

# The Bermuda Testbed Mooring and HALE-ALOHA Mooring Programs: Innovative Deep-Sea Global Observatories

Tommy Dickey<sup>1</sup>, Grace Chang<sup>1</sup>, Casey Moore<sup>2</sup>, Al Hanson<sup>3</sup>, Dave Karl<sup>4</sup>, Derek Manov<sup>1</sup>, Frank Spada<sup>1</sup>, Don Peters<sup>5</sup>, John Kemp<sup>5</sup>, Oscar Schofield<sup>6</sup>, and Scott Glenn<sup>6</sup>

<sup>1</sup>Ocean Physics Laboratory, University of California Santa Barbara, Santa Barbara, CA 93106

<sup>2</sup>WET Labs, Inc., Philomath, OR 97370

<sup>3</sup>SubChem Systems, Inc., Narragansett, RI 02835

<sup>4</sup>University of Hawaii at Manoa, Honolulu, HI 96822

<sup>5</sup> Woods Hole Oceanographic Institution, Woods Hole, MA 02543

<sup>6</sup>Coastal Ocean Observation Lab, Rutgers University, New Brunswick, NJ 08901

## I. INTRODUCTION

Interdisciplinary time series observations are important for understanding and predicting ocean variability on time scales from seconds to decades. Plans are being made to implement open ocean observatories at key sites in the world ocean (e.g., OceanSITES and ORION). The Bermuda Testbed Mooring (BTM), located southeast of Bermuda (BATS site), and the HALE-ALOHA (H-A) mooring, north of Hawaii (HOT site) are prototypes for autonomous sampling interdisciplinary open ocean observatories. Both moorings are located in the deep sea (over 4500 m water depth) and provide fundamental measurements of meteorological, physical, biogeochemical, biological, and optical variables. The BTM program was initiated in 1994 and the H-A program was implemented in 1997. These programs have served as magnets for oceanographers for testing new technologies and sensors, for satellite sensor calibration and validation (cal/val), and for scientific measurements used for novel analyses and model development and testing. In this paper, 1) key objectives of the BTM and H-A mooring programs are summarized, 2) some of the recent technologies being developed at the BTM and H-A sites are reviewed, and 3) a few of the recent scientific results are highlighted. Finally, we outline a few of the plans for expanding the utility of these two mooring projects.

## II. OBJECTIVES OF THE BTM AND H-A MOORING PROGRAMS

The BTM and H-A programs have four major objectives:

- 1) To develop and test new deep-sea technologies, interdisciplinary sensors, anti-biofouling techniques and hardware, and data telemetry systems. For example, a new interdisciplinary surface buoy design, which is now being used extensively, was developed for the two programs (Fig. 1). Representative instrumentation tested using the BTM and H-A include: an atmospheric dust and aerosol sampler, several different multi-wavelength
- optical sensors, chemical samplers and sensors (i.e., for macro- and micro-nutrients, carbon dioxide, oxygen, nitrogen, and noble gases), an *in situ* primary production device, and acoustic current meters (Fig. 2a). Several new data telemetry systems have been developed and tested. Plans are also underway to move an existing fiber-optic cable to the H-A/HOT site enabling collection of high volumes of data from instrumentation requiring high power. The H-A mooring could be linked to an underwater node connected to this cable. The BTM and H-A moorings are ideal test platforms for electrical-optical-mechanical (EOM) cable development and testing.
- 2) To facilitate scientific studies requiring high frequency, sustained interdisciplinary data. Complementary ship-based, sediment trap mooring, AUV, glider, and satellite data sets have been used along with BTM and H-A data to expand the utility of several regional scientific research efforts off Bermuda and Hawaii (Fig. 2b). The BTM and



Figure 1. Photographs of the buoys used for the Bermuda Testbed Mooring (left) and HALE-ALOHA mooring (right).

