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Interacting physical, chemical and biological forcing of phytoplankton thin-layer variability in Monterey Bay, California

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ABSTRACT

During the 2005 *Layered Organization in the Coastal Ocean* (LOCO) field program in Monterey Bay, California, we integrated intensive water column surveys by an autonomous underwater vehicle (AUV) with satellite and mooring data to examine the spatiotemporal scales and processes of phytoplankton thin-layer development. Surveying inner to outer shelf waters repeatedly between August 18 and September 6, the AUV acquired 6841 profiles. By the criteria: [(1) thickness ≤ 3 m at the full-width half-maximum, (2) peak chlorophyll at least twice the local background concentrations, and (3) a corresponding peak in optical backscattering], thin layers were detected in 3978 (58%) of the profiles. Average layer thickness was 1.4 m, and average intensity was 13.5 $\mu g\, l^{-1}$ above (3.2*x*) background. Thin layers were observed at depths between 2.6 and 17.6 m, and their depths showed diurnal vertical migration of the layer phytoplankton populations. Horizontal scales of thin-layer patches ranged from <100 m to $>10{,}000$ m. A thin-layer index (TLI), computed from layer frequency, intensity and thinness, was highest in mid-shelf waters, coincident with a frontal zone between bay waters and an intrusion of low-salinity offshore waters. Satellite observations showed locally enhanced chlorophyll concentrations along the front, and *in situ* observations indicated that phytoplankton may have been affected by locally enhanced nutrient supply in the front and concentration of motile populations in a convergence zone. Minimum TLI was furthest offshore, in the area most affected by the intrusion of offshore, low-chlorophyll waters. Average thin-layer intensity doubled during August 25–29, in parallel with warming at the surface and cooling within and below the thermocline. During this apparent bloom of thin-layer populations, density oscillations in the diurnal frequency band increased by an order of magnitude at the shelfbreak and in near-bottom waters of the inner shelf, indicating the role of internal tidal pumping from Monterey Canyon onto the shelf. This nutrient transport process was mapped by the AUV. Peak TLI was observed on August 29 during a nighttime survey, when phytoplankton were concentrated in the nutricline. Empirical orthogonal function decomposition of the thin-layer particle size distribution data from this survey showed that throughout the inner to outer shelf survey domain, the layers were dominated by phytoplankton having a cross-section of ~ 50 μm. This is consistent with the size of abundant *Akashiwo sanguinea* cells observed microscopically in water samples. During a subsequent and stronger intrusion of low-salinity offshore waters, spatially-averaged vertical density stratification decreased by $>50\%$, and phytoplankton thin layers disappeared almost completely from the AUV survey domain.

1. Introduction

1.1. Environmental Setting

Monterey Bay, California is a dynamic and productive coastal environment in the central California Current System (CCS). Nutrient-rich waters, supporting high primary productivity, shoal by wind-forced coastal upwelling and Ekman pumping, and by internal tidal forcing of transport from Monterey Canyon (Fig. 1) onto the shelf (Reid et al., 1958; Barber and Smith, 1981; Shea and Broenkow, 1982; Breaker and Broenkow, 1994; Rosenfeld et al., 1994). Bay waters are a mixture of relatively cold / saline upwelled water and relatively warm / fresh offshore waters of the CCS (Graham and Largier, 1997). The bay environment changes significantly with highly variable influxes of these primary source waters.

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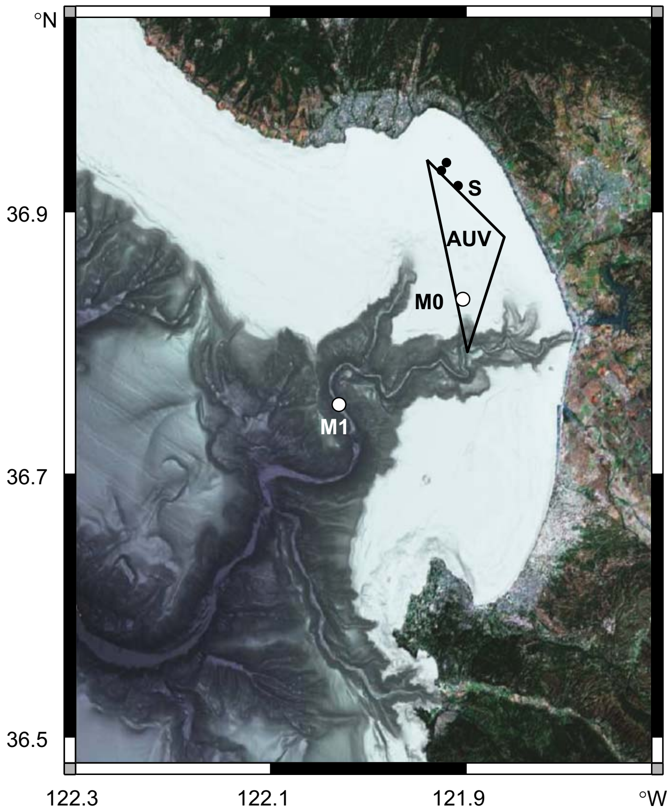

Fig. 1. Map of the study region, Monterey Bay, California. The triangular track over the northern shelf in the bay shows the AUV survey path that was repeatedly occupied. The AUV track is 38 km along-track and spans 16.3 km north–south; 7 km east–west. Data from the M0 (70 m water depth) and M1 (1000 m water depth) moorings provided oceanographic data. The 3 black circles in the northeastern bay show the locations of the LOCO primary mooring sites, data from station S are used in this study.

