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Coastal thin layer dynamics: Consequences to biology and optics

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ABSTRACT

Thin layers are fine-scale structures with high concentrations of organisms or particles occurring over very small vertical scales (a few meters or less), but with large horizontal scales, often extending for many kilometers. Because of their small vertical scales, thin layers are traditionally under sampled, but when proper measurement techniques are used, thin layers have been found to be ubiquitous in stratified oceans. A multi-investigator, interdisciplinary study of thin layers was sponsored by the US Office of Naval Research under a research initiative termed: Layered Organization in the Coastal Ocean (LOCO). The goal of this program was to understand the properties of coastal thin layers and the interacting physical, chemical, biological and optical processes responsible for their formation, maintenance and dissipation. As part of this program, fine-scale vertical profiles (cm resolution) of biological, physical and chemical properties were made hourly over periods spanning 1–3 weeks during three summers in Monterey Bay, California USA. The vertical profiles were made using arrays of moored autonomous profilers. In total, these profilers made ~2000 individual vertical profiles and provided a unique view of phytoplankton thin layer spatial-temporal dynamics. The autonomous profiler data were supplemented with high-resolution ship-based profiling and discrete water sampling for identifications of organisms.

Persistent phytoplankton thin layers were observed during each year in Monterey Bay; however, each year had very different biological and physical dynamics. During 2002, thin layers were dominated by the non-motile and potentially toxic diatom genus *Pseudo-nitzschia*; during 2005, thin layers were dominated by the highly motile dinoflagellate species *Akashiwo sanguinea*; and during 2006, a more complex phytoplankton assemblage was present, but thin layers of the toxic dinoflagellate species *Alexandrium catenella* frequently occurred. The variability in the vertical location of thin layers in 2002 was primarily controlled by physics, while behavior, e.g. diurnal vertical migration patterns and daytime near-surface aggregations, primarily controlled the location of thin layers in 2005 and 2006. In 2002, phytoplankton thin layers were present in the water column 87% of the time, in 2005, 56% of the time and in 2006, 21% of the time. The median integrated chlorophyll concentration within the thin layers was found to be approximately 47% of the total water column chlorophyll in 2002, 41% in 2005 and 33% in 2006. Additional results in this study describe the mechanisms driving the spatial-temporal dynamics of these phytoplankton thin layers with special emphasis on diel patterns and the specific relationships that thin layers have to biological and physical processes and water column optics.

1. Introduction

Thin layers are fine-scale structures with high concentrations of organisms or particles, e.g. bacteria, phytoplankton, zooplankton and marine snow, occurring over very small vertical scales (centimeters to a few meters), but with large horizontal scales (kilometers) and temporal persistence (hours to weeks). Thin layers are ubiquitous in stratified oceans and their importance in understanding coastal ecosystem dynamics can be substantial. Thin layers can play a critical role in such processes as fish and zooplankton feeding success (Lasker, 1975; Mullin and Brooks, 1976), optical and acoustical attenuation (Sullivan et al., 2005; Holliday et al., 2003), remote sensing reflectance (Zaneveld and Pegau, 1998; Petrenko et al., 1998) and harmful algal bloom (HAB) ecology (Rines et al., 2002; Sullivan et al., 2003; McManus et al., 2008). For an extensive background on thin layer ecology and dynamics please see the introduction to this special issue.

This study, and the companion studies within this special issue, was part of a US Office of Naval Research sponsored interdisciplinary research program to examine thin layer dynamics in the coastal ocean termed: Layered Organization in the Coastal Ocean (LOCO). This multi-investigator program used northern Monterey Bay, California USA as its primary field site.

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The goal of the LOCO program was to understand the properties of coastal thin layers and the interacting physical, chemical, biological and optical processes responsible for their spatial-temporal dynamics. The introduction to this special issue provides an extensive outline of the LOCO program, study design and participants.

The specific objectives of this paper were to (1) detect phytoplankton thin layers and quantify their intensity, thickness, temporal persistence and spatial coherence, (2) quantify their association with physical, chemical or biological structures and processes and (3) quantify their bio-optical characteristics and dynamics. To collect the necessary data, spatial arrays of autonomous moored vertical profilers were deployed during three summers in Monterey Bay. The autonomous profilers contain a suite of optical, physical, biological and chemical sensors, profile from the bottom-up at rates of 2–3 cm s^{-1}, and yield measurements at cm-scale vertical resolution (Sullivan et al., 1999, 2002, 2003, 2005; Donaghay, 2004). In total, the profilers made ~2000 hourly vertical profiles, and provided a unique resource to examine phytoplankton thin layer spatial-temporal dynamics.

The first section of this paper provides an overview of phytoplankton thin layer spatial-temporal distributions within the array site during each of the Monterey Bay field experiments. The second section quantifies thin layer characteristics and distributional statistics. The third section examines how thin layer properties varied over the diel cycle and the mechanisms that controlled these dynamics, and the last section examines thin layer optical properties. It is hoped that this study also provides a general context and background for the other studies in this special issue.

2. Materials and methods

Field experiments occurred during August 2002, August–September 2005 and July 2006 in Monterey Bay, California USA. Monterey Bay is a large, productive, open embayment (>500 square miles) located along the central California coast. The same study site was used during all three years and was located in the northeast corner of Monterey Bay centered on the 20 m isobath ~36.937°N, 121.919°W (approximately 2.5 km from shore). Meteorological data (winds, tides, surface light intensity) were provided by a weather station from the nearby Moss Landing Marine Laboratory (http://weathernew.mlml.calstate.edu/) and two research vessels that participated in the 2005 and 2006 experiments, the *R/V New Horizon* and the *R/V Thomas G. Thompson*, respectively.

