The USC Center for Integrated Networked Aquatic PlatformS (CINAPS): Observing and Monitoring the Southern California Bight

Ryan N. Smith [a,*], Jnaneshwar Das [a], Hörður Heiðarsson [a],
Arvind M. Pereira [a] Filippo Arrichiello [e] Ivona Cetinić [b],
Lindsay Darjany [c], Marie-Ève Garneau [c], Meredith D. Howard [c,d],
Carl Oberg [a], Matthew Ragan [b], Erica Seubert [c],
Ellen C. Smith [b,c], Beth A. Stauffer [c], Astrid Schnetzer [c],
Gerardo Toro-Farmer [b], David A. Caron [c], Burton H. Jones [b],
Gaurav S. Sukhatme [a]

[a]*Robotic Embedded Systems Laboratory, Department of Computer Science*
[b]*usCLAB, Department of Biological Sciences*
[c]*Caron Lab, Department of Biological Sciences*
University of Southern California, Los Angeles, CA 90089, USA
[d]*Southern California Coastal Water Research Project, Costa Mesa, CA*
[e]*Dipartimento di Automazione, Elettromagnetismo, Ingegneria dell'Informazione e Matematica Industriale, Cassino (FR), Italy*

1 Introduction

More than 75% of our earth is covered by water, yet we have explored less than 5% of the aquatic environment. Aquatic robots, such as Autonomous Underwater Vehicles (AUVs), and their supporting infrastructure play a major role in the collection of oceanographic data (*e.g.,* [6], [10] and [21]). To make new discoveries and improve our overall understanding of the ocean, scientists must make use of these platforms by implementing effective monitoring and sampling techniques to study ocean upwelling, tidal mixing or other ocean processes. Effective observation and continual monitoring of a dynamic system as complex as the ocean cannot be done with one instrument in a fixed location. A collection of static and mobile sensors must be deployed, and the information gleaned from the acquired data must be

---

* Corresponding author. Tel: +1 808 256 9562
Email address: `ryannsmi@usc.edu` (Ryan N. Smith).

Preprint submitted to IEEE Robotics and Automation Magazine *June 1, 2009*

distributed to all members of the team. Successfully orchestrating a multi-sensor, long-term deployment additionally requires a robust, rapid and cost-effective communication network. Only when all these components, which form an aquatic robotic system, are in synchronous operation can scientists begin to improve our overall understanding of the complex ocean environment.

CINAPS (pronounced [sin-aps]) is the Center for Integrated Networked Aquatic PlatformS located at the University of Southern California (USC) in Los Angeles, California. The goal of CINAPS is to bridge the gap between technology, communication, and the scientific exploration of local and regional aquatic ecosystems. Specifically, CINAPS is focused on providing timely dissemination of information related to Harmful Algal Blooms (HABs) and general water quality to scientists, policy makers and the general public. To accomplish this task, the CINAPS team has designed and deployed an embedded sensor network to monitor and observe the coastal regions of Southern California. In this article, we present the recent developments of an aquatic robotic system with the goal of providing a reliable and cost-effective data transfer framework to enable real-time, optimal trajectory design, based on ocean model predictions, to gather *in situ* measurements of interesting and evolving ocean features and phenomena.

We visualize CINAPS as a federated observing system with a specialized interface that forms a bridge between each of the pieces in a coastal observing system, allowing for optimization of sensing and sampling strategies and to provide information about the performance of the system as a whole. CINAPS attains this broad goal by bringing together the resources of experts in applied oceanography, robotics, phytoplankton ecology, and computer science from three research groups at USC:

- RESL (Robotic Embedded Systems Laboratory)[1]: Focusing on the robotic hardware and software tools and techniques to design and understand multi-scale, distributed estimation and control methods for robot networks.
- usCLAB[2]: The Oceanography team seeks to understand integrated coastal ocean processes such as the coupling between physics, chemistry and biology in the initiation of algal blooms.
- Caron Lab[3]: Studies the role of phytoplankton and protists in aquatic microbial ecology, and specifically focuses on the dynamics of harmful algal blooms in Southern California waters.

CINAPS is a highly collaborative group that brings together expertise from several fields to work towards the common goal of tackling some of the difficult problems facing aquatic ecosystems today. While this article focuses on the CINAPS build-out and recent experiments with aquatic robots, this collaboration extends beyond USC to a network of partners, as we aspire to wholly integrate the public into our understanding of Southern California's complex and important coastal ecosystem.

---

[1] `http://robotics.usc.edu/resl/`

[2] `http://usclab.usc.edu/`

[3] `http://www.usc.edu/dept/LAS/biosci/Caron_lab/index.html`

2 Oceanography Background

Southern California is a densely populated ($\backsim$ 20 million inhabitants), highly urbanized coastal region, representing approximately 25% of the nation's coastal population. The primary region of interest of the CINAPS team's research is a coastal region referred to as the Southern California Bight (SCB). The SCB is the coastal ocean region contained within 32° N to 34.5° N and $-117°$ E to $-121°$ E, as seen in Fig. 1(b). Southern California represents a critical locale to assess how changes driven by urbanization and climate impact the physical and biological state of the coastal region. Given the ecological and socio-economic importance of coastal regions [19], it is important to be able to accurately assess, and ultimately predict, these changes. The observations that we make are intended to produce results that can be used for management, decision making, policy development by local, regional, state and federal agencies.

Anthropogenic impacts on both terrestrial and marine ecosystems in this coastal environment are associated with the rapid rate of urbanization and accompanying changes in land use and land cover. For example, nearly 90% of the coastal wetlands in Southern California have been lost. Watersheds draining into these wetlands have likewise been altered, with a significant increase in impervious surfaces observed. These changes in land cover and land use impact both the quantity of freshwater runoff, and its particulate and solute loadings (nutrients, sediments, pollutants, pathogens, etc.). However, fluxes in freshwater runoff and terrestrial loadings, and their impact on the physical, biogeochemical, biological and ecological conditions of the coastal ocean remain largely unknown [20].

Superimposed on these regional anthropogenic disturbances are poorly described coastal fluctuations driven by climate variability (*e.g.,* [7]). Southern California experiences significant decadal and internannual variability associated with the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO) (see *e.g.,* [4]). These climatic phenomena impact the frequency and intensity of the regional episodic storm events that are responsible for the bulk of freshwater runoff from land, as well as the physical and biogeochemical dynamics of the coastal marine ecosystem.

Much of the coastal ocean variability in the Southern California Bight is regulated by remote processes (*e.g.,* [4]), in contrast to the central and northern California coasts where local wind forcing often accounts for significant fractions of the variability (c.f., [18]). The effects of large-scale climatic variability (*i.e.,* ENSO, PDO) on the local coastal ocean are conveyed directly through ocean processes and indirectly through atmospheric processes. The ocean processes include a deepening of the pycnocline within a wide coastal zone resulting from propagating, poleward, coastally-trapped Kelvin waves (oceanic teleconnection) and weakening of southward California Current flow, coastal upwelling, and offshore water transport, resulting from change of local wind patterns (atmospheric teleconnection). Atmospheric influences include changes in upper level circulation that result in the displacement of moisture-laden onshore flows southward toward Southern California. This results in increased winter storms, typically characterized by more frequent, intense and longer-lasting rain events, which all lead to elevated river runoff to the coastal ocean. In particular, average rainfall in downtown Los Angeles during El Niño years is 67.5 cm, compared with 33.0 cm for non-El Niño years. This rainfall results in freshening of surface waters through direct rainfall into the ocean and from freshwater inflow at the coastal boundary from coastal streams and rivers. These streams and rivers additionally entrain large amounts of suspended and dissolved material from their respective watersheds. Atypical wind conditions that often accompany these storms can locally force ocean circulation and transport runoff plumes in a manner much different from what would be expected during non-storm conditions.

Based upon the complex ocean dynamics and the many factors affecting the variability of the SCB, we focus our research efforts in answering the following open questions about the region.

- What are the effects of anthropogenic inputs on the coastal processes in the ocean? This includes issues of plankton blooms, some of which could be harmful. Can we distinguish anthropogenically affected processes natural variations and effects?
- What are the effects of major climate change issues facing the Southern California coastal ocean - including ocean warming, ocean oxygen and acidification issues, sea level rise, etc.?
- What is the the region's biogeochemistry and what are the fluxes of carbon and nitrogen associated with the coastal margin of Southern California?
- What is the optimal placement and sampling regimen necessary for evaluation and monitoring the long-term success of marine protected areas?

