (Derenbach et al., 1979; MacIntyre et al., 1995). Secondly, moderate turbulence in the transition layer can increase plankton concentrations there by preventing sinking through the pycnocline by mixing aggregations upward (MacIntyre et al., 1995). In a one-dimensional model, sinking organic matter of any type will lead to a deep biomass maximum (Hodges and Rudnick, 2004). The magnitude of the deep biomass maximum depends mostly on sinking rate and diffusivity, while its depth depends mostly on phytoplankton growth rate (Hodges and Rudnick, 2004). These intriguing results further suggest the effects of the stratified and moderately turbulent transition layer on the magnitude of chlorophyll maxima is of first order. However, realistic values of vertical convergence due to different sinking rates in the mixed layer, transition layer, and the interior cannot produce thin layers in the Hodges and Rudnick (2004) model (B. Hodges, personal communications).

Another process contributing to thin layer formation is the vertical shear of horizontal currents (Franks, 1995; Osborn, 1998;