

High-Resolution Measurements of Coastal Bioluminescence

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LONG-TERM GOALS

Integrated field sampling programs are essential to accurately depict coastal biological oceanography. The distribution of bioluminescence – the production of light by living organisms – is of particular interest as a potential indicator of the presence of zooplankton. Our long-term goal is to understand and predict the distribution of marine bioluminescence through time, using the most advanced technology available, and coordinating analyses with like-minded modellers. We are especially interested in the organisms that cause luminescence, their distributions and residence times in the coastal oceans, and relative contributions to the oceanic light-field.

OBJECTIVES

The objectives of this study are to use data gathered from autonomous underwater vehicles (AUVs) and other platforms to develop an understanding of the scales (space and time) over which bioluminescence varies in coastal environments. We hope to understand large-scale bioluminescence features in the context of the physics, chemistry, and biology of the environment, and to observe the changes in luminescence distribution through different oceanographic seasons. Because the ultimate sources of bioluminescence are the plankton populations, we are keenly interested in integrating accurate measurements of zoo- and phytoplankton into our otherwise instrument-based programs. Bioluminescence is one of the few ways to sample a fraction of the zooplankton population both rapidly and optically, and we hope to develop robust predictive methods of relating light measurements back to plankton community composition. Another important objective is to improve the ability to predict plankton distributions – a challenge at this stage for most coastal oceanic models.

APPROACH

Bioluminescence is an important component of the community ecology of coastal oceans. Although some level of luminescence is always present, episodic events such as glowing red-tides or even the elusive “milky seas” (Miller, *et al.*, 2005) can create anomalously high levels of light, potentially disrupting normal ecosystem functions. Toward the goal of understanding the factors determining plankton and bioluminescence distributions, for several years we have conducted seasonal studies of bioluminescence in Monterey Bay, California. Our fieldwork was focused on intensive week-long field studies that were conducted during the night time aboard the R/V *Point Sur*. All five proposed cruises are now complete: August 2000, August 2002, August and December 2003, and March-April 2004. On each of these expeditions, we measured BL using multiple platforms including towfish and

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autonomous underwater vehicles (AUVs). Concurrent measurements of physical, chemical and optical properties of the water, and enumerations of zooplankton and phytoplankton (pigments and whole cell counts) were also obtained.

Bioluminescence Comparisons: Two autonomous vehicles and shipboard profiles

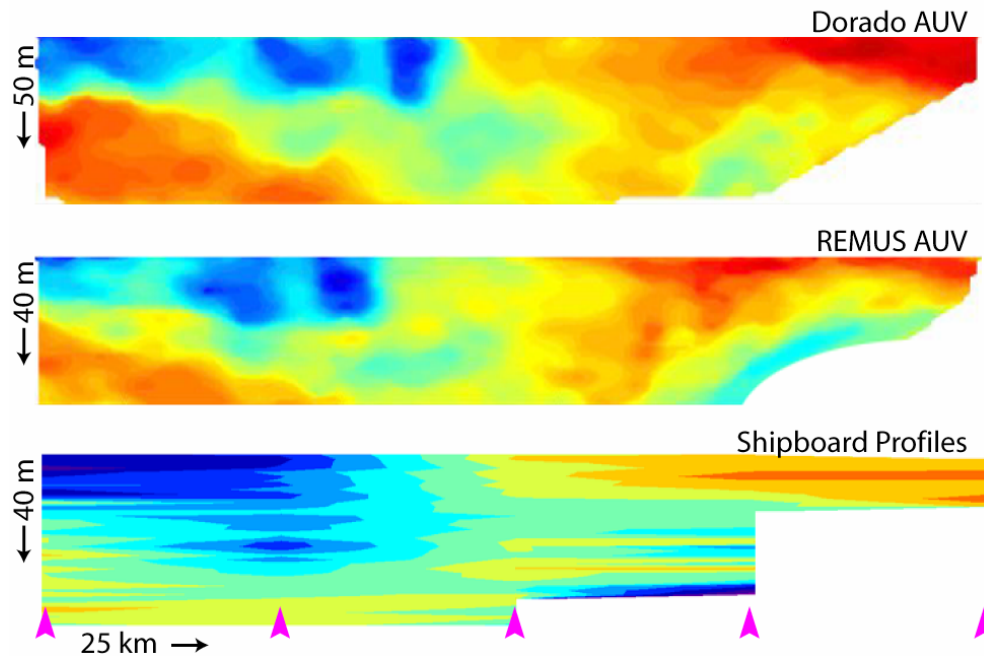


Figure 1: Comparison of data resolution and features resolved by MBARI's Dorado and CalPoly SLO's REMUS AUVs, along with traditional ship-based profiling. [Top panel shows an AUV run from the Dorado compared with the middle panel from a REMUS vehicle. The reproducibility of the bioluminescence signal between the two data sets is almost suspiciously similar. The profiler captures the major details, but not the fine structure. Samples for zooplankton and phytoplankton were taken at the locations marked by the magenta arrows.]