The intensity and biological consequences of coastal upwelling in this region are greatest between March and November (Pennington and Chavez, 2000). Within this period, circulation and water mass distributions respond strongly to changes in wind forcing. Equatorward winds produce cold filaments of upwelled waters north and south of the bay, and the upwelling from Point Año Nuevo, 27 km north of the bay, often flows southward across the mouth of the bay (Rosenfeld et al., 1994). A cyclonic gyre forms in the northern bay as a dynamic response to active upwelling (Breaker and Broenkow, 1994). This circulation transports nutrient-rich upwelled waters into the bay and creates a phenomenon known as the 'upwelling shadow', in which residence time and thermal stratification are enhanced (Graham and Largier, 1997). Periods when equatorward winds decrease in intensity ($<3\ \mathrm{m\,s^{-1}}$) or reverse to poleward are termed 'relaxation events'. During relaxation events, offshore low-salinity waters are transported shoreward (Bolin and Abbott, 1963; Broenkow and Smethie, 1978; Rosenfeld et al., 1994; Ramp et al., 2005). These low salinity waters are warm relative to recently upwelled waters but may be cool relative to bay waters that have warmed during residence in the upwelling shadow. Responses to relaxation events include rapid flushing of much of the bay by intrusions of offshore low-salinity waters containing relatively low phytoplankton biomass (Ryan et al., 2008a, 2009), as well as mixing and destratification of the inner shelf water column (Storlazzi et al., 2003).

A summary of foundational research on thin layers is presented in the introductory paper of this special issue. Here we summarize some studies of phytoplankton ecology in Monterey Bay relevant to the present study. The upwelling shadow, within which much of the LOCO observations were made, functions as a dinoflagellate "red tide" bloom incubator (Ryan et al., 2005, 2008b, 2009; Rienecker et al., 2008; Kudela et al., 2008). This area has also been observed to host intense and persistent thin layers of toxin-producing diatom species (McManus et al., 2008). Frontal zones formed by inflow of upwelling filaments and offshore waters are important sites for aggregation of diatom and dinoflagellate biomass, as well as phytoplankton thin-layer formation by vertical shear (Pennington and Chavez, 2000; Ryan et al., 2005, 2008a, 2008b, 2009; Rienecker et al., 2008).

1.2. Research objectives

The primary objective of this research was to understand the interacting physical, chemical and biological processes that influence phytoplankton thin-layer development in Monterey Bay. Our approach was to (1) intensively map the physical, nutrient and optical properties of inner- to outer-shelf waters (~20 to 200 m depth) at spatial and temporal scales permitting resolution of phytoplankton thin-layer structures, their synoptic patterns of patchiness, and their evolution, and (2) to relate thin-layer variability to regional oceanographic forcing. These intensive AUV observations were also used to quantitatively compare thin-layer attributes observed at the inner shelf array site (Fig. 1) with those observed in deeper waters of the bay.

2. Methods

2.1. Dorado autonomous underwater vehicle (AUV) surveys

The MBARI AUV *Dorado* repeatedly occupied a triangular survey track (Fig. 1) during the period August 18 to September 6, 2005, taking 6841 profiles in total. The survey was comprised of two cross-shelf transects and one along-shelf transect, with one of each type of transect extending away from the LOCO primary mooring array site (Fig. 1). Of the 20 repeated surveys, 18 were conducted over an 8-day period, between August 25 and September 1, for the purpose of high-resolution thin-layer quantification. The other two surveys, on August 18 and September 6, were for the purpose of thin-layer characterization before and following the intensive AUV observation period.

The AUV was equipped with physical, chemical and optical sensors. We present observations from five sensors: (1) a SeaBird SBE 25 CTD that measured temperature and conductivity, (2) a Paroscientific 8CB/4000-I pressure sensor, (3) a HOBI Labs HS-2 sensor that measured optical backscattering at 470 and 676 nm, centered on a scattering angle of 140°, and chlorophyll fluorescence, (4) an *in situ* ultraviolet spectrophotometer (ISUS) sensor that measured nitrate concentrations (Johnson and Coletti, 2002), and (5) a Sequoia Scientific LISST-100 (Laser In Situ Scattering and Transmissometer) that measured the particle size distribution between 1 and 250 μm. The LISST-100 has proven effective for studying the patchiness and evolution of coastal ocean dinoflagellate and diatom blooms (Rienecker et al., 2008).

At a speed of $\sim 1.75\ \mathrm{m\,s^{-1}}$ and a 17° pitch through yo–yo profiling, the AUV provided synoptic high-resolution sections through shelf waters. A single transit around the 38 km triangular survey track (Fig. 1) averaged 342 profiles in ~6.5 h. Profile depth tracked bottom depth, with the AUV remaining ~4 m above bottom on all profiles. Horizontal resolution thus varied with water depth, ranging from ~15 profiles $\mathrm{km^{-1}}$ (70 m $\mathrm{profile^{-1}}$) for the along-shelf transect to ~3 profiles $\mathrm{km^{-1}}$ (330 m $\mathrm{profile^{-1}}$)