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Spatial and Temporal Variability of Zooplankton Thin Layers: The Effects of Composition and Orientation on Acoustic Detection of Layers

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LONG-TERM GOALS

Our primary long-term objective is to better understand the physical and biological mechanisms of formation and maintenance of thin layers of zooplankton. Because zooplankton can be strong sound scatterers, acoustic instruments are effective at detecting and describing zooplankton thin layers. Using a combination of instruments (acoustics, image-forming optics, ADCP's, CTD's, and bio-optical sensors) and sampling platforms (a fleet of gliders and a profiling package), we plan to determine the temporal and spatial scales of acoustic backscatter from zooplankton aggregations, the taxonomic and size composition of the zooplankton in such layers, and the associations of zooplankton thin layers with physical parameters. To do this, it is imperative that we understand the factors influencing the frequency dependent backscatter from the organisms. In particular, the orientations of the plankton relative to the acoustic source can have significant effects on the resultant backscatter. Hence, a

secondary objective is to improve our understanding of *in-situ* acoustic backscatter from zooplankton so that moving platforms that change orientation, such as gliders, can provide accurate acoustic survey data on the distribution and composition of scattering features.

Questions to be addressed by the proposed research:

1. What is the temporal and horizontal spatial variability of zooplankton scattering layers and the spatially coincident physical and biological parameters associated with these layers?
2. What is the time-scale of zooplankton layer generation (aggregation) and destruction (dispersal) and how do these correlate with physical characteristics and phytoplankton thin layer formation?
3. What are the composition of zooplankton scattering layers and the *in-situ* orientation of the organisms and how does this affect the spectrum and magnitude of measured backscatter?
4. How do physical and biological mechanisms together form and maintain scattering layers?

APPROACH

To address the first two question listed above, we used acoustic backscatter and physical data collected in the summer of 2005 and 2006 from a fleet of gliders in Monterey Bay (part of the LOCO program). This data will be analyzed to describe the temporal and spatial variability of zooplankton scattering layers and the associated physical and biological parameters and the time-scales of zooplankton layer formation and destruction.

We are using data collected in July 2006 to address zooplankton composition and orientation in the thin layers. These data will allow us to determine some of the taxa specific and behavioral responses that are important to zooplankton thin layer formation and persistence and to address the question of how orientation of the scatterers affects the backscatter intensity. In addition to the glider surveys, we conducted field work consisting of a detailed investigation of the taxonomic composition of the scattering layers at different depths using a shipboard CTD profiling package equipped with a 6-frequency TAPS (Tracor Acoustic Profiling System) and the ZOOVIS-SC (the self-contained Zooplantkon visualization System) imaging system in conjunction with a vertical net samples and discrete pump samples (Figure 1). These instruments provided data on the taxonomic composition of the scattering layers and the *in-situ* orientation of the zooplankton, and allow us to resolve the spectral character and magnitude of the acoustic backscatter.

Figure 1. ZOOIS-SC, the TAPS, and the pump sampler intake mounted on the R/V Thompson's CTD frame.

WORK COMPLETED

Field Work

The July 2006 field work has been completed. There were 15 ZOOVIS/CTD/TAPS casts completed with complementary net and pump sampling. Six of these casts were day/night pairs and two of these pairs were part of 24 hour sampling regimes as part of the LOCO program. Over 150,000 images were collected with ZOOVIS-SC.

The glider operations were successful and are described in more detail by D. Fratantoni (WHOI) in his annual report. One glider successfully operated continuously for 10 days, completing approximately 2400 vertical profiles and covering 210 km. The glider occupied a section line with one end point near the mooring array (near the 20 m isobath) and extending to the Southwest across the 75 m isobath. Profiling operations were conducted near the glider on several occasions to allow for comparison of the instrument data on both platforms.

The glider was outfitted with the following sensors: CTD, Wetlabs BB2F (chlorophyll fluorescence and optical backscatter at XX-red and XXX-blue wavelengths), and a Nortek 1 mHz ADCP.

Analysis of Glider ADCP data

The ADCP backscatter data from the gliders deployed in 2005 and 2006 has been corrected for transmission loss and converted into volume backscatter (S_V). The corrected data were then interpolated over space and time using the geostatistical interpolation method of kriging.

A calibration of the ADCP used to collect data in 2005 and 2006 was conducted by A. Lavery and M. Sutor using a standard target in a tank facility at WHOI. The results of that calibration are still being analyzed in consultation with the ADCP manufacturer, Nortek. This is the first known attempt to calibrate an ADCP using a standard target and the results of this calibration may prove useful for other ADCP users who would like to convert backscatter data from relative magnitudes into absolute magnitudes.

In additional to this calibration, M. Sutor and P. Wiebe conducted a calibration of the Nortek ADCP, and the TAPS at the WHOI dock with standard targets. This calibration was completed in early October M. Sutor and A. Lavery are analyzing the results.

Analysis of ZOOVIS data

The image data from ZOOVIS have been merged with the data from the roll and pitch sensor and the CTD so that there is a corresponding value of roll, pitch, pressure, temperature, salinity, and fluorescence to accompany each image from the camera system. Qualitative analysis of all of the ZOOVIS casts has been completed and detailed manual sorting of the images is ongoing..

Analysis of Pump and Net Samples

An undergraduate student who participated in the cruise and is completing a UROP (Undergraduate Research Opportunities) project on this data, conducted silhouette analysis of the net and pump samples. The student continued that work as a full-time research technician. Samples are analyzed based on a priority list of completing samples 1) collected in close spatial and temporal proximity to the glider, 2) those from paired day-night pump collections, 3) and additional samples that add to the spatial information on zooplankton composition and abundance over the course of the cruise.