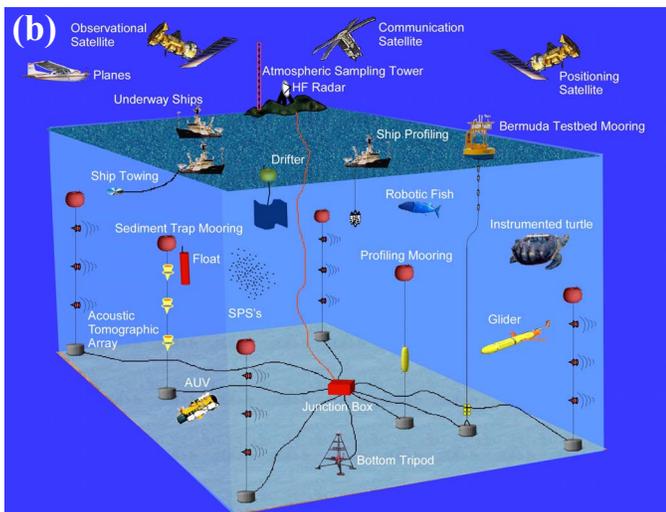
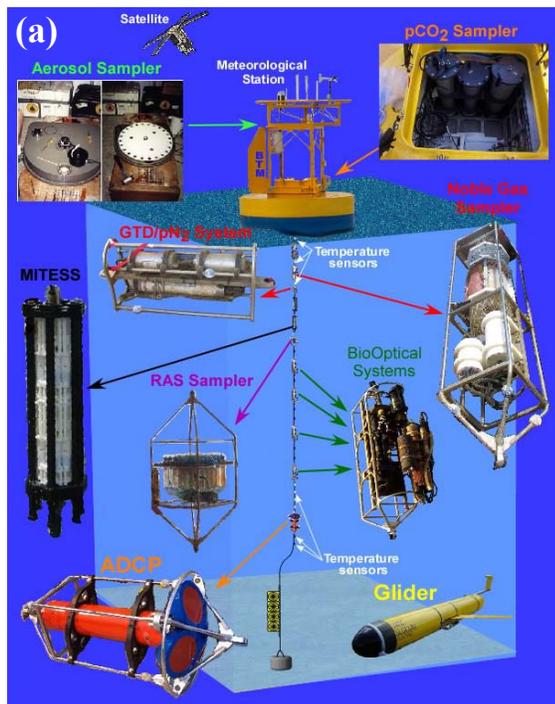


Figure 2. (a) Schematic diagram of the BTM. Photographs of some novel sensors and systems are shown (Aerosol Sampler, E. Sholkovitz (WHOI); pCO<sub>2</sub> Sampler, C. Sabine (PMEL); Noble Gas Sampler and Gas Tension Device (GTD)/pN<sub>2</sub>, W. Jenkins (WHOI); Moored In-situ Trace Element Sampler (MITESS), E. Boyle (MIT); Remote Access Sampler (RAS), P. Quay (U Washington); Buoy + METs, Temperature Sensors, Bio-optical Systems and ADCP, OPL/UCSB; Glider, (Rutgers University). Satellite data are made available via the OPL/UCSB website. The configuration of the H-A is similar. (b) Illustrations of various platforms that have been or are planned for complementary measurements at the BTM and H-A mooring sites.

H-A moorings have proven their value in detecting and observing extreme and episodic processes that cannot be captured with ship- or satellite-based sampling. For example, BTM data have been collected during direct hits by two hurricanes and one tropical storm and several mesoscale eddies. H-A data have been collected during subtropical storms, mesoscale eddies, and Rossby waves.

- 3) To provide data for developing and testing interdisciplinary models. BTM and H-A data sets have been used to

develop and test improved models of several upper ocean processes during and in the wakes of extreme wind forcing events and nutrient injections and plankton blooms, ecological shifts associated with eddies, and Rossby waves.

- 4) To calibrate and validate (cal/val) satellite-derived ocean observations. Ocean color measurements have been the primary focus thus far. However, several other cal/val opportunities will be pursued in the future for other variables.