Our measurements were supported by physical data such as moorings, CODAR, satellite, and ADCP, which provided a picture of the larger oceanographic context of Monterey Bay. We have mapped the extent of BL communities at fronts, in discrete layers, across upwelling plumes, and during transition periods between upwelling and relaxation. In addition, two new generation prototypes of MBBPs have been integrated into a variety of platforms and field-tested. An intercomparison of the bathyphotometer data from two AUVs (as well as a traditional ship-based method) shows that reproducibility has been achieved (Figure 1), and measurements from two instruments mounted on different platforms can give highly reproducible results. Even a variable biological process such as stimulated light emission can be well quantified.

WORK COMPLETED

Past Data:

From 2000-2004, using the MBARI AUV, we collected 27 nights of transects, ranging from the surface to 100 m for a total of over 362 km of high-resolution data. These high-resolution records include simultaneous measurements of CTDO, OBS, fluorescence, bioluminescence and nutrients. During 22 nights and 8 days of towing, we gathered over 2000 km of towfish data. In addition, 137 stations were occupied with vertical profiles taken along each of the AUV transect lines, along with water and plankton samples to quantify zooplankton, phytoplankton, chlorophyll, nutrients, and HPLC-measured pigments. Most importantly, these data were collected across a variety of hydrographic features, and through representative seasons.

Present surveys:

AUV methods have improved to the point that in 2005 bathyphotometer measurements are now taken routinely (every three weeks) as part of MBARI's AUV time-series (Figure 2). The range of the vehicle has doubled as well, so that we are now crossing the entire Bay, and receiving the equivalent of two of the survey range that we got during our field seasons in 2000-2003. This extended range, unattended operation, and the stability of the bathyphotometer have led to routine achievement of what formerly took a month of preparation.