Ultimately, it is the goal of the CINAPS team to understand all the processes that occur in the SCB, how these processes are affected by climate variability and change, the role of coastal urbanization and how we can best preserve the marine resources presently available. Such a task requires the orchestration of many expert scientists, avaialable technology and local government. By deploying multiple sensor platforms, connected with a reliable communication infrastructre, to form an embedded robotic network, we present a module to facilitate this collaboration in the observation and monitoring of the intriguing coastal ecosystem of the SCB.

3 Robotic Sensor Networks

Robotic sensor networks [8] are networks in which some or all nodes can move either under their own control (autonomous or robotic mobility) or under the control of other agents in the environment (teleoperated or human-portable nodes). These systems combine advanced concepts in perception, communication, and control to create computational systems capable of interacting in meaningful ways with the physical environment, thus extending the individual capabilities of each network component and network user to encompass a much wider area and range of data.

Several challenges exist in the design of a static sensor network. Examples include deployment, energy management, routing, to name a few. Approaches to solve some of these problems, while not comprehensive, are starting to become available. However, naively using these for robotic sensor networks is usually ineffective. In some cases, mobility may exacerbate what is usually a fairly difficult problem to begin with (*e.g.,* routing). In other cases however (*e.g.,* data dissemination), mobility may be leveraged in interesting ways to solve the problem.

Robotic sensor networks have several advantages over static networks. First, the ability to move allows them to support multiple modalities of sensing and spatio-temporally focusing sensor 'attention' according to the task and the environment. The network could change sensing modalities and density according to sensory feedback. Second, such systems can autonomously self-organize to best match the network topology [13] required by the application and to adapt to the environment. Third, these networks are fault-tolerant. The network can use redundancy in its nodes, coupled with adaptive control algorithms, to extend its lifetime. Fourth, these networks can function as distributed information repositories for the task and the environment. Fifth, and finally, these types of networks can support seamless failure and addition of new nodes, and constitute long-lived systems whose functionality can be changed incrementally, without taking the entire system down.

The CINAPS system is *heterogeneous.* It is composed of two different kinds of underwater and surface vehicles as well ground stations and static floating buoys. The overarching objective of CINAPS is to build an *aquatic observing system* for the purpose of measuring physical (*e.g.,* temperature, pressure, seismic, currents) and chemical (*e.g.,* contaminant concentration) phenomena and biological processes (*e.g.,* the concentration of algae) leading to technical innovations in algorithms and systems for networked robotics, new scientific discoveries, and useful information regarding the human impact on the environment and its mitigation via effective and timely public policy.

CINAPS is focused on the tools and algorithms to design and understand large-scale, distributed, networked robotic systems with a particular focus on the aquatic environment. A key issue in networked robotics is to understand how coordinated behavior arises from an aggregate of individual robotic elements where each robot is constrained in the fidelity and accuracy of its sensors and actuators, has limited communication range and a finite energy reservoir. CINAPS develops this understanding by designing efficient, robust algorithms for networked multi-robot coordination and state estimation that cope with these constraints. We have focused on two major areas: communication-constrained multi-robot coordination algorithms and perception, estimation and control multi-robot algorithms.

4 Deployed Marine Robotic Systems

In 2005, a red tide (common name for an algal bloom) resulted in a massive fish kill in King Harbor of the City of Redondo Beach, California. This created a nuisance for commercial and recreational use of the harbor for several weeks [9]. In response to this event, a monitoring program was developed for King Harbor and the surrounding coastal region (SCB) to help predict and avoid future toxic blooms, [3]. As part of this monitoring program, the CINAPS team has developed and implemented an embedded robotic network to aide in the collection, assessment and dissemination of data relating to algal bloom events.

CINAPS is utilized to address specific scientific questions related to ocean research in the SCB. Each posed question defines associated sampling region(s) in the SCB, which are outfitted with the necessary equipment and instrumentation to help us understand the processes driving ocean variability in that area. By design, the deployed platforms can be outfitted with a variety of sensors that specialize in measuring variables such as temperature, salinity, depth, optical properties, surface and subsurface currents, chlorophyll fluorescence, dissolved oxygen and turbidity. The collected data are then transmitted via a communication network to a central storage location at USC for detailed analysis and dissemenation.

4.1 Robots, Platforms and Hardware

CINAPS utilizes a combination of Commercial-Off-The-Shelf (COTS) hardware, complete internal fabrications, as well as slightly to fully-modified COTS components to comprise the sensor nodes that make up the embedded sensor network throughout the SCB. Here we describe some of the major sensor platforms available for deployment or currently in use.

4.1.1 Marina Buoys

A static sensor node, or buoy, as seen in Fig. 3(a) and 3(d) is an example of a platform that is assembled by the CINAPS team for a specific purpose in the SCB. These buoys are deployed in many locations, including King Harbor, Redondo Beach, Huntington Beach, Marina del Rey and Newport Beach marinas.

Each buoy consists of a Gumstix Verdex computer (Intel 400MHz PXA270 CPU), ADC board, battery, fluorometer and an array of six thermistors, all of which are mounted on a wooden chassis and sealed in a water-proof housing. These static nodes are also capable of accomodating two water quality instruments (*e.g.,* Hydrolab^{TM} MS5 and DS5 Sondes).

The fluorometer measures the concentration of chlorophyll-a, which is indicative of the density of certain photosynthetic micro-organisms in the environment. The six thermistors measure the water temperature accurately to 0.1° Celsius at uniform depths ranging from $0.5 - 2.5$ m. The sensor data are stored locally on the node and transmitted wirelessly to the CINAPS server at USC. Each buoy is powered by a standard, 12 V car battery that is recharged by an external solar panel. The buoy is configured to operate for up to one week on a single battery charge.

4.1.2 Coastal Moorings

The CINAPS team is in the process of incorporating two AXYS Technologies, shallow-water moorings into the network. These moorings are located off of Redondo Beach and El Segundo in approximately 50 m of water. Figure 3(b) depicts one of the moorings just before deployment. The purpose of these two moored platforms is to monitor physical and biological properties of the SCB coastal waters. The solar-backed, battery-powered moorings are outfitted with sensors that measure temperature, salinity, dissolved oxygen, oxygen saturation, chlorophyll fluorescence and turbidity. These are a ruggedized version of the marina buoys presented in Section 4.1.1, designed to handle harsh, open-ocean conditions. Such a platform provides the ability to carry out high-resolution, temporal sampling on a continual basis, and provide real-time information to the central database.

4.1.3 High-Frequency Radar Installations

Environmental variability of the coastal ocean is partially determined by the wind and surface currents in the local area. To assess these factors, we employ four CODAR Ocean Sensors High Frequency Radar (HFR) sites located at Malibu Beach, Dockweiler Beach, Point Fermin and Santa Catalina Island. Two additional sites are planned for HFR installation; Torrance Beach and Newport Beach. Each site operates at a frequency of 25 MHz, which gives a radial coverage area of approximately 40 km. The installation located on Catalina Island operates at 12 MHz and provides a radial coverage area of approximately 70 km. The spatial resolution of the acquired data is 1 km.

These radar systems measure ocean surface currents (restricted to the upper 0.5 m) using continuousy transmitted/received radio waves. Each site produces a radial estimation of the currents in the SCB, which is then combined with overlapping data from the other sites to produce a current vector map for the entire area. Each site is networked and the data is updated hourly.

4.1.4 Freewave Base-Stations

Many large-scale marine sensor networks rely upon satellite phones for communication. Although it is reliable and offers global coverage, satellite communication can be expensive. Since our main region of interest is a *coastal* environment, we are able to take advantage of technologies not feasible to open-ocean research.

To lower satellite modem costs and increase communication bandwidth, we set up a network of line-of-sight radio base stations around the SCB; locations are denoted by the orange arcs in Fig. 1(b). Making use of the existing infrastructure of the surface radar installations, we implemented an inexpensive communication network based on Freewave$^{\text{TM}}$ radio modems. The base station hardware consists of a Freewave$^{\text{TM}}$ 900MHz FGR-series modem, antenna and an internet-connected computer (Intel Atom CPU running a variant of Linux). Additional information is provided in [12].