Phytoplankton and microzooplankton samples that were collected concurrently with the mesozooplantkon samples from the pump system are currently being analyzed by M. Sutor using a FlowCAM (purchased with a DURIP grant awarded to M. Sutor). These data will be used to interpret the optical fluorescence and backscatter data collected with the glider and on slow-drop profiles conducted by T. Cowles on the R/V Thompson.

RESULTS

Physical Regimes

The mesoscale physical environment of Monterey Bay is dominated by regional wind forcing. Northwesterly winds drive surface waters offshore resulting in upwelling of cold, salty, nutrient-rich water along the coast of central California. While upwelling is concentrated in the vicinity of headlands, such as Pt. Ano Nuevo to the north of Monterey Bay, and Pt. Sur to the south, the upwelled water spreads widely and contributes significantly to the surface properties within the Bay. Occasional relaxations and/or reversals in the upwelling-favorable winds can result in marked changes in both the circulation and stratification within Monterey Bay.

Figure 2 summarizes wind observations during the study period. Moderate upwelling-favorable northwesterly winds of 10-12 m/s were in force until a relaxation event began on July 17. Wind speeds diminished dramatically to less than 5 m/s, and wind direction reversed becoming southeasterly. Upwelling favorable winds began again on July 22.

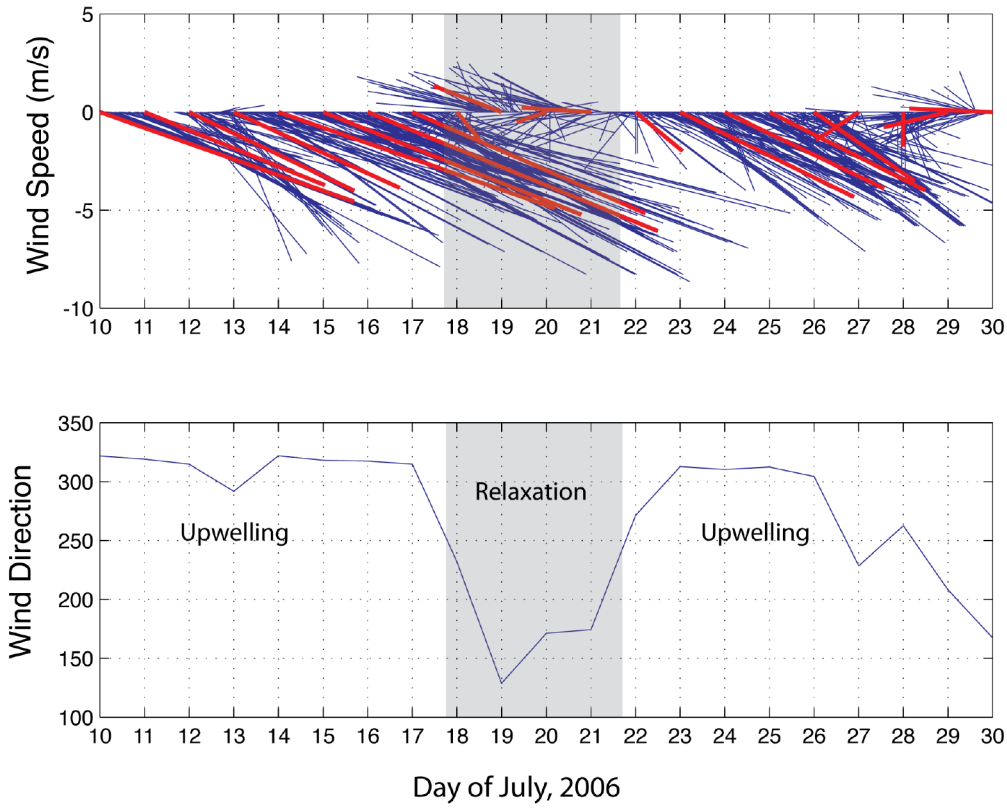

Figure 2. Wind speed and direction taken from the M1 mooring (MBARI) in Monterey Bay from 10-30 July. The period of relaxation in the upwelling favorable winds is shaded.

Physical, optical, and acoustic measurements collected by the glider in the northeastern sector of Monterey Bay do not directly reflect the upwelling-relaxation oscillation evident in the wind record. Rather, these measurements suggest a more gradual, secular change from a relatively cool and unstratified initial state to a warmer and more stable configuration near the end of the record. Figure 3 summarizes the evolving vertical structure of several parameters during the 10-day occupation of the cross-shelf transect. A gradual intensification and deepening of the thermocline is evident in the temperature record as surface waters warm by several degrees.

Biological parameters also show changes in vertical structure and intensity similar to changes in the physical structure. There is an increase in the intensity and deepening of the diel acoustic backscatter signal. There are also changes in the bio-optical signal with a decrease in the intensity of the fluorescence signal during the period of relaxation of upwelling-favorable winds (18-22 July) and a decrease and deepening of the blue and red optical backscatter signal after 23 July, during the second period of upwelling-favorable winds.