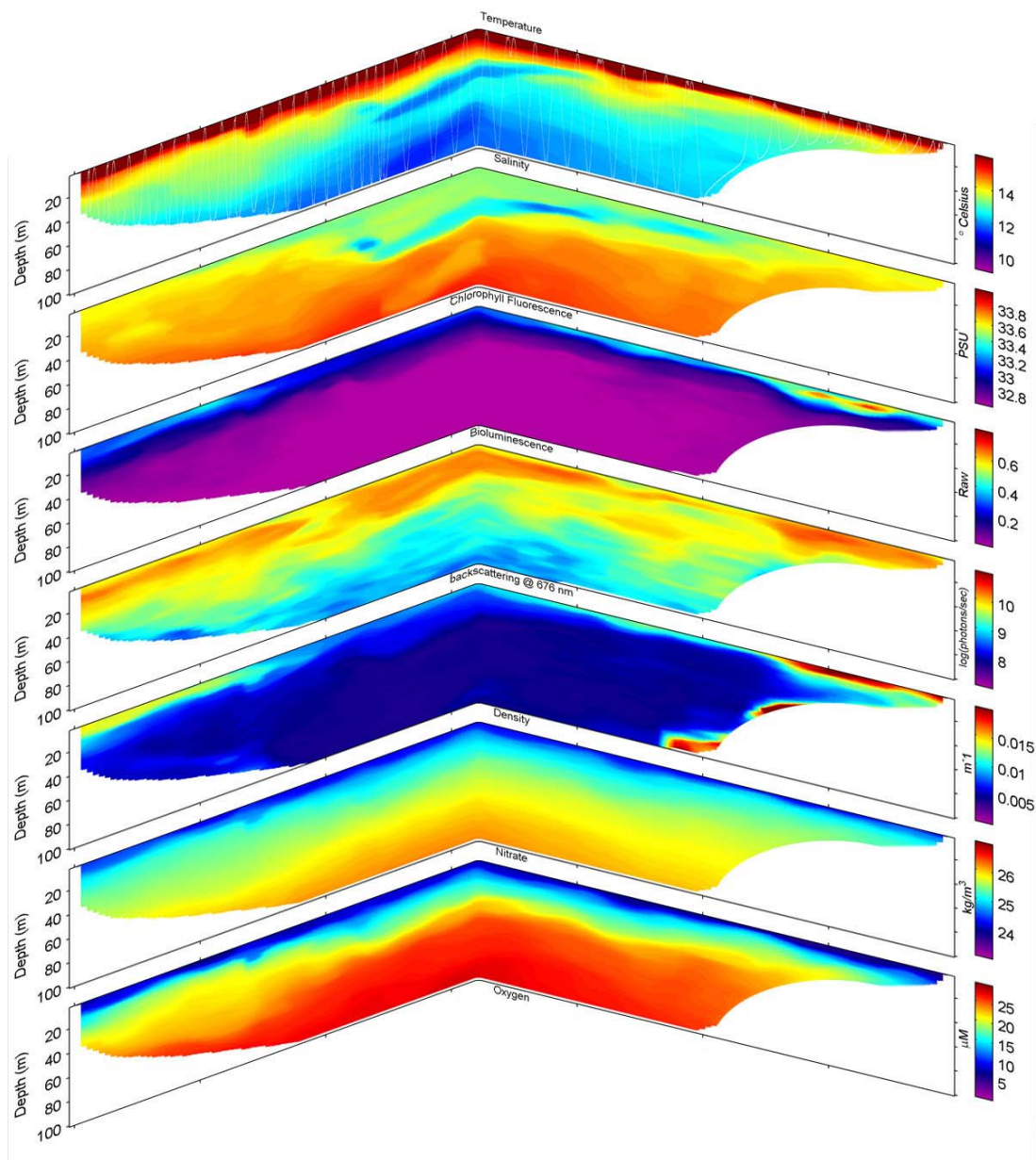


Figure 2: One example from MBARI's time-series of luminescence and physical oceanography parameters. [This multi-panel plot shows sections of AUV data which span the Monterey Bay. From the top are shown Temperature, Salinity, Fluorescence, Bioluminescence, Backscatter, Density, and Nitrate. The fluorescence signal is limited to the uppermost surface, but bioluminescence reveals the presence of significant biomass throughout the water column sampled (100m).]

Examination of this dataset shows a continuation of the patterns which we detected in our dedicated cruises: typically, the subsurface chlorophyll max (SCM; third panel from the top) co-occurs with the bioluminescence maximum (fourth panel) close to shore, whereas offshore the BL max is consistently located below the SCM offshore, and remains high whereas fluorescence decreases with depth. Deeper waters contain more zooplankton offshore, and as a result their luminescence is higher in the middle of the bay.

RESULTS

Although fluorometers can give an estimate of the abundance of phytoplankton, there are few reliable ways to autonomously sample zooplankton populations. Existing optical and acoustic methods each have strengths and potential drawbacks, mainly limited ability to resolve species composition. Toward the goal of measuring plankton abundance and understanding the factors determining their distributions, we have conducted seasonal studies of bioluminescence and plankton in Monterey Bay in August 2002, August and December 2003, and March-April 2004, as well as a pilot program in August 2000. On each of these expeditions, we measured bioluminescence using AUVs, towfish, and other platforms. Concurrent measurements of physical, chemical and optical properties of the water, and enumerations of phytoplankton (pigments and whole cell counts) and zooplankton were also obtained.

The lessons learned and the patterns observed during these cruises, however, are limited to a particular snapshot of time. So while early examinations of the data suggest some general rules for predicting plankton distributions, these “rules” vary greatly across seasons, and between years. In order to develop relationships between physical features and plankton, and to predict time-varying distributions of plankton, we have been using the AUV runs to establish a regular presence in the Bay.

The data thus far show an unmatched view beneath the “skin” of Monterey Bay. Satellite observations can disclose information something about the distribution of certain types of pigments in the uppermost water column, but as seen in the AUV data, most of the biomass lies below, especially considering the zooplankton, which graze down phytoplankton and repackaging material for its eventual sedimentation.

An example of this improved view of the ocean is shown in Figure 3, from August 2006. Information from the fluorescence signal (A) by itself, which would also be visible from a satellite, suggests that the biological community consisted of a thin layer of phytoplankton. However the backscatter (B) shows a signal that could be a plankton aggregation swarm or resuspended material, both of which have been seen at the canyon edge. The bioluminescence signal confirms that this is biological, and likely a swarm of krill, which it also detects high levels of heterotrophic plankton offshore (D) and even a deeper plankton layer (E). So our understanding of the complexity of the daily signal is vastly improved by our sensor suite. Now the remaining goal is to see how this picture varies with seasonality.