4.1.5 Autonomous Gliders

One example of a slightly-modified, commercially-available, mobile sensor platform used in this study is a Webb SLOCUM autonomous underwater glider, as seen in Fig. 3(c). The SLOCUM glider is a type of AUV designed for long-term ocean sampling and monitoring [14]. These gliders *fly* through the water by altering the position of their center of mass and changing their buoyancy. Due to this method of locomotion, gliders are not fast moving AUVs, and generally have operational velocities on the same order of magnitude as oceanic currents ($\backsim$ 1 km/h).

The CINAPS team owns and maintains two Webb SLOCUM gliders; Rusalka and He Ha Pe. We have upgraded the communication capabilities of our gliders to make them a node in our network. The details of this upgrade and the associated network communication protocol are described in [12].

4.1.6 Autonomous Surface Vehicles

Autonomous Surface Vehicles (ASVs), based on the Q-Boat-I from OceanScience^{TM}, represent an example of a sensor platform whose internal components are designed and assembled in-house. The commercially produced hull is designed to be a radio-controlled, surface craft that is 2.1 m in length with a maximum beam of 1.2 m. The vehicle is actuated by electric motors driving two propellers, and a rear rudder for attitude control at high speeds. The CINAPS team owns and operates two Q-Boats, one of which can be seen in operation near a harbor buoy in Fig. 3(d)

Autonomy was added to the vessels by incorporating an x86-based Linux computer, 802.11g wireless capabilities and navigation sensors (*i.e.,* 3-axis gyro-compass, 3-axis accelerometer and a Global Positioning System (GPS)). Each surface craft is monitored and supervised via a PC-based front-end, equipped with tools to create new missions, display data from the vehicle or remotely operate the vehicle. The ASVs are a portable, mobile platform that can be equipped with different instrumentation based upon the monitoring needs. For example, in some missions the ASVs are equipped with sonar and/or stereo-vision systems to perform bathymetric surveys and reactive obstacle-avoidance. Additionally, each craft is equipped with a winch system to control the deployment of aquatic sensors. This feature enables 3D sampling capabilities. Navigation and guidance software was developed in-house. Examples such as adaptive sampling and multi-vehicle coordination are discussed in the sequel.

4.1.7 Pier and Marina Sampling

The aforementioned mobile and moored, large-scale sensing platforms provide information on the broad vertical and horizontal distributions of chemistry and physics, but it is also vital to monitor these parameters, and the resulting biological responses, at small scales. Generally, large-scale patterns are a result of processes taking place at much smaller scales that directly affect organismal growth and mortality. For example, to characterize shortterm temporal and spatial variability within King Harbor, we employ six Hydrolab$^{\text{TM}}$ water quality Sondes, deployed at three locations within the harbor (see Fig. 2). Each deployment site consists of two instruments located approximately 0.5 m below the water surface and 0.5 m above the bottom ($\backsim 3-4$ m). These sensors acquire depth, temperature, turbidity, dissolved oxygen, chlorophyll-a fluorescence and conductivity measurements within in the marina's water system. The Hydrolab$^{\text{TM}}$ Sondes have been used in conjunction with several monitoring and experimental campaigns to examine the development, persistence and decline of HABs.

Weekly water samples collected from the harbor have provided a two-year, continuous time series of algal species and community composition within the harbor. This information, and ancillary chemical/physical data collected by the sensor platforms, has been used to plan and conduct experimental studies to measure rates of population growth and mortality of important harmful algal species. In addition, high-resolution temporal (every few hours for two-day periods) and spatial ($0.5-1$ m depth intervals) observations have examined algal dynamics as a consequence of tidal mixing and vertical migratory behavior of the algae. Discrete water samples have also been analyzed for major nutrients (*e.g.,* phosphate, nitrate, ammonia) and specific algal toxins to examine relationships between these factors, algal community composition, and chemical and physical parameters measured using the CINAPS network.

4.2 Algorithm and Software Development

Placing and operating multiple sensors in the field to collect data is only a portion of the robotic system necessary to produce products that can be used for management, decision making and policy development by local, regional, state and federal agencies. Some major, but physically invisible, components are the software and algorithms which are responsible for such actions as data routing, vehicle control, data acquisition optimization, data analysis and presentation of results. As in Section 4.1, CINAPS uses a combination of COTS software and internally-designed algorithms to create the infrastructure necessary to orchestrate a multi-platform, dynamic data acquisition deployment. In this section, we present some of the software tools and algorithms employed by the CINAPS system.

4.2.1 Sampling Based on Scalar Field Estimation

In general, optimal path planning for mobile sensor platforms heavily depends on the estimation or *a priori* knowledge of the region to be sampled. Model-based estimation (and hence optimal sampling design based on linear or non-linear models) has been well studied [15]. In the environmental monitoring context a prior model is normally unknown and it might even be the goal of the project to develop or learn a model from the data collected by the sensors. Therefore, non-parametric estimation is appropriate. In recent work [22], CINAPS members present an adaptive sampling algorithm based on local linear regression, which is guaranteed to be optimal in the sense of minimizing the integrated mean square error (IMSE) of the field reconstruction. The energy consumption model depends on the dynamics of the mobile sensor platform. The adaptive sampling algorithm does not depend on the energy consumption model, however this is considered in the generation of the optimal paths. Tests of the algorithm were performed on robotic boats executing optimal trajectories (exceeding an aggregate of 3 km in length) operating with data collected from the harbor buoys.

4.2.2 Station Keeping Algorithm

Vertical profiling from an ASV with a Hydrolab$^{\mathrm{TM}}$ water quality Sondes attached to a winch system, as mentioned in Section 4.1.6, requires the vehicle to remain at a particular location for up to 5 minutes. Local winds and surface currents make it impossible to stay on station for long durations without external corrective action.

To this end, we have developed a station-keeping algorithm to prevent the vehicle from realizing large displacements during sampling. The details of this algorithm can be found in [11] in the form of a controller that stabilizes the vehicle by use of a combination of line-of-sight measurements and alignment with the external disturbances. This controller can maintain the position of an under-actuated craft (in particular, the ASV from Section 4.1.6) to within 2 m of the desired location under moderate wind conditions ($\backsim 2.5$ m/s).

4.2.3 Multi-Robot Collaboration Algorithm

In an effort to conduct time-efficient sampling missions, CINAPS has investigated coordinated, multi-sensor deployments. Such algorithms have been designed to control the ASVs as well as the autonomous gliders. One example of this technique is requesting two ASVs to visit (sample) at designated way-points in a given region. In [2] we describe a hierarchical control structure including a supervisory module that gives each vessel its prioritized elementary tasks, a behavior-based controller that generates the motion directives to achieve the assigned tasks, and a maneuvering controller that generates the actuator control commmands to follow the motion directives. Static obstacle avoidance is also implemented for the region where tests were conducted. This system allows the vehicles to collectively accomplish one large sampling task while continuously satisfying known communication constraints.

4.2.4 Communication Infrastructure Development

In Section 4.1.4, we presented the hardware details of the base-stations utilized for communication with the deployed sensor platforms and sending acquired data back to the central data server. We continue here by introducing the software component of the commmunication framework.

The base station's and glider's Gumstix computers run communication software that treat the Freewave$^{\mathrm{TM}}$ modems as an unreliable serial link. We employ a custom lightweight communication protocol with incoming and outgoing packet queues which provide feedback to vary both inter-packet delay and packet-sizes. The protocol supports both guaranteed delivery as well as a non-guaranteed mode of transmission.

On the sensor platform (glider) side, our software parses text output and retrieves data files from the glider's computer. Important information and data files, after being compressed, are then sent to the base stations. Upon receipt, the base stations relay these messages via TCP/IP to a centralized data server at USC. The data server can also send commands and missions to the deployed platforms. These commands are either generated automatically by path-planning algorithms or manually by a human operator, and can be as simple as altering a sampling epoch to defining a week long trajectory plan for a fleet of gliders, or other mobile sensor platforms. Further details on the communication protocol can be found in [12] and [17].

4.2.5 Model-based Retasking Algorithm

It is a goal of the CINAPS team to enable real-time, optimal trajectory design based on ocean model predictions for the use of tracking features of interest (*e.g.,* fresh water plume, eddy, HAB, etc.). The basic idea is to continually assimilate collected data into a regional ocean model, which then predicts the evolution of the given feature. Since a complete prediction output from a complex ocean model for the SCB takes roughly 12 hours, we plan the trajectory design and implementation in two steps. First, we identify a feature of interest in the SCB and get a prediction of its evolution for a 12-16 hour period. The prediction output is used as input to a waypoint generation algorithm that defines the trajectories that steer the AUV to regions of scientific interest based on the given feature. After the AUV executes the planned trajectory, the collected data is uploaded and assimilated into the ocean model. A new prediction is generated and the process is repeated until the feature dissipates or is no longer of interest. Specific details and implementation results can be found in [16] and [17].