Fine-scale optical and hydrographic measurements were made using Ocean Response Coastal Analysis System (ORCAS) autonomous moored vertical profilers (Sullivan et al., 1999, 2002, 2003, 2005; Donaghay, 2004). The ORCAS moored profiler is a totally self-contained autonomous vertical profiling system consisting of an underwater winch with associated wire attached to a bottom anchor, a data logger and profiler controller with embedded GPS and spread spectrum radio, a suite of oceanographic sensors, battery packs, syntactic foam floats to provide positive buoyancy, and a polycarbonate shield to reduce drag and protect the sensors. The ORCAS profiler collects data from the bottom-up by slowly reeling out winch wire (~2–3 cm s^{-1} ascent rate) until it reaches the surface. Once at the surface, it transmits data and returns to the bottom by rapidly reeling in the winch wire. The slow ascent rate of the ORCAS profilers and relatively high sampling rate of the onboard instruments (6 Hz or greater) yields vertical profiles at cm-scale vertical resolution. During each deployment, the ORCAS profilers were set to continuously profile once every hour. Service intervals for the profilers (e.g. cleaning optics, fresh battery packs) occurred approximately every 4–5 days. For ~1 week in 2002, a single ORCAS profiler was deployed at the study site. For ~3 weeks in 2005, three ORCAS profilers were deployed at the study site in a triangular spatial array separated by a maximum distance of 2 km. For ~2 weeks in 2006, three ORCAS profilers were deployed in a smaller, more linear spatial array with two of the profilers within 300 m of each other and the third about 1 km offshore of the others.

Routinely, two different ship-based profilers were deployed (using the *R/V Shana Rae*) around the ORCAS profilers in "slow-drop" mode (Donaghay et al., 1992; Cowles et al., 1998; Hanson and Donaghay, 1998), where the profiler buoyancy is set only a few pounds negative (relative to seawater) and slowly hand lowered on a cable independent from the ship's normal winch controlled hydro-wire and associated ship roll. Slow-drop profiling can produce high-vertical resolution (cm scale) profiles that are necessary for adequate measurement definition and sampling of thin layers. One of the ship-deployed profilers was a high-resolution optical profiler (described below) and the other was a Seabird (Bellevue, Washington, USA) SBE 32C sub-compact carousel water sampler equipped with 1 and 2 L sample bottles, Seabird SBE 25 CTD and WET-labs (Philomath, Oregon, USA) chlorophyll fluorometer. The protocol for ship-based profiling was to identify the location of thin layers using the optical profiler and then collect water samples inside and outside of the thin layers using subsequent profiling with the SBE 32C micro-rosette. Phytoplankton species identifications were determined by microscopic examination of both preserved and live water samples (for details see Rines et al., this issue).

The instrument payload for the ship-deployed high-resolution optical profiler included a Seabird SBE-25 CTD with dissolved oxygen sensor, two WET-Labs AC-9s, two WET-Labs AC-S, a WET-Labs Eco-VSF, a WET-Labs BB-3, and WET-Labs chlorophyll and CDOM fluorometers. The AC-9 is a 9 wavelength absorption and attenuation meter and the AC-S is a hyper-spectral (80+wavelengths) absorption and attenuation meter. The Eco-VSF is a 3 angle (100°, 125°, and 150°) backscattering sensor at one wavelength (532 nm) and the BB-3 is a three wavelength backscattering sensor (480, 532, 650 nm) at one angle (117°). The ORCAS autonomous profilers normal instrument payload included a Seabird SBE-49 CTD and SBE-43 dissolved oxygen sensor, one WET-Labs AC-9 or AC-S, WET-Labs chlorophyll and CDOM fluorometers, and either a WET-Labs BB-1 or BB-3 backscattering sensor. Two of the ORCAS profilers carried Nortek (Annapolis, Maryland, USA) Vectors for measurements of fine-scale current velocities and small-scale turbulence and one of the ORCAS had a 4 wavelength downwelling irradiance sensor (OCR4, Satlantic, Nova Scotia, Canada).

On the ship-deployed optical profiler, an AC-9 and AC-S were run without pre-filters and measured the absorption (a) and attenuation (c) of all in water constituents except water: a_{pg} and c_{pg}. The other AC-9 and AC-S on the profiler had 0.2 μm pre-filters on their water intakes to measure the dissolved fraction of absorption (a_g). By subtraction, this allowed the particulate absorption (a_p) and attenuation (c_p) coefficients to be obtained (e.g. $a_{pg}-a_g=a_p$). The AC-9 or AC-S on the ORCAS profilers were run without pre-filters and measured a_{pg} and c_{pg}. All AC devices were calibrated before, during and after each cruise. The methods used for AC-9 calibration and corrections for temperature and salinity are described in Twardowski et al. (1999) and similar methods for the AC-S are described in Sullivan et al. (2006). Scattering errors in the AC-9 or AC-S absorption channels were corrected using the proportional correction algorithm of Zaneveld et al. (1994). The scattering coefficient (b) was obtained by subtracting the scattering corrected absorption coefficients from attenuation coefficients. The hyperbolic slope of the attenuation