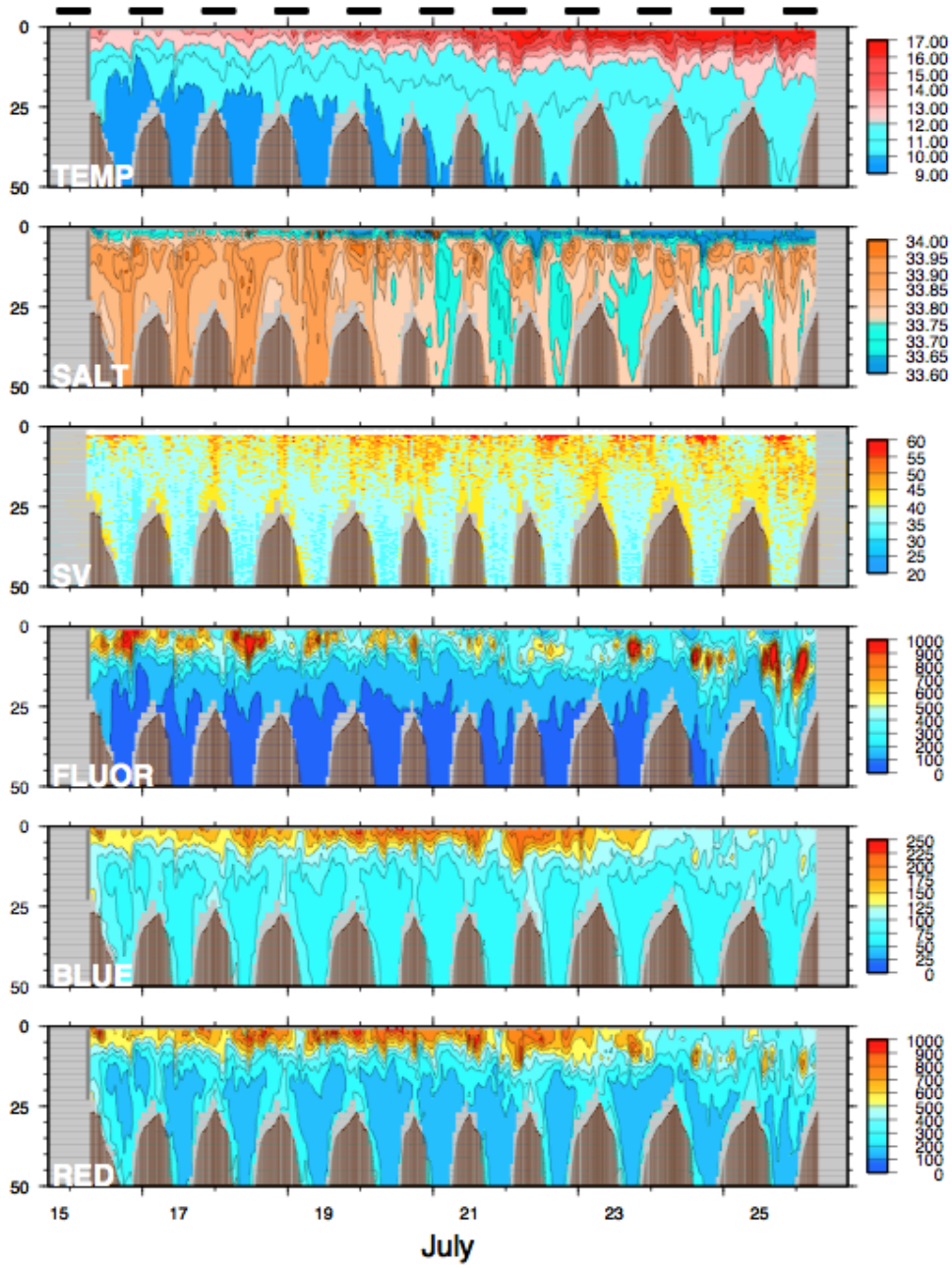

Figure 3. Time series of temperature, salinity, acoustic backscatter, chlorophyll fluorescence, and blue and red optical backscatter from the glider.

ADCP Backscatter Data

The backscatter data from the ADCP mounted on a glider shows that there was a diel signal in the backscatter data with a layer of increased backscatter forming in the upper water column at night, but disappearing during the day (Figure 4). This pattern was seen both in 2005 and 2006. The increase in

backscatter intensity in the upper water column at night is not a function of location as it was observed in both the offshore (Figure 5) and inshore (Figure 6) portions of the glider track. What may be an aggregation of zooplankton moving up in the water column at night to form the layer and descending at dawn as the layer dispersed was also observed. The layer was located above 3 m, was 1-3 m thick and had a spatial gradient of 5 dB (more than a two-fold increase on a linear scale) calculated over 1 m vertical bins. The layer appeared to form rapidly (in less than 1 hour), though this cannot be definitively quantified as the glider data is spatially aliased. These data demonstrate the ability of glider mounted acoustic systems to resolve sharp spatial and temporal gradients in backscatter and to provide a long-term, continuous data set of acoustic backscatter measurements.

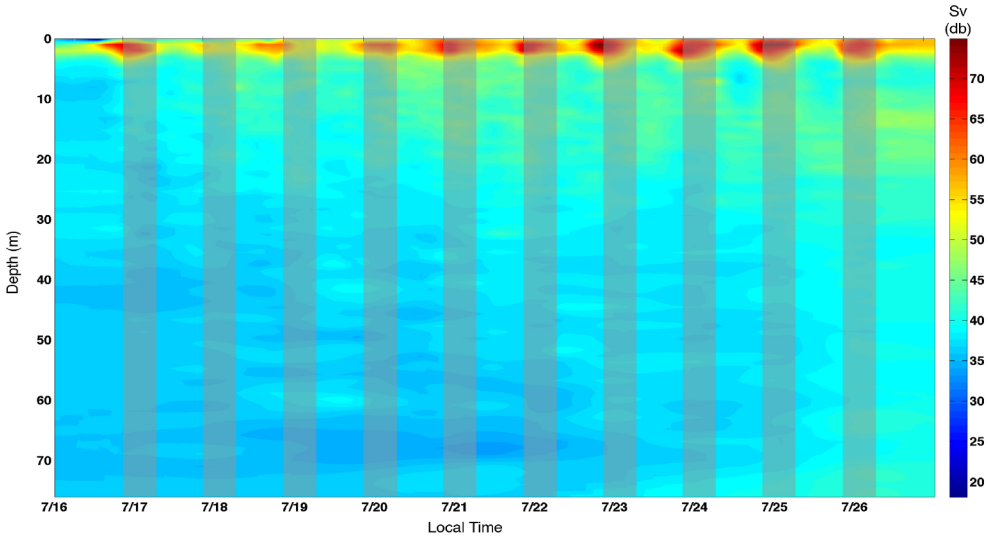

Figure 4. Interpolated backscatter data from the glider mounted ADCP in Monterey Bay in July 2006. The shaded regions mark the time period between sunset and sunrise.