4.2.6 Website and Web-Tools

So far, we have only discussed the collection of data. However, many decisions are based upon the story that the data tells. Thus, CINAPS has developed a website (http://cinaps.usc.edu/) for the presentation of data acquired by use of the system components previously mentioned. Also included on this site is background information on the center, the collaborations on which it is built and general and technical information on our technologies and projects.

In addition to the web-based data presentation, we have also developed web-based graphical user interfaces for managing and visualizing the entire CINAPS network. Google Web Toolkit and the Google Maps API were utilized to quickly build fluid and functional interfaces for controlling the vehicles and to geometrically visualize the data acquired by all of our platforms. Through these tools, data are exported in KML format, which can be visualized by many applications, including Google Earth and ESRI ArcGIS.

5 Ocean Sampling in Southern California

Even with all of the aforementioned technology, we are still confronted with the problem that algal blooms are not predictable in their occurrences. In the case of HABs in California, we know that we are looking for markers such as an increased concentration of marine toxins such as domoic acid or saxitoxin, or the existence of harmful algal species such as *Pseudo-nitzschia* (Fig. 4(a)), *Lingulodinium polyedrum* (Fig. 4(b)), *Alexandrium spp.*, *Dinophysis spp.*, *Phaeocystis spp.*, *Cochlodinium spp.* or *Akashiwo sanguineain* in collected water samples. While several of these species generally appear during specific seasons, the dynamics and environmental factors initiating bloom development, maintenance and toxicity are still poorly understood. Through the implementation of the tools described in Section 4, we intend to build a significant time-series of data for the SCB to better guide future sampling. Additionally, these data will be included in future biological models. This will help us understand and predict the formation and evolution of harmful and other algal blooms. We continue this section by presenting some of the data collected by use of the system infrastructure described so far.

5.1 Discussion on Collected Data

5.1.1 Large-Scale Data Analysis

Autonomous underwater gliders provide one approach to observing the processes that occur in the SCB. Gliders are capable of long-term deployments; remaining out in the ocean for periods of time ranging from several weeks to several months (c.f., [5]). Although their horizontal speeds are only about 1 km/hr, their longevity, coupled with the use of multiple gliders, can compensate by providing an extended temporal and spatial series of observations.

To examine some of the local and regional processes in the SCB, we have deployed gliders on smaller-scale, *coastal* missions, typically with $25 - 30$ km alongshore scales and 20 km cross-shelf scales. A recent effort focused on monitoring the development of phytoplankton blooms that have the potential to include harmful algal species. The examples in Figs. 5(a) and 5(b) show a glider survey from a deployment in early April 2009. The portion of the SCB surveyed was in a region south and east of San Pedro and Long Beach Harbors with the planned glider trajectory depicted by the magenta line in Fig. 1(b). Figures 5(a) and 5(b) show the distribution of temperature and chlorophyll-a fluorescence, an indicator of phytoplankton biomass. These observations provide a guide for targeting sampling to evaluate whether harmful algal species are present or not. From this deployment, we see three important patterns emerging from the data. The first pattern apparent throughout the data set is that the maximum chlorophyll concentration is located below the surface, at a median depth of about 15 meters. Secondly, we notice a general decline in maximum chlorophyll concentration from the most northern to the most southern portion of the survey. Lastly in these figures, we see that where the shelf narrows in the southern portion of the survey, low chlorophyll concentrations are observed near the coast and increase as we move farther off shore.

The April 2009 deployment in the SCB had at lesast one glider continuously observing the region for two months. This time series of spatial maps enables us to couple variations in these distributions with processes occurring in the region. This allows us to evaluate the dependence of algal blooms on various meteorological and oceanographic processes that contribute to the variability in the coastal ocean.

By deploying gliders, or other mobile sensor platforms, for longer periods, it is then possible to begin to resolve seasonal, annual and longer time scales of variability. Because gliders provide a 3-dimensional view of the distributions, and the observations are telemetered in near real-time, their data can be used to target sampling from a ship for measurements that cannot be made by the glider.

5.1.2 Small-Scale Data Analysis

A primary goal of robotic and networked sensing of aquatic ecosystems is an improved understanding and predictive capability of the biological processes taking place in nature and the dynamics of the micro- and macroorganisms carrying out those processes. A prerequisite for accomplishing that goal is the acquisition of chemical, physical and biological information at scales that are appropriate for the organisms under study. Continuous, high-resolution, spatial and temporal measurements, provided by networked sensors, facilitate the identification of causal relationships between aquatic biological processes and their environmental forcing factors. Chemical and physical factors stimulating population growth or fostering mortality of planktonic microbes can vary at spatial scales vertically and horizontally of less than one millimeter to meters, and on temporal scales of less than one second to hours or days. Observations performed at *large* scales (temporal scales of days-weeks; spatial scales of kilometers) provide a valuable, integrated view of biology but the response of microbial populations to their environment typically takes place on much smaller scales.

The development, persistence and decline of harmful algal blooms of microalgae in coastal ecosystems provides an example. Noxious or toxic blooms of certain species of algae (*e.g., Pseudo-nitzschia*) can cause outbreaks of marine animal and human illness and death via the accumulation of toxins through marine food webs. These events have increased in frequency and severity in recent years, and have become a topic of intense research activity [1]. The response of toxic and noxious algal species are strongly affected by the physical and chemical parameters that vary with depth and time in coastal ecosystems, and these features can be adequately captured using dense sensing and sampling approaches. Figure 6 presents five environmental parameters (temperature, chlorophyll fluorescense, salinity, turbidity and dissolved oxygen) collected over a four-day period in King Harbor, City of Redondo Beach, California. The dynamics of these important chemical and physical factors are controlled by tidal currents (*i.e.,* note the distinct oscillations in Fig. 6) and various other nearshore water movement, including longshore currents, waves, eddies and fronts. Water movement can affect the availability of nutrients (*e.g.,* mixing of nutrients into surface waters by upward mixing of deep water), movement of algal cells into or away from lighted surface waters, and physical accumulation (or dispersal) of planktonic cells. Characterization of these forcing factors is essential to understanding the response of planktonic microbes and the development of bloom events.

Algal blooms are also affected by microorganismal behavior. Directed algal motility (upward or downward) in response to the availability of light and nutrients, or life cycle events, such as aggregation for sexual reproduction, often leads to significant, non-random distributions of algae in a water column, as can be seen in the contour plot in Fig. 7. These aggregations are typically subsurface and not readily apparent by sampling/sensing at the water surface, and are often ephemeral in time and space. Figure 7 presents a two-dimensional contour plot of the vertical distribution of algal biomass (depicted by chlorophyll fluorescence) in the water column. Note the temporal variations in the subsurface chlorophyll distribution shown in this figure. We point out that a pronounced subsurface maximum in algal biomass (red) was observed, but the absolute magnitude of the maximum changed dramatically during the examination period. The data for this experiment were collected during a two-day period in King Harbor during August 2008. Algal behavior, population growth in response to nutrient/light conditions, and population mortality due to physical dispersal, sinking, and consumption by herbivores combine to make prediction of bloom dynamics a difficult task. These features also make the study of HABs an ideal testbed for the application of embedded sensor networks in aquatic ecosystems.

6 Future Applications and Deployments

Understanding the intricacies of algal blooms, even in a regional area like the SCB, requires examination of both the small and large-scale ocean processes applicable to the region. Such examination cannot be effectively accomplished by use of a single, stand-alone sensor platform, but is best handled through the long-term, collaborative acquisition and analysis of data collected via a networked aquatic sensor system, consisting of multiple sensor platforms. The goal of the USC CINAPS team is the development of robotic approaches for documenting the movement of river discharge into the coastal ocean, coordinating these measurements to establish the movement of river plumes into the coastal ocean, and observing the consequences of these releases vis-à-vis the stimulation of algal blooms. We are also using this approach for characterizing natural sources of nutrients for phytoplankton by documenting upwelling events. The dynamic feature mapping and tracking represented by these topics are being tackled by use of wirelessly-networked static sensor packages (moorings, buoys and pier-mounted sensor packages), as well as dynamic, mobile sensor platforms (*e.g.,* autonomous gliders and ASVs). Data collected from these instruments is used to characterize and track water movement, and thereby directing the mobile platforms (and human-assisted sampling) to document the biological response.