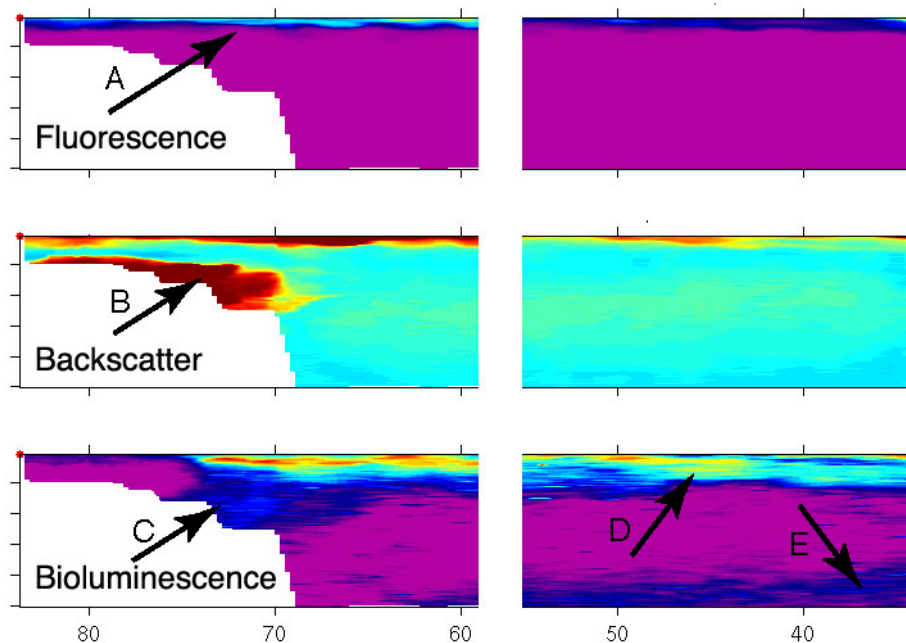


Figure 3. Subset of autonomous transect run 7 Aug 2006.
[This figure shows a detail of fluorescence, backscatter, and bioluminescence. The impression of the community structure derived from each of the images is extremely different, but analyzing a combination of the sensors gives a fairly complete picture of plankton distributions.]

IMPACT/APPLICATIONS

Surveys done here provide a comprehensive view the bioluminescence and plankton distributions in Monterey Bay. In addition, the data provided ground-truthing, initialization, and near-complete ecosystem coverage for the AOSN-II experiment. Bioluminescent organisms can have tremendous and critical effects on the coastal marine environment. This project provides a framework for modelers and biologists to improve predictive skill of coastal bioluminescence, and most importantly, the critical information needed to extend their models to different seasons and locations. Ultimately we hope that these data will help bathyphotometers become standard oceanographic instruments; they are one of the only ways to quantify heterotrophic macroplankton. These analyses will vastly increase our ability to predict the distribution of coastal zooplankton communities.

PATENTS

In process: A small-scale bathyphotometer for use on autonomous underwater vehicles (Case, Johnson, Haddock, Herren).

RELATED PROJECTS

Principal collaborators include James Case (UCSB; bathyphotometer development), Mark Moline (Cal. Poly SLO; coastal bioluminescence), Igor Shulman (Stennis Space Center).

PUBLICATIONS

Miller, S.D., S.H.D. Haddock, C.D. Elvidge, T.F. Lee. (in press) Twenty-thousand leagues over the seas: the first satellite perspective on bioluminescent ‘milky seas’. *Intl. J. Remote Sens.* (cover)

Mills, C.E. and S.H.D. Haddock. (in press) Key to the Ctenophora. For *Light and Smith’s Manual: Intertidal invertebrates of the central California coast*. J.T. Carlton, ed. U.C. Press

Mills, C.E. and S.H.D. Haddock, C.W. Dunn, P.R. Pugh. (in press) Key to the Siphonophora. For *Light and Smith’s Manual: Intertidal invertebrates of the central California coast*. J.T. Carlton, ed. Univ of California Press

Gasca, R., E. Suárez-Morales, S.H.D. Haddock (2006) Symbiotic associations between crustaceans and gelatinous zooplankton in deep and surface waters off California. *Marine Biology*.

Haddock, S.H.D. (2006) “Luminous marine organisms” in *Photoproteins in Bioanalysis*, S. Daunert & S.K. Deo, eds. Wiley-VCH. New York, p. 25-47

Collins, A.G., B. Bentlage, G.I. Matsumoto, S.H.D. Haddock, K. Osborn, B. Schierwater. (2006) Solution to the phylogenetic enigma of *Tetraplatia*, a worm-shaped cnidarian. *Biology Letters* (Royal Society). 2: 120-124

Haddock, S.H.D. and J.N. Heine. (2005) *Scientific blue-water diving*. Calif. Sea Grant, La Jolla.