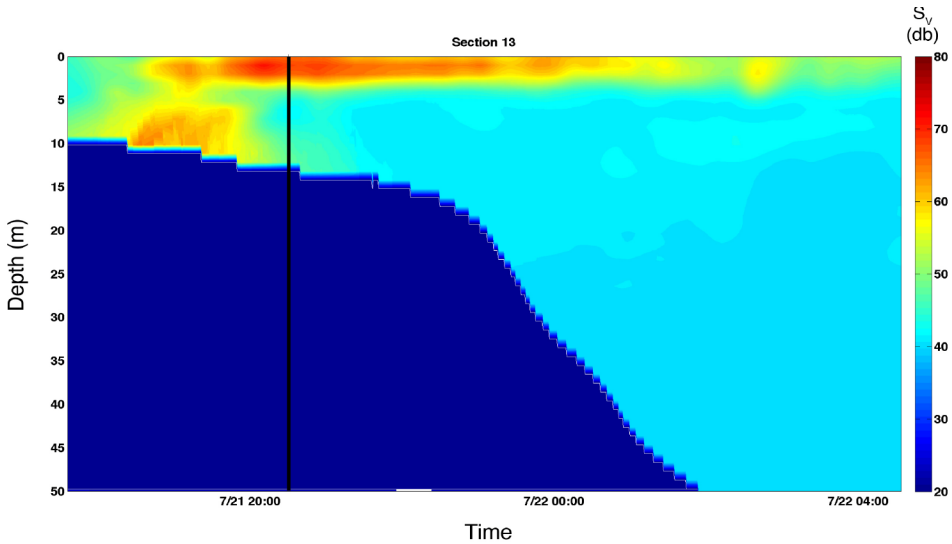

Figure 5. One inshore-offshore section (13) of interpolated backscatter data from the glider mounted ADCP in Monterey Bay in July 2006. The black line marks sunset.

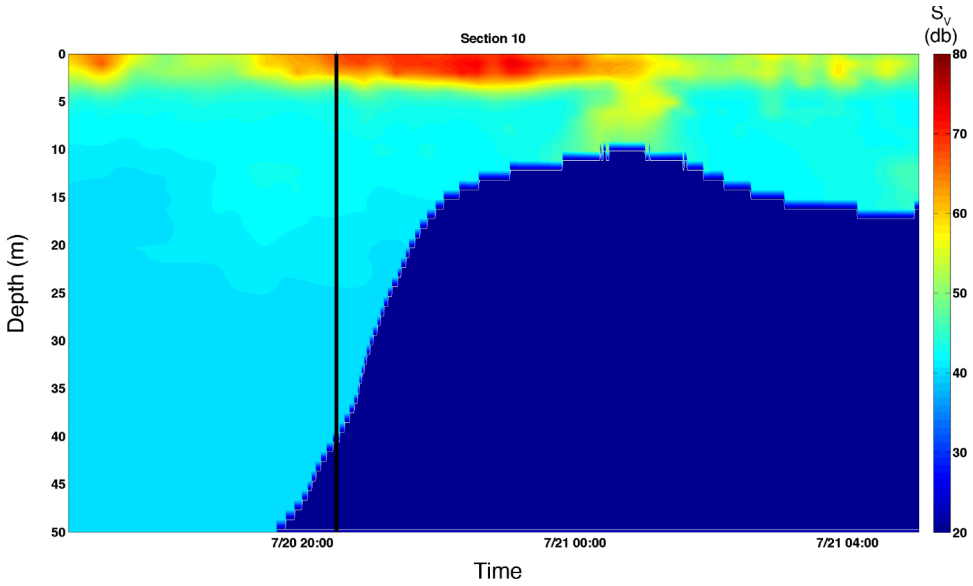

Figure 6. One offshore-inshore section (10) of interpolated backscatter data from the glider mounted ADCP in Monterey Bay in July 2006. The black line marks sunset.

ZOOVIS Data

Our initial analysis of the image data shows that ZOOVIS-SC collected numerous, clear, images of zooplankton. We saw many images that contained multiple copepods and delicate gelatinous taxa such as larvaceans and medusae (Figures 7 and 8). Images of small targets including ciliates (Figure 9, panel A), dinoflagellates (Figure 9, panel B), radiolarians (Figure 9, panel C), and diatom chains (Figure 10) were also collected. The system clearly resolved small individuals (copepods less than 1 mm in length) and provided striking images of marine snow and other particles in the water column. Combined with the CTD data and information from the camera's roll and pitch sensor, we will be able to resolve the vertical distribution of zooplankton, their *in-situ* orientation, and in many cases nearest neighbor distances. Qualitative analysis of the data has shown that copepods are oriented predominantly head-up or head-down, and are rarely horizontal in the water column. Additionally, orientation does not appear to be random as images with multiple copepods show that all of the individuals are oriented in the same direction (Figure 6).

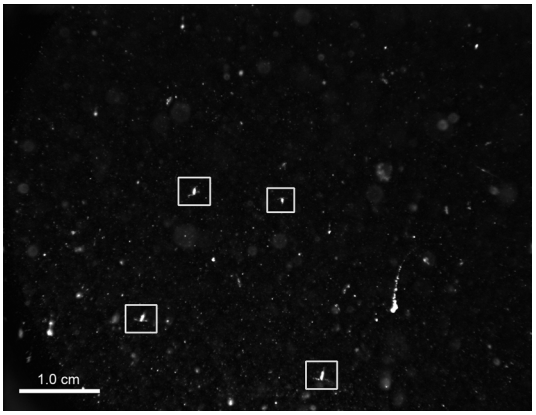

Figure 7. Image of multiple copepods taken with ZOOVIS-SC in Monterey Bay in July 2006.