We have chosen this important environmental problem as a *model scenario* for the development and application of our environmental sensor network, because we believe that this approach can greatly improve decisions by municipalities, counties and states for dealing with coastal pollution and HABs. However, this sensor network is not strictly limited to phytoplankton research. With the exception of a few specialized sensors, the majority of the acquired data are important in the study of any regional, coastal ocean process. Additionally, the individual nodes of the system, and accompanying network infrastructure, are not based upon the existing sensor packages. In particular, we are able to add or replace data acquisition devices, based upon the scientific interest, with no impact upon the overall network.

Collaborative and adaptive sensor systems provide us with important data relating to the health of the SCB's coastal ocean. However, an overall assessment cannot be accomplished by a single group. Our efforts dovetail with the efforts of the Southern California Coastal Ocean Observing System (SCCOOS). SCCOOS is one of eleven Regional Associations comprising the coastal component of the Integrated Ocean Observing System (IOOS). Our scales of measurement within the SCB fit well within the geographic breadth of SCCOOS and provide a detailed data set to the IOOS. For example, we make use of the larger-scale, SCCOOS surface current data to provide overall context and meteorological information for the SCB. In turn, our studies provide a more fine-scale resolution of plume tracking and biological response

With the proof of concept phases for each piece of our robotic, marine network system nearing completion, we are poised for a full-scale monitoring effort within the SCB. This undertaking will play an important role with the Southern California Bight Study planned for Spring 2010. The Bight study is a regional (Santa Barbara to the U.S.-Mexico border) study conducted once every five years. The main coordinator is the Southern California Coastal Water Research Project (SCCWRP), a public agency charged with assessing the condition, and factors that affect the condition, of a 500 km section of Southern Californias coastal environment. One stated focus of the Bight study is an analysis of the importance of natural and anthropogenic nutrient sources (upwelling, river discharge, water treatment discharge, storm drain, runoff) to the promotion of HABs in the SCB and surrounding regions. Implementation of the feature tracking algorithms based on data acquired by the entire aquatic robot network will constitute a significant contribution to this overall investigation.

References

[1] D. M. Anderson and J. S. Ramsdell. HARRNESS: a framework for HAB research and monitoring in the United States for the next decade. *Oceanography*, 18:238–245, 2005.

[2] F. Arrichiello, J. Das, H. Heidarsson, A. A. Pereira, S. Chiaverini, and G. S. Sukhatme. Multi-robot collaboration with range-limited communication: Experiments with two underactuated ASVs. In *The 7th International Conference on Field and Service Robots*, Cambridge, Massachusetts, July 2009. Accepted, to appear.

[3] X. Bai, B. Stauffer, L. Darjany, D. A. Caron, B. Zhang, A. Dhariwal, A. Pereira, J. Das, C. Oberg, and G. S. Sukhatme. Monitoring and detecting harmful algal blooms in king harbor, city of redondo beach, ca, using a wireless sensor network. `http://repositories.cdlib.org/cens/Posters/365`, October 2007. Center for Embedded Network Sensing. Posters. Paper 365.

[4] M. D. Dailey, D. J. Reish, and J. W. Anderson, editors. *Ecology of the Southern California Bight*. University of California Press, Berkley, 1993.

[5] R. E. Davis, M. Ohman, D. Rudnick, J. Sherman, and B. Hodges. Glider surveillance of physics and biology in the southern california current system. *Limnol. Oceanogr.*, 2008.

[6] M. A. Godin, J. G. Bellingham, K. Rajan, Y. Chao, and N. E. Leonard. A collaborative portal for ocean observatory control. In *Proceedings of the Marine Technology Society / Institute of Electrical and Electronics Engineers Oceans Conference*, Boston, MA, 2006.

[7] V. S. Kennedy, R. R. Twilley, J. A. Kleypas, J. J. H. Cowan, and S. R. Hare. Coastal and marine ecosystems & global climate change. In *Pew Center on Global Climate Change*, page 52, 2002.

[8] V. Kumar, D. Rus, and G. S. Sukhatme. Networked robots. In B. Siciliano and O. Khatib, editors, *Springer Handbook of Robotics*, chapter 41. Springer, 2008.

[9] G. Ohst. Clean waterfront redondo. `http://www.cleanwaterfrontredondo.org/FISH_KILLS.htm`, 2009. viewed May 2009.

[10] D. Paley, F. Zhang, and N. Leonard. Cooperative control for ocean sampling: The glider coordinated control system. *IEEE Transactions on Control Systems Technology*, 16(4):735–744, 2008.

[11] A. Pereira, J. Das, and G. S. Sukhatme. An experimental study of station keeping on an underactuated ASV. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3164–3171, 2008.

[12] A. Pereira, H. Heidarsson, D. Caron, B. Jones, and G. Sukhatme. An implementation of a communication framework for the cost-effective operation of slocum gliders in coastal regions. In *Proceedings of The* 7^{th} *International Conference on Field and Service Robotics*, Cambridge, MA, July, 2009. Accepted. To appear.

[13] S. Poduri, S. Pattem, B. Krishnamachari, and G. S. Sukhatme. Using local geometry for tunable topology control in sensor networks. *IEEE Transactions on Mobile Computing (TMC)*, 8(2):218–230, February 2009.

[14] O. Schofield, J. Kohut, D. Aragon, E. Creed, J. Graver, C. Haldman, J. Kerfoot, H. Roarty, C. Jones, D. Webb, and S. Glenn. Slocum gliders: Robust and ready. *Journal of Field Robotics*, 24(6):473–485, 2007.

[15] S. D. Silvey. *Optimal Design.* Chapman and Hall, 1980.

[16] R. N. Smith, Y. Chao, B. H. Jones, D. A. Caron, P. P. Li, and G. S. Sukhatme. Trajectory design for autonomous underwater vehicles based on ocean model predictions for feature tracking. In *Proceedings of The* 7^{th} *International Conference on Field and Service Robotics*, Cambridge, MA, July 2009. Accepted, to appear.

[17] R. N. Smith, J. Das, H. Heidarsson, A. Pereira, D. A. Caron, B. H. Jones, and G. S. Sukhatme. Implementation of an embedded sensor network for the coordination of slocum gliders for coastal monitoring and observation. In *Workshop on UnderWater Networks; ACM SenSys 2009*, Berkeley, CA, November 2009. Submitted.

[18] P. T. Strub, J. S. Allen, A. Huyer, R. L. Smith, and R. C. Beardsley. Seasonal cycle of currents, temperatures, winds and sea levels over the northeast pacific continental shelf: 35° n to 48° n. *Journal of Geophysical Research*, 92:1507–1526, 1987.

[19] U.S. Commission on Ocean Policy, Washington, D.C. *An Ocean Blueprint for the 21st Century*, September 2004. ISBN#0-9759462-0-X, `http://oceancommission.gov/`.

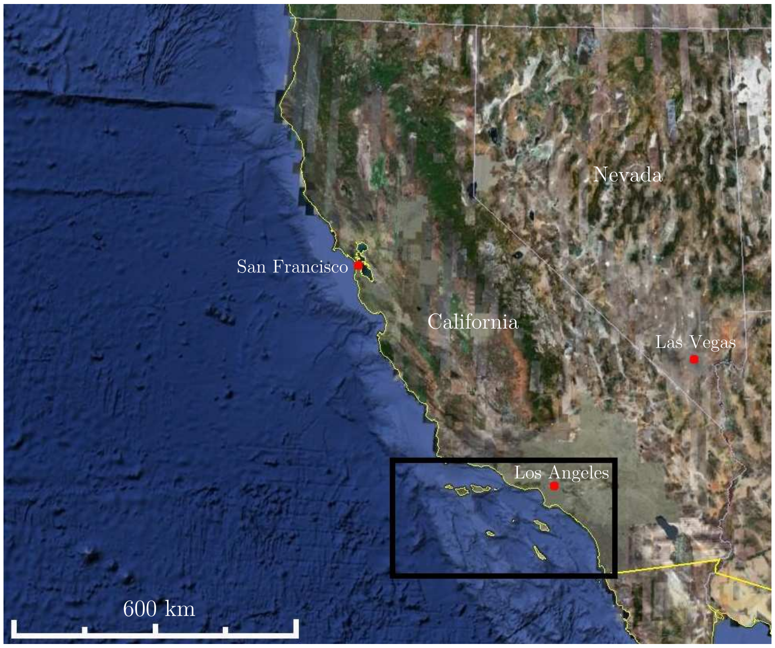
[20] J. A. Warrick and D. A. Fong. Dispersal scaling from the world's rivers. *Geophysical Research Letters*, 31(4):L04301, 2004. DOI: 10.1029/2003GL019114.