### III. TECHNOLOGIES

The BTM and H-A programs provide deep-water platforms for community-wide development and testing of new observatory technologies, interdisciplinary sensors and samplers, and data telemetry systems. The programs are developing infrastructure for the oceanographic community (both open ocean and coastal), particularly for new measurements from moorings, drifters, profiling floats, gliders, and autonomous underwater vehicles (AUVs). The BTM and H-A moorings have been used as models for several new observatories within the U.S. and internationally. In this regard, the programs are especially important at this critical point in time as the NSF ORION and other initiatives (e.g. OceanSITES, IOOS, etc.) come on line. A new BTM buoy was conceived, developed, and tested by OPL and WHOI scientists and engineers; the same buoy design was used to build the H-A mooring (Fig. 1) and several other locations in the world ocean. The buoy can accommodate specialized meteorological and chemical sensors and systems as well as novel data telemetry hardware. Its modularity feature allows it to be easily transported to distant locations in a standard shipping container. A diverse suite of new sensors and systems has been tested on the BTM and H-A moorings by U.S. and international groups (Fig. 2a); well over 100 individuals have benefited directly from these programs to date. New deep-sea measurements enabled by the programs have included atmospheric aerosols and dust, pCO<sub>2</sub>, noble gases and pN<sub>2</sub>, nitrate+nitrite, trace elements, several spectral inherent and apparent optical properties, <sup>14</sup>C for primary production, and zooplankton biomass using acoustics. A major barrier to long-term observations by all in situ platforms has been biofouling of sensors. New anti-biofouling methods and systems (e.g., copper shutters and tubing) developed during the programs have been adopted by private industries, which have commercialized them and made them available to the research and applied oceanographic communities (Fig. 3). Of particular note, a 400+ day record of virtually non-biofouled bio-optical data has been obtained off Japan using one of our anti-fouling devices. Several new in situ and satellite data telemetry systems have been successfully tested and utilized for real-time telemetry of meteorological and oceanographic data. Interestingly, duplex satellite telemetry has also been used to change scales of in situ instruments mounted on the BTM from as far away as California. Moving toward the use