Seibel, B.A., B.H. Robison, S.H.D. Haddock. (2005) First observations of brooding in a squid. *Nature*. 438: 929

Dunn, C.W., P.R. Pugh, and S.H.D. Haddock. (2005). Molecular phylogenetics of the Siphonophora (Cnidaria), with implications for the evolution of functional specialization. *Systematic Biology*. 54: 916-935. (cover)

Dunn, C.W., P.R. Pugh, and S.H.D. Haddock (2005) *Marrus claudanielis*, a new species of deep-sea physonect siphonophore (Siphonophora, Physonectae). *Bull. Mar. Sci.* 76: 699-714.

Haddock, S.H.D., C.W. Dunn, P.R. Pugh. and C.E. Schnitzler. (2005) Bioluminescent and red-fluorescent lures in a deep-sea siphonophore. *Science*. 309:263

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Herren, C.M., S.H.D. Haddock, C. Johnson, M.A. Moline, C.M. Orrico, J.F. Case. (2005) A multi-platform bathyphotometer for fine-scale, coastal bioluminescence research. *Limnology and Oceanogr. Methods* 3: 247-262.

Miller, S.D., S.H.D. Haddock, C.D. Elvidge, T.F. Lee. (2005) Detection of a bioluminescent milky sea from space. *Proc. Nat. Acad. Sci.* 102:14181-14184.

Shulman, I., D.J. McGillicuddy, Jr., M.A. Moline, S.H.D. Haddock, J.C. Kindle, D. Nechaev, and M.W. Phelps. (2005) Bioluminescence intensity modeling and sampling strategy optimization. *J. Atmospheric and Oceanic Technol.* 22:1267-1281

Widder, E.A., B.H. Robison, K.R. Reisenbichler, and S.H.D. Haddock (2005) Using red light for in situ observations of deep-sea fishes. *Deep Sea Res.* 52: 2077-2085.

HONORS/ACTIVITIES

Assistant Adjunct Professor: University of California, Santa Cruz, Dept of Earth and Marine Sciences

Invited Member, Editorial Board of the journal *Luminescence*, 2003-2006

Patent in process: Long-wavelength fluorescent proteins, (Haddock, Schnitzler, Keenan, McCord)

Patent in process: A small-scale bathyphotometer for use on autonomous underwater vehicles (Case, Johnson, Haddock, Herren)

Alan Berman Publication Award, one of best NRL-related publications of 2005

Int'l. Steering committee: Census of Marine Zooplankton, a Census of Marine Life project.

Elected Councillor, Int'l Society for Bioluminescence and Chemiluminescence: 2002-06

Ecosystem Team Leader, AOSN-II ocean sampling program, 2003

Bioluminescence Web Page: Educational site about bioluminescence. Top-ranked in all major search engines. <http://lifesci.ucsb.edu/~biolum/>

Invited talks,

Outreach articles:

Sep. 2006. *Science Year 2007*. Photos and research discussion in Worldbook supplement.

Jun. 2006. *Wholphin* DVD magazine from McSweeney's.

May 2006. Ivanhoe Television News piece about milky seas.

Apr. 2006. *Chemical & Engineering News*. Article by Rachel Pepling about research.

Apr. 2006. *Appl Env. Microbiol.* Cover article by Nealson & Hastings about Milky Sea research.

Feb. 2006. *SPIE Newsroom*. Article by Miller and Haddock about Milky Sea research

Jan. 2006. *Zoogoer* magazine. Cover photo; Article by Alison Frome about research.

Dec. 2005. Articles about brooding squid paper in Nature News, NY Times, BBC, AP, etc.

Oct. 2005. Articles about milky-sea research by BBC, *Nature*, NPR, *Nat'l Geo*, *New Scientist*, *Biophotonics*, *Discover* top 100 science stories of 2005, etc.

Invited Talks:

Jul. 2006. COSMOS program for gifted high-school students. UCSC.

Apr. 2006. Biological Oceanography Class. Moss Landing Marine Labs.
Mar. 2006. Dept. of Biochemistry, Rutgers University, NJ.
Feb. 2006. Hawaii Pacific University.
Dec. 2005. Living Lights. The Exploratorium, San Francisco, CA.
Nov. 2005. Duke University, Dept of Biology, Durham, NC
Nov. 2005. Cal State Univ. Monterey Bay, CA
Nov. 2005. Lockheed/Martin Advanced Technology Center, Palo Alto, CA