[21] L. L. Whitcomb, D. R. Yoerger, H. Singh, and J. Howland. Advances in underwater robot vehicles for deep ocean exploration: Navigation, control, and survey operations. In *Robotics Research - The Ninth International Symposium*, London, 2009. Springer-Verlag Publications.

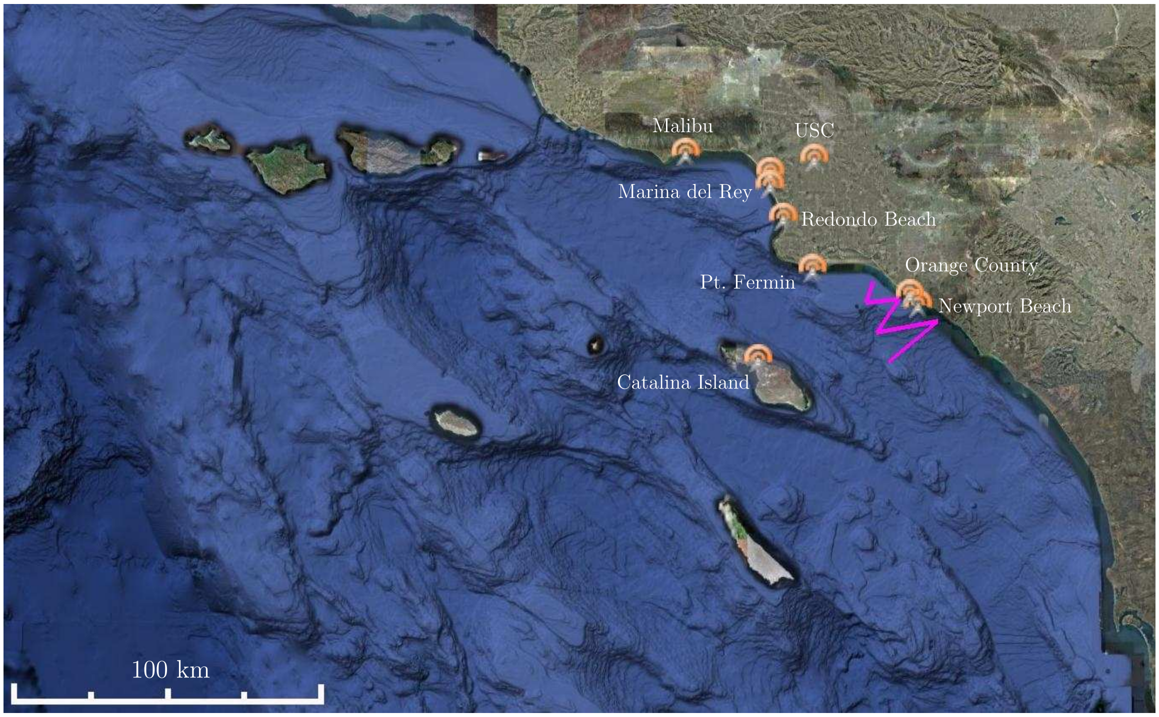
[22] B. Zhang and G. S. Sukhatme. Adaptive sampling for estimating a scalar field using a robotic boat and a sensor network. In *IEEE International Conference on Robotics and Automation*, pages 3673–3680, 2007.

List of Figures

Figures



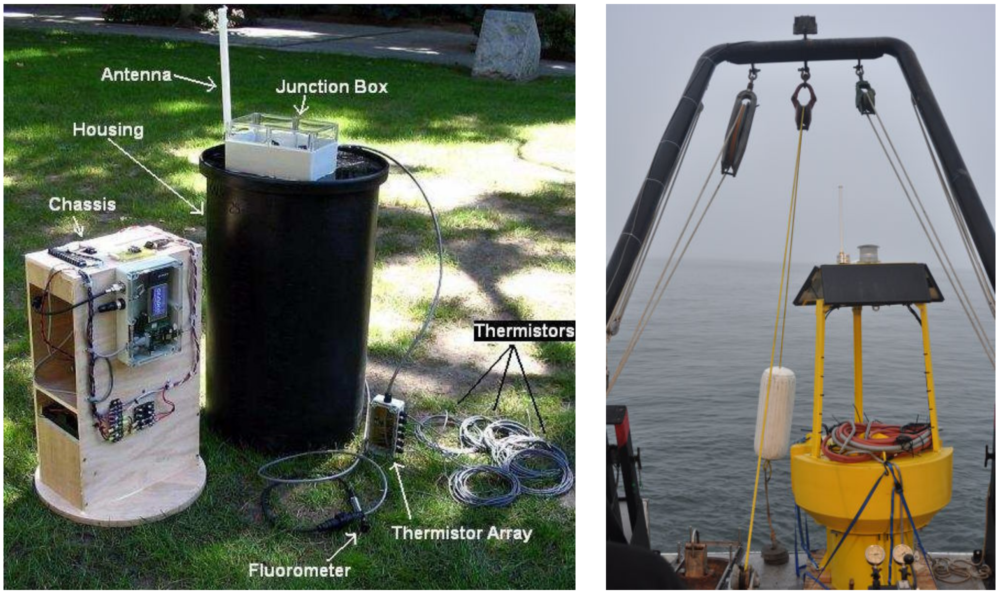
(a) California coastline. The SCB is the region in the black box, which is expanded in Fig. 1(b).



(b) The Southern California Bight.

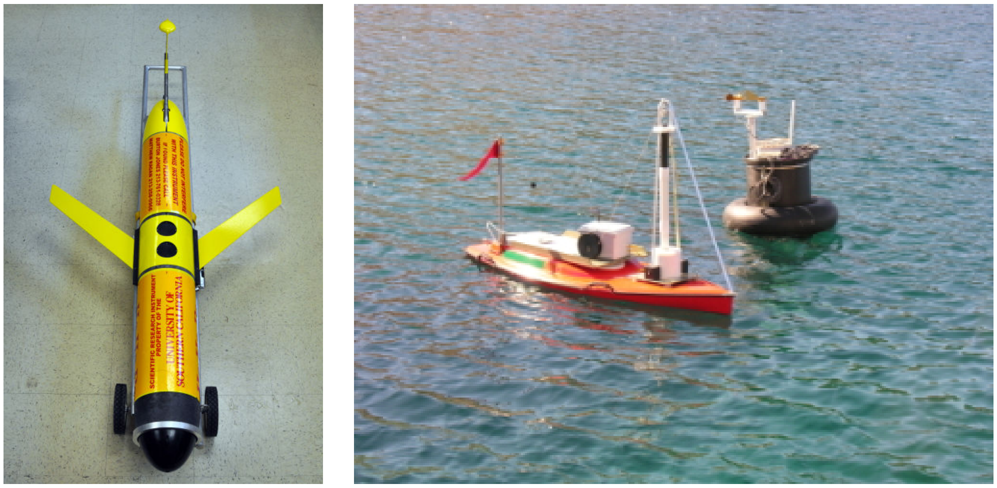
Figure 1. Primary areas of interest for CINAPS research.

Figure 2. King Harbor Marina with Hydrolab^{TM} Sondes locations identified by blue dots.



(a) Marina buoy components.