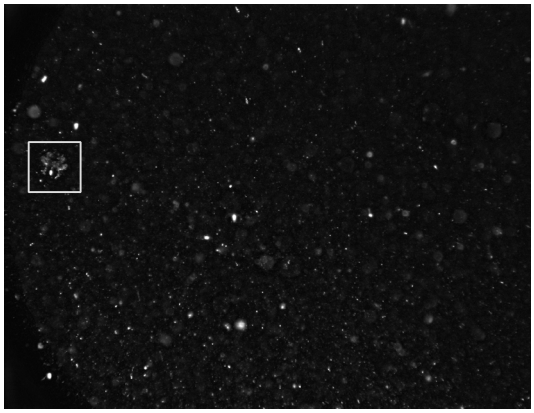

Figure 8. Image of larvacean with intact mucous house taken with ZOOVIS-SC in Montery Bay, July 2006.

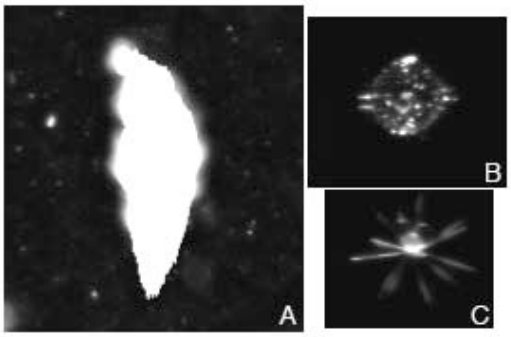

Figure 9. Image of a ciliate (Laboea, panel A), dinoflagellate (Protoperidinium, panel B), and radiolarian taken with ZOOVIS-SC in Monterey Bay in July 2006.

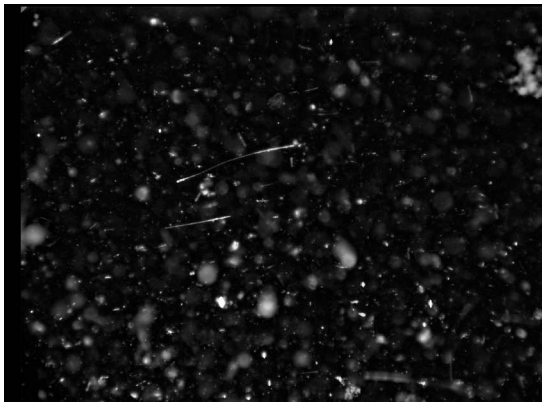

Figure 10. Image of multiple diatom chains taken with ZOOVIS-SC in Monterey Bay in July 2006.

Two nighttime downcasts were manually sorted to determine the vertical distribution of different zooplankton taxa and the vertical distribution of copepods with different orientations. The data were binned into 1 m depth intervals. The downcast on July 26 (Figure 11) had more targets in the deeper portion of the water column, between 12 and 18 m, while the cast on July 27 (Figure 11) had a more uniform distribution throughout the water column.

There was no vertical pattern in copepod orientation in either cast. On July 26, the majority of copepods were in the horizontal orientation (69.8%) (Figure 11, Table 1) while on July 27 the majority were in the vertical orientation (57.25%) (Figure 12, Table 1). There were slightly more copepods in the head-up orientation than the head-down orientation in both casts.

Table 1. Copepod orientation for two night casts on July 26 and 27, 2006.

	July 26, 2006		July 27, 2006	
	Actual No.	Percent of Total	Actual No.	Percent of Total
Head Up	48	13.6%	353	23.2%
Head Down	34	9.6%	341	22.4%
Unknown Vertical	25	7.1%	176	11.6%
Total Vertical	107	30.2%	870	57.2%
Horizontal	247	69.8%	650	42.8%

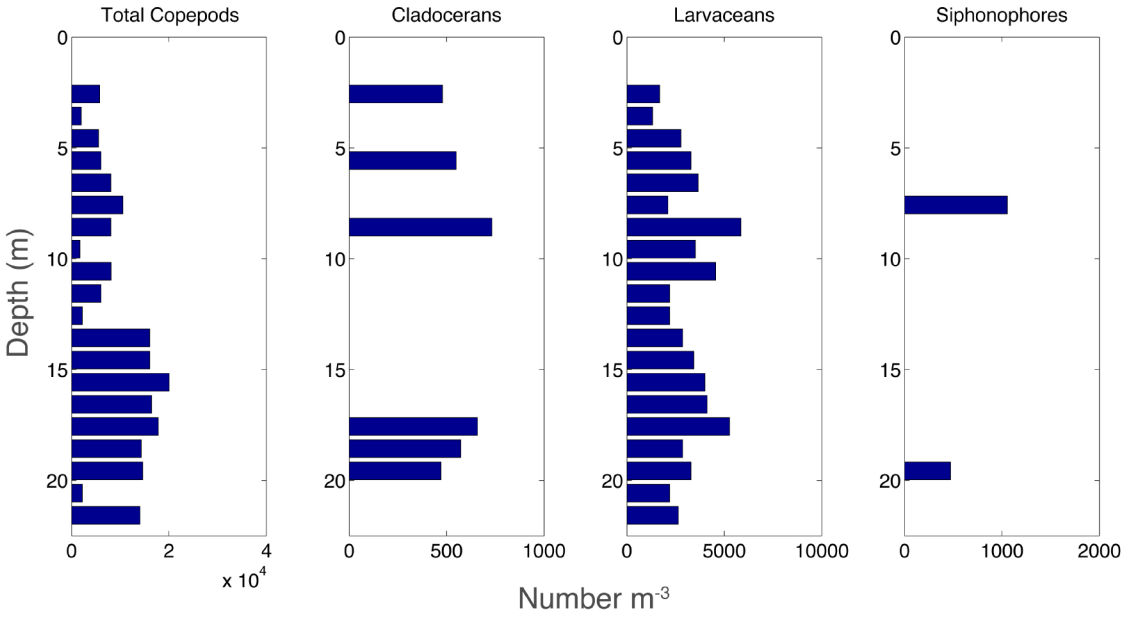

Figure 11. Vertical distribution of dominant taxa as imaged by ZOOVIS-SC on the night of July 26, 2006.

