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Acoustic scattering in the coastal ocean at Monterey Bay, CA, USA: Fine-scale vertical structures

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ABSTRACT

Fine-structure (centimeters to meters) in vertical profiles of acoustic volume scattering strength is a common and ecologically significant characteristic of the coastal marine water column. The processes that create these structures modify the availability of food and exposure to predation for secondary producers at and below spatial and temporal scales that characterize their daily ambits. Thin acoustic scattering layers may persist for weeks at a particular coastal location, but they may also appear and disappear in only a few hours. These layers are usually evidence of mesozooplankton and micronekton having aggregated at peaks, gradients, or boundaries in the vertical distribution of various water column properties that characterize a marine ecosystem. The behaviors of both predators and prey are implicated in the generation of complex, time-dependent patterns of fine-structure. Specifically, diel vertical migration to layers of prey, isolumes, isotherms, isopycnals, or chemoclines can be responsible for the nighttime formation of thin acoustic layers. Physical processes such as horizontal shear, internal waves, water mass intrusions, tidal forcing, wind mixing of the upper water column, and horizontal advection modify acoustic scattering patterns by changing the vertical distributions of organisms that scatter sound.

1. Introduction

The coastal ocean is home to an impressive collection of living organisms, both in numerical abundance and in diversity. Of all the ocean areas, it is the most easily accessible for scientific study as well as for exploitation. Yet, most of the coastal marine water column is far less well described physically or biologically than is almost any terrestrial ecosystem, including grasslands and forests. Because it is difficult and expensive to observe, we still know remarkably little about the structure of the upper ocean as a habitat or of the ongoing processes that enable marine organisms to make it their home. The impression of mixing and turbulence that we often see from the beach when looking offshore, or at sea from the deck of a ship, would seem to suggest that fine-scale inhomogeneities in vertical distributions of biomass in the upper water column could not possibly survive long enough to be ecologically significant. Yet evidence gathered with near-neutrally buoyant profiling instrument platforms, airborne lidar, and bottom-mounted, up-looking acoustical profilers strongly suggests otherwise (Donaghay et al., 1992; Johnson et al., 1995; Cowles and Desiderio, 1993; Cowles et al., 1993, 1998; Hanson and Donaghay, 1998; Holliday et al., 2003; Churnside and Donaghay, 2009).

The use of a new generation of high-resolution sensors has led to the discovery of several kinds of fine-scale vertical distributions in the sea. When a fine-scale structure is characterized by a vertical extent of a few meters or less and it is strongly anisotropic, i.e., its horizontal dimensions are many times its vertical dimension (hundreds of meters to several kilometers), it is often called a "thin layer". While continuity in the horizontal is required for the key property of a thin layer, spatial heterogeneity is allowed. In fact, some mechanisms for generating thin layers require a degree of heterogeneity (i.e., horizontal distributions that contain "holes"-like those found in Swiss cheese). Perceptions of temporal continuity for a thin layer can depend on how we observe it, i.e., with sensors deployed from Eulerian or Lagrangian platforms, and the spatial resolution of our measurements. The limitations of either sampling mode can confound attempts to separate variability in time and space. While there is no theoretical lower limit on the lifetime of a thin layer, it should be detected on several sequential samples, else it be confused with temporal or spatial patchiness or sensor noise.

For the purposes of this contribution, we focus on layers with a biotic composition, e.g., phytoplankton, zooplankton, and micronekton. Our primary concern is with fine-scale structures that

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modify animal behavior and impact the way marine ecosystems function. Such layers can be created when an organism finds its preferred conditions in some other thin layer, but many biotic thin layers are a response to gradients at boundaries such as a the sea surface, the seabed, another layer, a thermocline, pycnocline, nutricline, chemocline, or an isolume. Other living organisms that have been found in thin layers include bacteria, protists, and fish. Some of the biotic thin layer aggregations may be passive, forming when buoyancy or sinking to particular density surfaces occurs. Detritus and fine cohesive flocs including marine snow have also been found aggregated in thin layers. Other mechanisms are likely active, forming layers when organisms aggregate for the purpose of feeding, hiding, or reproducing. Avoidance behaviors can also create thin layers when vertically migrating organisms prefer to stop at a depth beyond which conditions are threatening or in some other way non-optimal. Aggregation also results when vertically migrating organisms decide that further expenditure of the effort they are spending in swimming would not obtain a better environment for hiding or feeding.

The processes that lead to the formation of thin layers are among several phenomena that appear to concentrate prey organisms in the sea. Without the concentration of prey biomass, survival and recruitment would be much more tenuous, if even possible in the marine environment. The evidence suggests that thin layers may rival biological patchiness and the intensity of the seasonal chlorophyll maximum (Cassie, 1963; Lasker, 1975; Mullin and Brooks, 1976) as concentrating mechanisms for food particles. The response of zooplankton to the presence of fine-structure in vertical distributions of phytoplankton is well documented (Alldredge et al., 2002; Cowles et al., 1993, 1998; Donaghay et al., 1992; Donaghay and Osborn, 1997; Holliday et al., 2003; Johnson et al., 1995; Nielsen et al., 1990; McManus et al., 2003; Holliday and Stanton, 2005; Cheriton et al., 2007; Woodson et al., 2007; Ryan et al., 2008). Often the response is to aggregate on the possible food resource (Johnson et al., 1995), but avoidance has also been observed (Holliday et al., 2003; Nielsen et al., 1990; Fiedler, 1982).