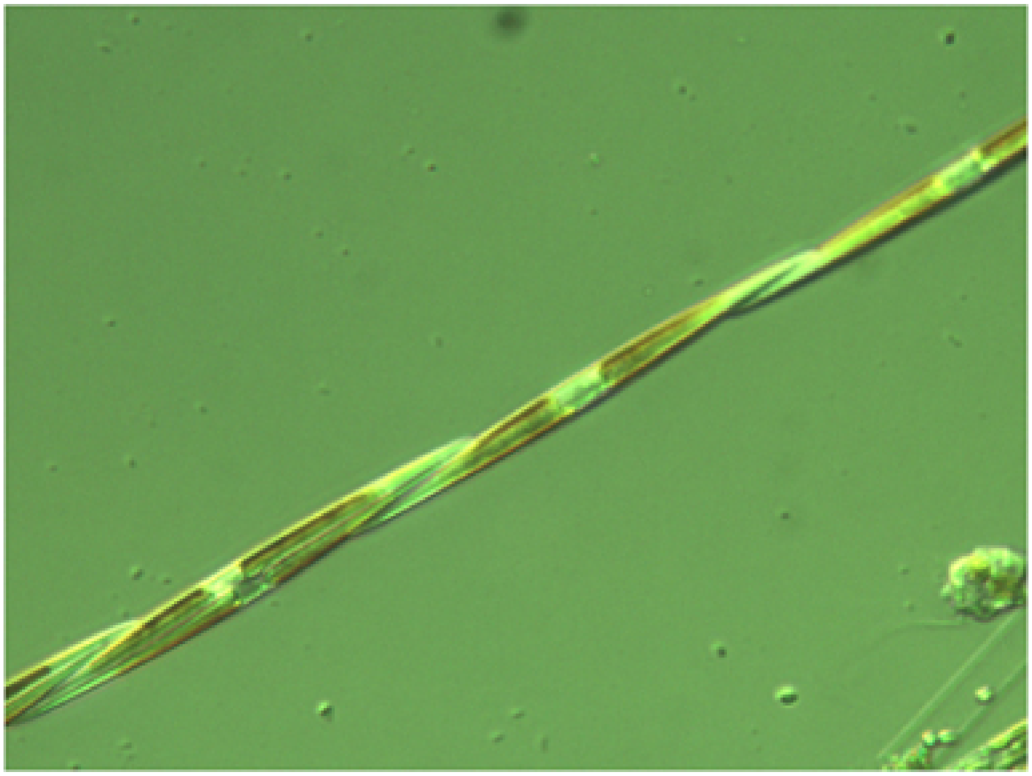
(b) Coastal Mooring.



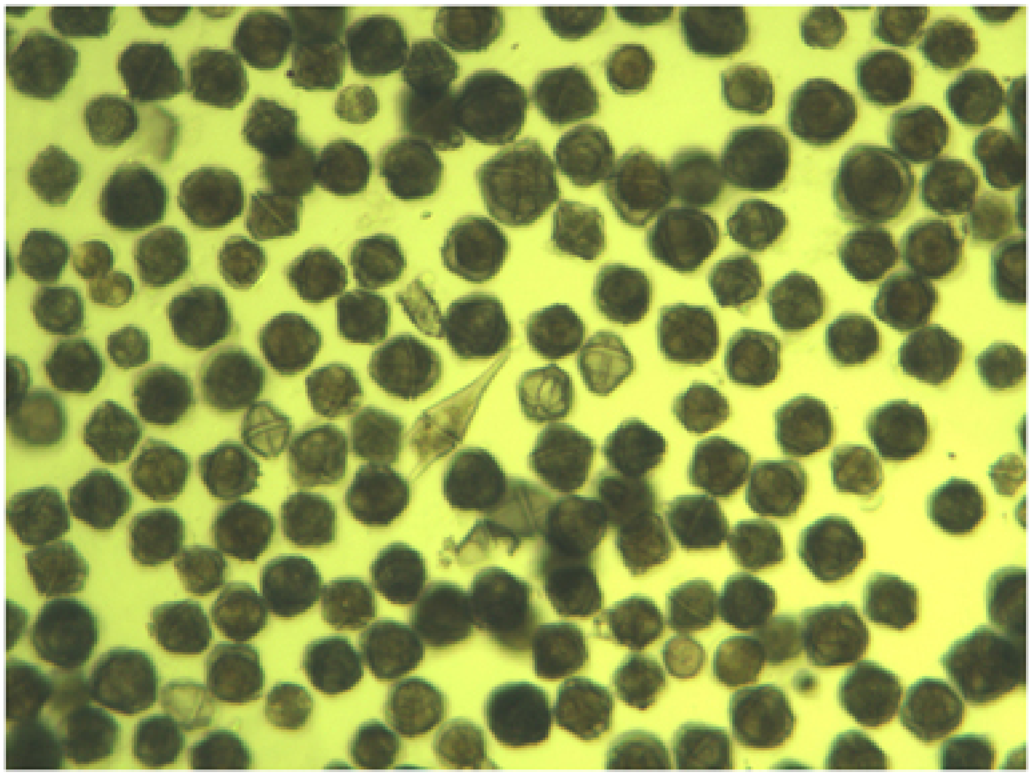
(c) Webb SLOCUM glider, *He Ha Pe*.

(d) Autonomous Surface Vehicle (ASV) and deployed marina buoy.

Figure 3. Deployed Marine Sensors.

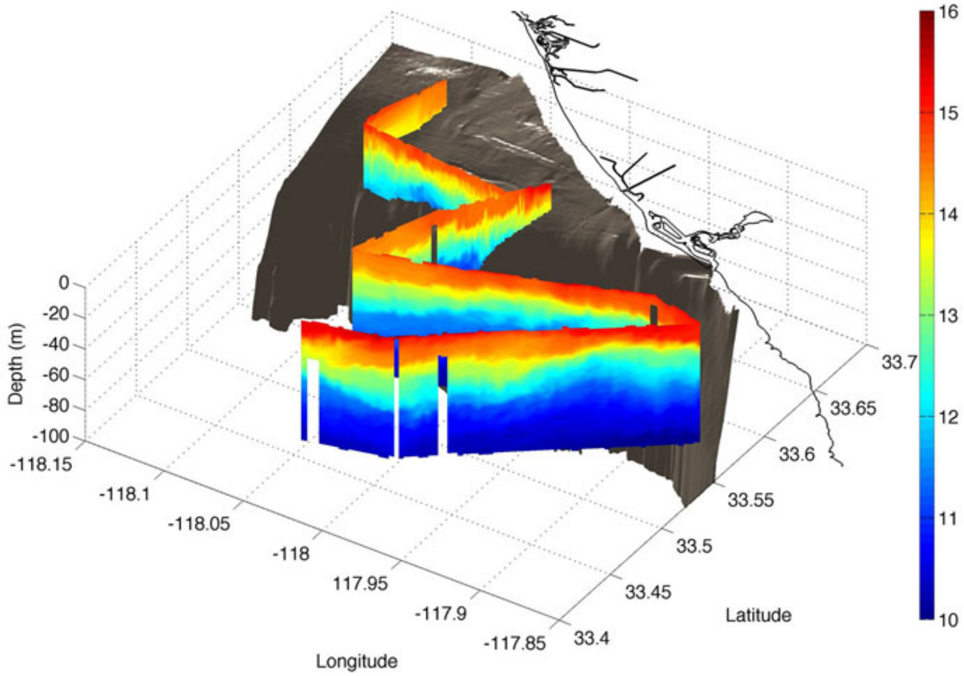


(a) *Pseudo-nitzschia*

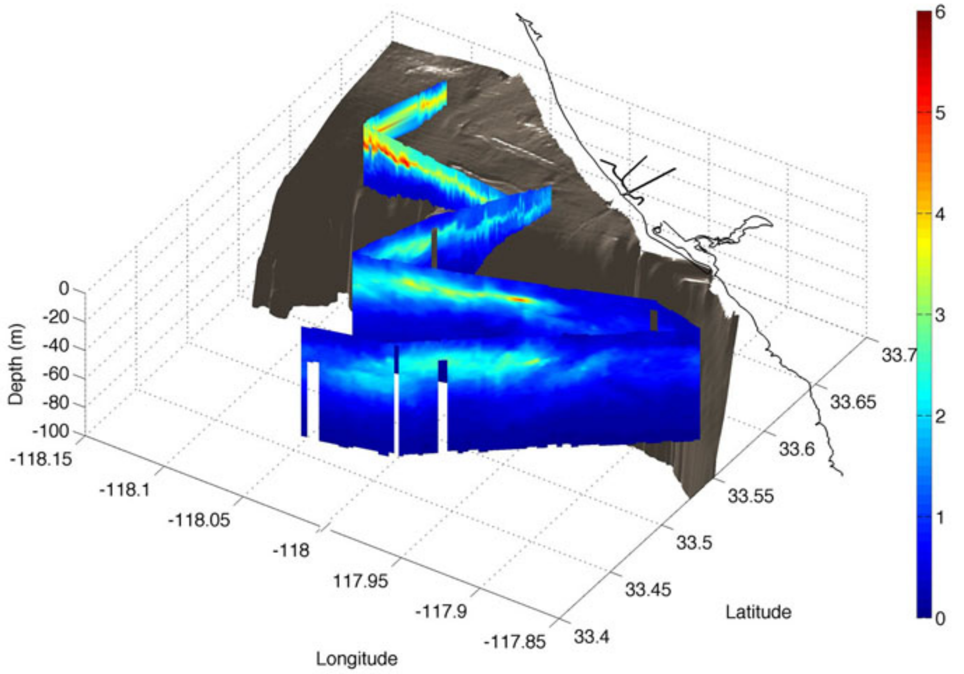


(b) *Lingulodinium polyedrum*

Figure 4. Two species of toxic phytoplankton found in Southern California waters.