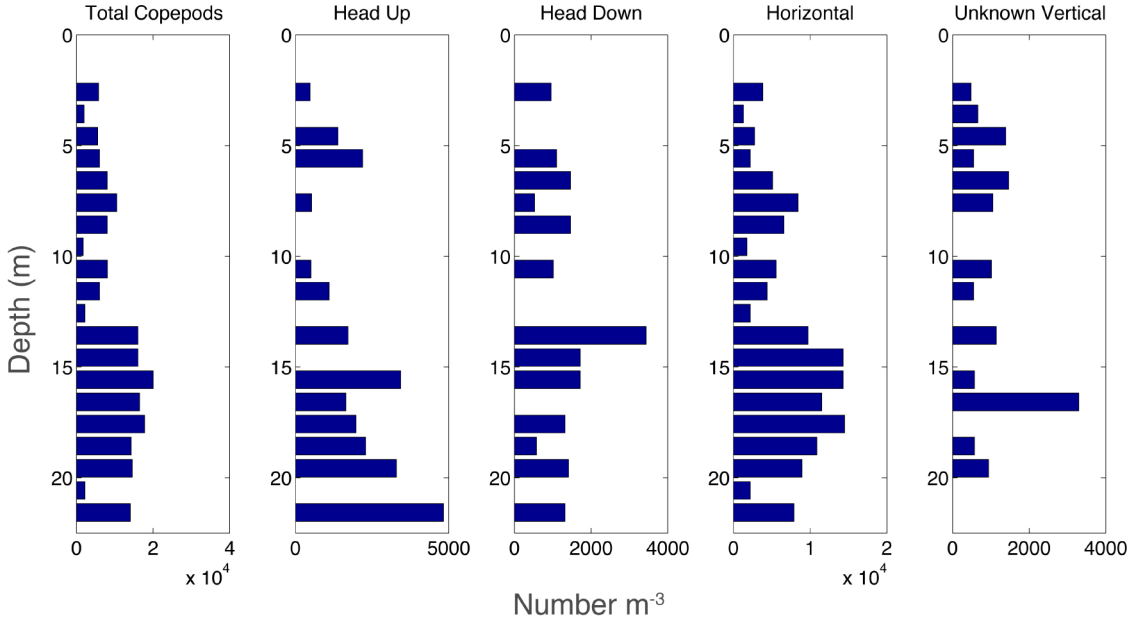

Figure 12. Vertical distribution of copepods in different orientations as imaged by ZOOVIS-SC on the night of July 26, 2006.

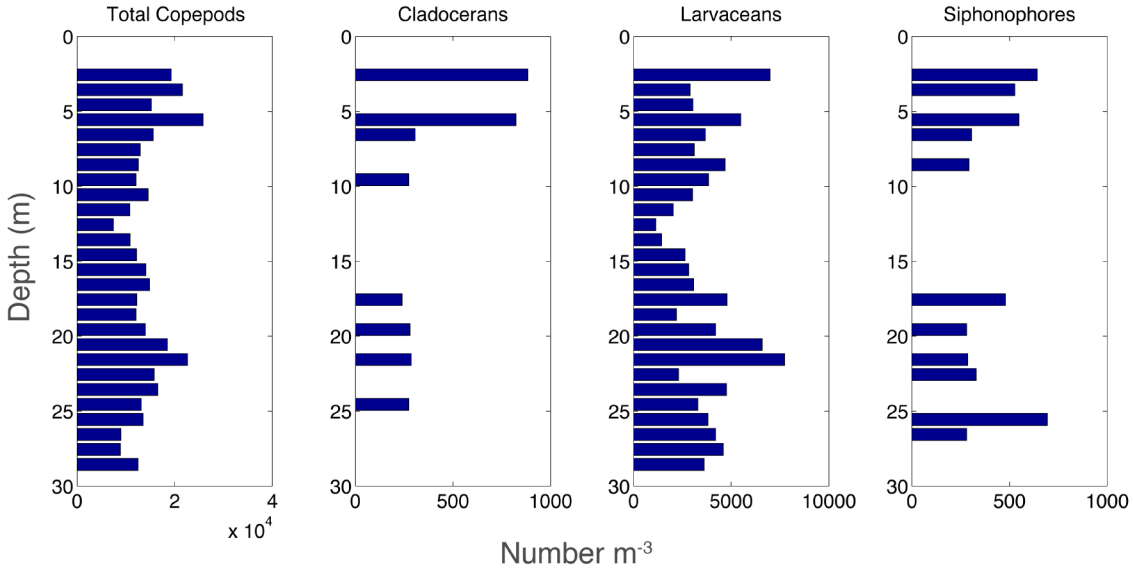

Figure 13. Vertical distribution of dominant taxa as imaged by ZOOVIS-SC on the night of July 27, 2006.