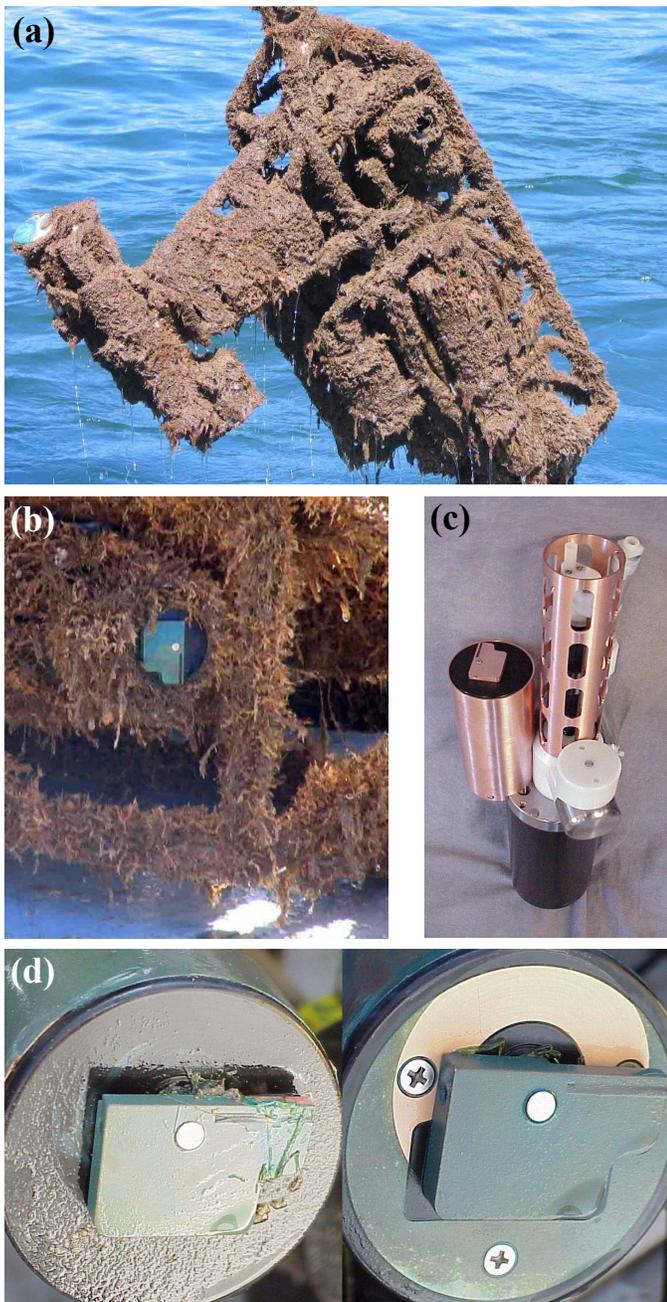


Figure 3. (a) Photograph of a moored optical package that shows extensive biological growth except in the area of a copper shutter device. (b) Detailed photograph of copper shutter area that is relatively free of biological growth. (c) Photograph of a WET Labs, Inc. WQM instrument package for measurements of dissolved oxygen and spectral optical absorption and attenuation. This holistic system utilizes copper extensively to reduce biofouling as well as a liquid bleach flow-through anti-biofouling system. (d) A WET Labs, Inc. ECO optical system with an all copper shutter device is shown at left. To the right is shown the same optical system equipped with an all copper faceplate. Both systems are effective in reducing biofouling.

of autonomously sampling vehicles, the Autosub AUV and gliders have operated in the vicinities of the two mooring sites, enabling calibration and validation of the mobile measurement systems and expansion of observations in time and space scales.

#### IV. BRIEF SUMMARY OF BTM AND H-A SCIENCE RESULTS

Both the BATS and HOT ship-based programs, which date back to 1988, are providing indications of significant decade-scale variations in ecosystem processes. However, undersampling and aliasing issues associated with monthly or even less frequent ship sampling necessitate the complementary measurements of the BTM and H-A mooring. High frequency, long-term data collected from the BTM and H-A moorings have been used for detailed studies of a variety of physical, chemical, bio-optical, and ecological processes from minutes to years.

Several new discoveries and results have been obtained off Bermuda using the BTM. For example, data collected during the passages of eddies have been used to estimate the role of such features on new production and carbon flux to the deep ocean. Interestingly, in some cases high chlorophyll concentrations were observed only at depth and thus were unobservable with satellite ocean color imagers. Recent work has also shown the influence of mesoscale features on primary production and their relation with deep ocean sediment flux events. As another example, the dynamics and biological responses of the upper ocean have been observed at the BTM site during passages of hurricanes and other intense storms. The hurricane observations are unique and are enabling development and testing of models.

The H-A mooring program has also provided several new and exciting results. Data collected from the H-A mooring have demonstrated the importance of short-term events. Using data collected from the H-A mooring, it has become clear that mesoscale eddies play an important role in explaining biogeochemical and ecological variability. Satellite data sets obtained in conjunction with H-A mooring high temporal resolution time series data, have also suggested that Rossby waves likely play major roles in ocean productivity and biogeochemistry. In particular, they have noted that Rossby wave effects should be incorporated into models of carbon uptake and export from the euphotic zone. Clearly, high frequency, long-term sampling from moorings will be needed for interdisciplinary model development and validation.