(a) Temperature (C)



(b) Chlorophyll-a Fluorescence (μg/L)

Figure 5. Three-dimensional depiction of data collected along a glider trajectory during a deployment in April 2009.

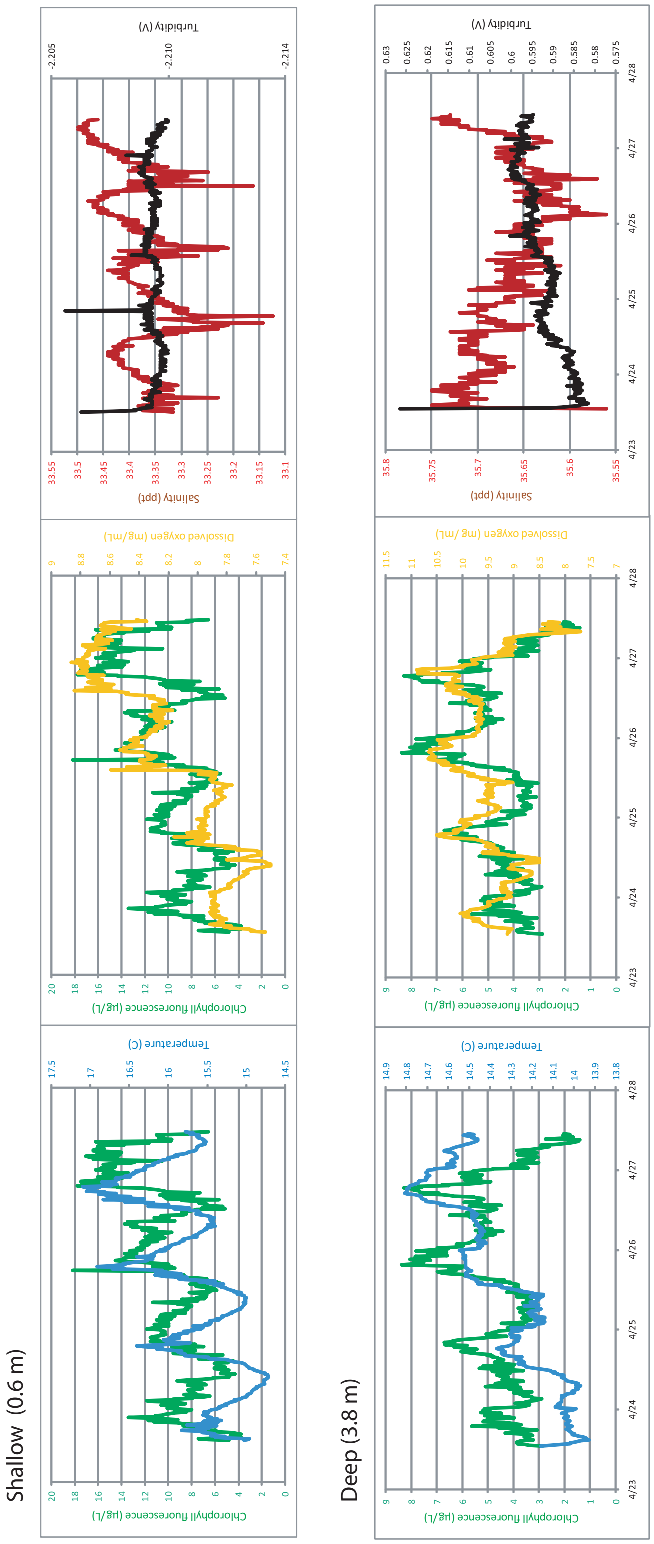
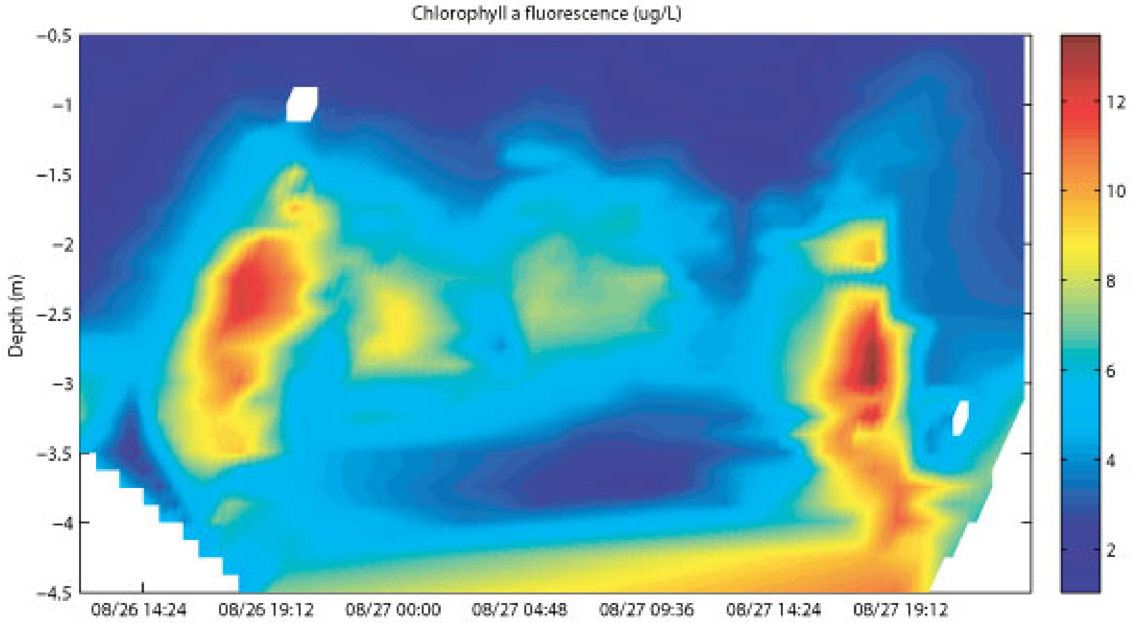
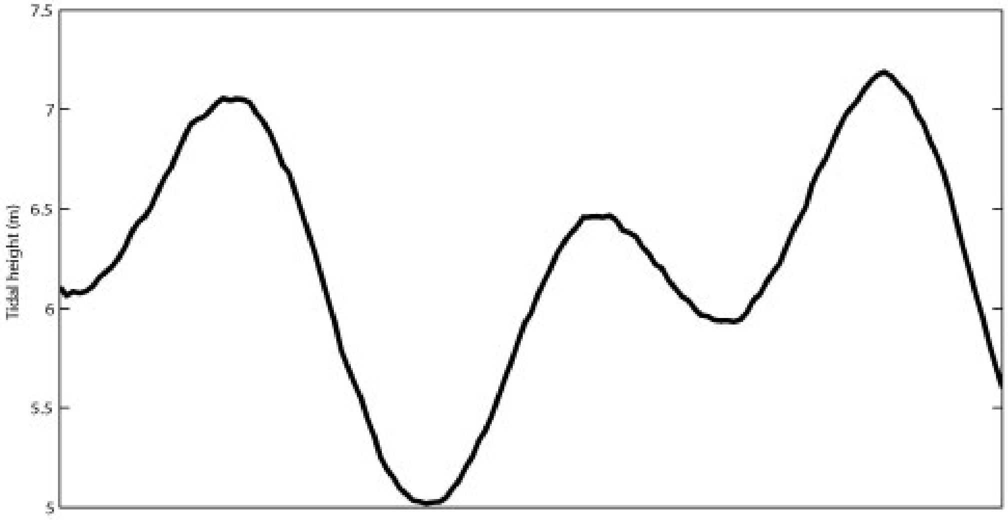


Figure 6. Environmental parameters collected over a four-day period in King Harbor, City of Redondo Beach.



(a) Two-dimensional (depth and time) contour plot of the vertical distribution of algal biomass in the water column.



(b) Tidal cycle variation.

Figure 7. Examination of the vertical distribution of algal biomass in the water column of King Harbor, City of Redondo Beach.