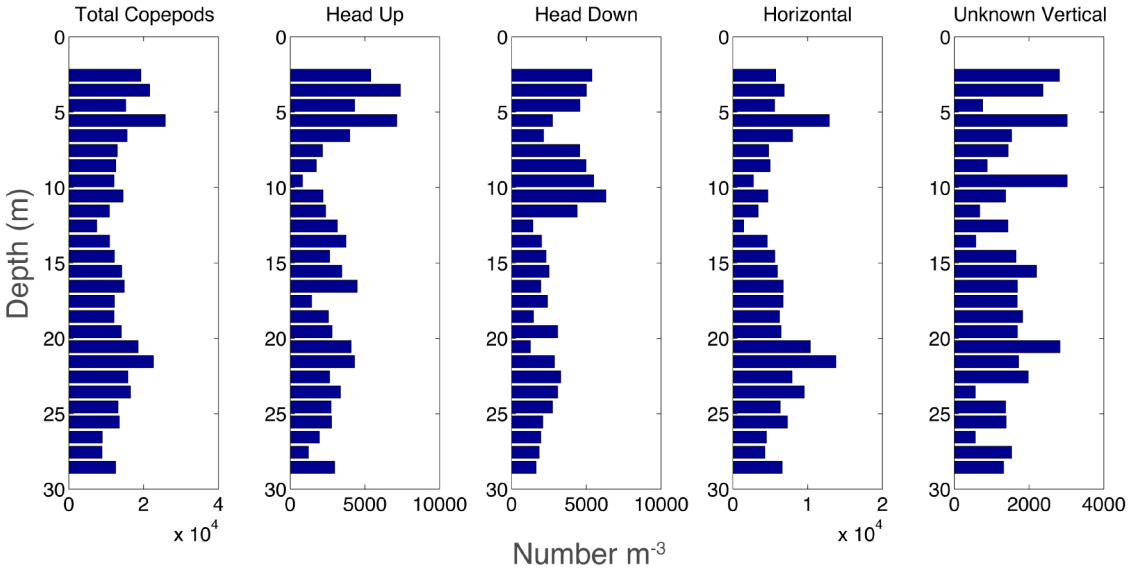

Figure 14. Vertical distribution of copepods in different orientations as imaged by ZOOVIS-SC on the night of July 27, 2006.

The taxonomic composition, abundance, and orientation data can be combined with average length data from the pump and net samples and used to compute predicted acoustic backscatter which can then be compared with the pattern of backscatter from the ADCP and the absolute magnitude of backscatter from the TAPS.

Net and Pump Data

Silhouette analysis of the net and pump samples is ongoing. Priority has been given to samples that can be used to groundtruth the acoustic data from the gliders and the ZOOVIS image data. An example of the type of data that results from silhouette analysis is shown in Figure 15. These plots show the abundance of different zooplankton taxa and the mean length of individuals in each taxonomic group for seven integrated water column pump samples. Small copepods (less than 1 mm) numerically dominate the zooplankton community in each sample, but the overall abundances, sizes, and proportion of less abundant taxa varies a great deal between samples.

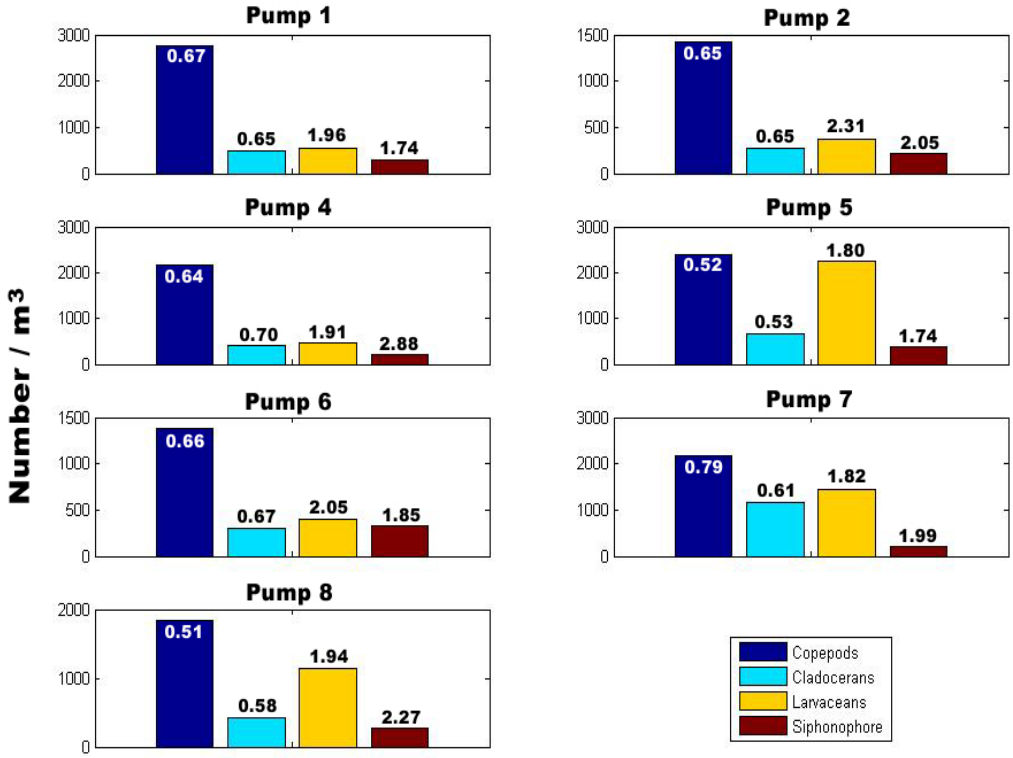

Figure 15. Abundance estimates derived from the silhouette analysis of the pump samples. The average length for each taxa is noted at the top of each bar. Lengths are in millimeters.

In both downcasts, it was evident that ZOOVIS-SC imaged a higher abundance of zooplankton targets than the pump system collected (Figures 16 and 17, Table 2). ZOOVIS-C imaged more targets of abundant taxa (copepods and larvaceans), whereas the pump collected more rare taxa (cladocerans and siphonophores). These differences could be due to the volume sampled. ZOOVIS-SC imaged approximately 27 L per downcast while the pump filtered approximates 2000 L.