This contribution will mostly focus on thin acoustic scattering layers. These are horizontally extended features characterized by levels of volume scattering that are statistically distinguishable from lower levels of scattering at greater and lesser depths. At relatively low acoustic frequencies (e.g., <100 kHz), most acoustic scattering layers are known to be the result of living organisms aggregating in horizontally stratified layers, e.g., mesopelagic fish or krill in the ocean's deep scattering layer (Hersey and Backus, 1962; Farquhar, 1970). Thin layers of shelled pteropods have also been observed passively aggregating on a pycnocline under the Arctic ice (Hunkins, 1965; Hansen and Dunbar, 1970). For acoustic frequencies >100 kHz, mesozooplankton and micronekton are most commonly the organisms found in thin acoustic scattering layers (Greenblatt, 1981). Large protists (i.e., *Noctiluca scintillans*) have also been observed forming such layers during feeding migrations in East Sound, WA.

Since thin layers are a relatively new discovery, the processes involved in their formation and their utilization by different trophic assemblages are not completely known. Donaghay and Osborn (1997) provided a theoretical summary of several of the more important ways in which thin layers of phytoplankton can be formed, maintained, and eventually destroyed. Many thin acoustic scattering layers appear to be created by the aggregation of some specific organism or community of organisms at a boundary of a physical or chemical feature of the water column, e.g., the surface or bottom, the thermocline, a halocline, a nutricline, an isolume, or a layer of prey organisms. Thin acoustic scattering layers often vary in thickness and depth as the plankton that are scattering the sound actively respond to their physical or food environment. Both active (behavioral) and passive (sinking or rising) aggregation mechanisms can lead to the formation of these fine-scale sound scattering structures. Under some circumstances, purely physical processes such as shear can turn patches into thin acoustic scattering layers. At times, under the influence of various ocean processes and organism behaviors, relatively diffuse layers with thicknesses of several meters will evolve to become more densely populated thin layers less than a meter thick. Some evolve further until they are only tens of cm in vertical extent.

In this contribution, data are presented to illustrate some of the more common fine-scale acoustical scattering patterns that are found in the coastal zone.

2. Monterey Bay study site

Monterey Bay is a bight in the north central Pacific coastline of California (Fig. 1). The north–south axis, which spans the mouth of the bay, is about 37 km and the east–west dimension measures about 19 km. The continental shelf is only a few kilometers wide along most of this coast. Water mass characteristics and large-scale circulation in Monterey Bay are largely controlled by the slow, southward-flowing California Current modified by episodic inputs of nutrients and colder water from wind-driven upwelling associated with several headlands between Santa Cruz and San Francisco. As wind stresses vary, episodic upwelling/relaxation events occur, forming a counter-clockwise surface gyre that impacts local water circulation in the northeastern part of the bay where our site-specific thin layers work was conducted (Storlazzi et al., 2003). A very limited freshwater input is occasionally introduced by runoff from the Elkhorn Slough at Moss Landing, about halfway between the city of Santa Cruz at the north end of the bay and the city of Monterey at the southern end. The head of a large submarine canyon that cuts across most of the narrow shelf bisects the bay along its east–west axis and is sometimes the source of deep water that is pumped by wind and tides up onto the narrow shelf. Diurnal and semi-diurnal tidal flows also contribute to variability in the advection of water at different depths at fixed locations. Various combinations of these processes lead to the formation of very complex, dynamic water column profiles. Both temperature and salinity intrusions are common phenomena. Internal tides are also present in the bay and packets of internal waves frequently modulate the depth of the pycnocline as they propagate across the bay in different directions, occasionally breaking as they interact with the shallow seabed. The reader is directed to Storlazzi et al. (2003) and its citations for an excellent discussion of the physical oceanography of Monterey Bay. Additionally, Breaker and Broenkow (1994) provide a comprehensive conceptual model of the numerous driving forces that interact and contribute to complex 4-D patterns of circulation in the bay.

2.1. Array location and distribution of sensors

For the research described in this contribution, underwater instrumentation was deployed on the narrow coastal shelf a few kilometers south southwest of the city of Aptos, CA (Fig. 1, Table 1). Multiple instruments were placed on the seabed within ca. 50 m of each of the labeled locations. Shore stations were established at several base stations on a steep bluff bordering the beach, each of which was chosen to provide line-of-sight views to the instrumented study area for two-way telemetry. Small-boat support was based at the nearby harbor at Santa Cruz.