#### V. SUMMARY AND VIEW TOWARD THE FUTURE

Many of the present national and international ocean observatory plans have benefited from BTM and H-A research and development. Both programs provide stimuli for many forward-looking ideas concerning ocean technologies and the synergistic use of observations and models. New measurement systems and scientific results from the BTM and H-A projects are leading to improved sampling relevant to global biogeochemical cycling, ecosystem dynamics, and climate change as well as to improved predictive modeling in these areas along with air-sea interaction and hurricanes. High frequency, sustained measurements obtained by these programs have also enabled the evaluation of undersampling/aliasing effects; results from these studies are

crucial for the design of ocean observatories (e.g., relative placement and sampling rates of sensors, length of deployments, etc.). Already, several interdisciplinary modelers have used BTM and H-A data to test and reconfigure models for phenomena including mesoscale eddies, hurricanes, and seasonal cycles. We have several plans for increasing the effectiveness and expanding the utility of measurements at the BTM and H-A sites. For example, we anticipate testing new *in situ* instrumentation such as flow cytometers, mass spectrometers, genetic sensors and samplers, biogeochemical sensors and samplers, primary productivity instrumentation, biochips, hyperspectral optical and acoustical systems, 3-D video systems, and emerging MEMS- and nanotechnology-based sensors. Surface mooring profilers will likely be tested at our two sites or even as part of our moorings. In addition, new ideas for data telemetry, novel methods for local power generation (i.e., wave energy), and anti-biofouling for extending deployments will be enabled by the BTM and H-A programs. Besides ocean color remote sensing calibration and validation (cal/val), which has proven effective from past BTM and H-A research, future remote sensing cal/val variables will likely include wind stress, surface heat fluxes, precipitation, salinity, and carbon dioxide. Optimal sampling using multiple platforms remains a major goal. Thus, new methods will be developed to effectively synthesize and visualize concurrently collected mooring, glider, AUV, ship-based, drifter, profiling float, and satellite data sets. Modeling (including data assimilation) will be executed in close collaboration with other groups to enhance this work. Adaptive sampling will be done using synthesized data sets and model predictions. Complementary glider sampling strategies will likely include: 1) routine sampling in the vicinity of the BTM to provide enhanced vertical resolution ('virtual mooring' sampling mode), spatial context, and estimates of advection and 2) 'event-response' sampling mode by directing gliders to special areas of interest, e.g., hurricane paths and wakes, fronts, and mesoscale eddies.

Importantly, the BTM and H-A programs will continue to facilitate the commercialization and accessibility of newly developed instruments, platforms, and data telemetry systems for academic and government laboratories. Societal impacts will include improved monitoring and prediction of the health of the ocean, weather including hurricanes, and climate change. The educational impacts of the programs will be manifest in several ways: use of results for K-12, undergraduate, and graduate education through inclusion of results in classes, books, websites, and special programs. In the future, we plan to transmit data in near real-time for use in aquaria, museums, and potentially, the JASON Project and the Rutgers University COOL Classroom. In conclusion, it is anticipated that the BTM and H-A mooring programs will continue to serve the oceanographic community in its quest for long-term global ocean observations in the deep sea.

#### ACKNOWLEDGMENT

We would like to thank our many collaborators for their contributions. Support of our research has been provided by the U.S. National Science Foundation, Office of Naval Research, National Ocean Partnership Program, and National Aeronautics and Space Agency.

#### SELECTED BIBLIOGRAPHY

- T.D. Dickey and R.R. Bidigare, "Interdisciplinary oceanographic observations: the wave of the future," *Scientia Marina*, Vol. 69 (Suppl. 1), pp. 23-42, 2005.
  - T.D. Dickey, G.C. Chang, and M.R. Lewis, "Optical oceanography: recent advances and future directions using global remote sensing and in situ observations," *Rev. Geophys.*, Vol. 44 (No. 1), RG1001 10.1029/2003RG000148, 2006.
  - T. Dickey, C. Moore, and O-SCOPE Group, "New sensors monitor bio-optical / biogeochemical ocean changes," *Sea Tech.*, Vol. 44 (No. 10), pp. 17-24, 2003.
  - D.V. Manov, G.C. Chang, and T.D. Dickey, "Methods for reducing biofouling of moored optical sensors," *J. Atmos. Ocean. Tech.*, Vol. 21 (No. 6), pp. 957-967, 2004.
- UCSB OPL website: <http://www.opl.ucsb.edu/>.