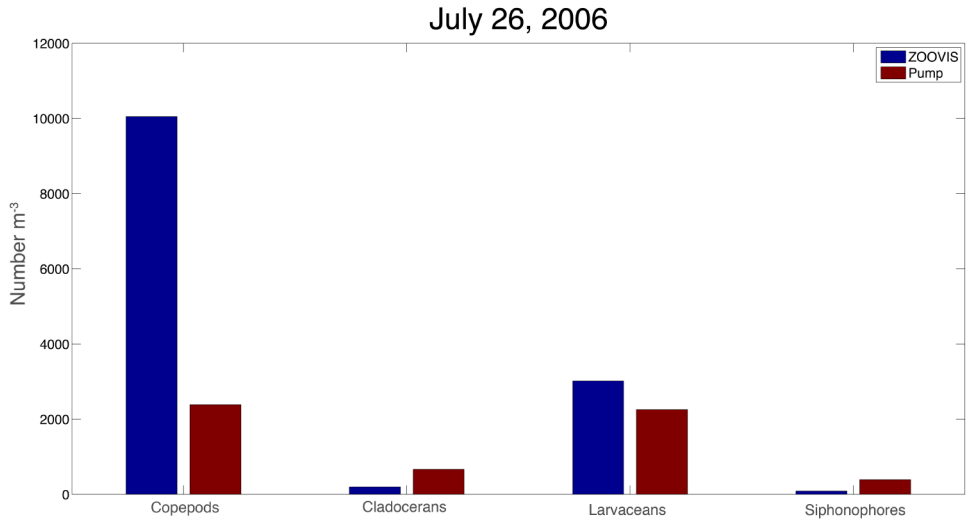

Figure 16. Water column integrated density estimates of dominant taxa from ZOOVIS-SC and the pump on July 26, 2006.

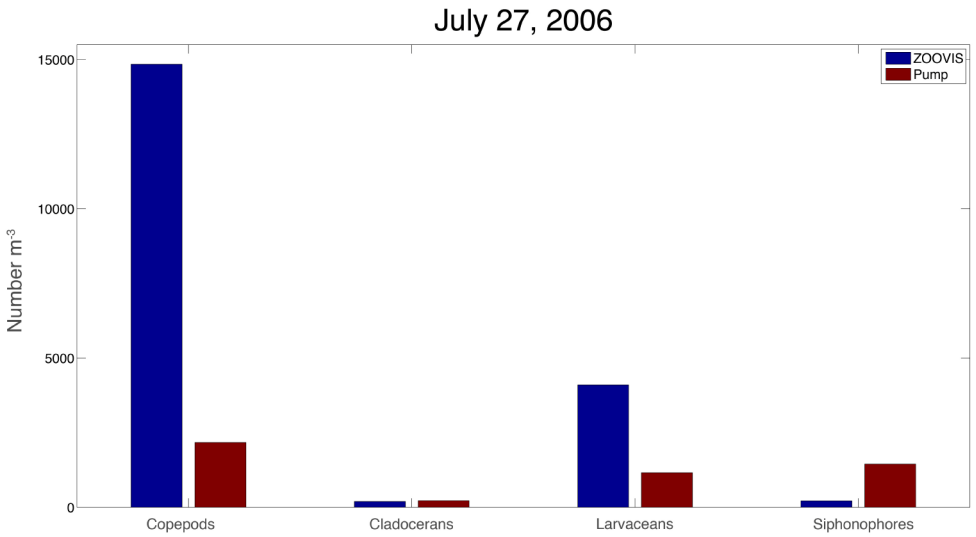

Figure 17. Water column integrated density estimates of dominant taxa from ZOOVIS-SC and the pump on July 27, 2006.

Table 2. Density estimates of dominant taxa from ZOOVIS-SC and corresponding multiple of pump-derived estimates.

	July 26, 2006		July 27, 2006	
	Density (m^{-3})	Magnitude	Density (m^{-3})	Magnitude
Total Copepods	10005	4.2x	14848	6.8x
Cladocerans	199	0.3x	195	0.88x
Larvaceans	3016	1.3x	4102	3.5x
Siphonophores	85	0.2x	215	0.14x

IMPACT/APPLICATIONS

The image data from ZOOVIS-SC can be used to determine the composition of observed scattering layers, improve upon scattering models used to interpret acoustic signal, and help us to make some inferences about behavioral mechanisms of zooplankton aggregation. Utilizing a suite of sensors (acoustics, image-forming optics, CTD, nets and pumps) and two different platforms (ship-board profiler and gliders) will greatly expand our understanding of the dynamics of zooplankton layers and how we interpret acoustic backscatter signal from layers.

RELATED PROJECTS

This work is directly related to several past and current ONR projects. Project N00014-98-1-0563 "Development of a Vertically Profiling, High-Resolution, Digital Still Camera System" awarded to Mark Benfield (LSU) provided the initial funding for the development of the ZOOVIS imaging system that was used in this work. The current project is also tightly linked to all of the funded LOCO projects and is most closely linked to "The physical context for thin layers in the coastal ocean" (N00014-04-1-0250), awarded to Dave Fratantoni (WHOI) and "Finescale planktonic vertical structure: horizontal extent and the controlling physical processes" (N00014-04-10277), awarded to Tim Cowles (COAS-OSU).

This work is also related to ongoing research on the interpretation of acoustic scattering in the coastal ocean by A. Lavery (WHOI) in the current ONR project "High-frequency broadband acoustic scattering from temperature and salinity microstructure: From non-linear waves to estuarine plumes" (N00014-02-0359).