AQU 01 Aquatic Microbial Observing Systems

AQU 01.1 People

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AQU 01.2 Overview

The central theme of the center’s Aquatic application area continues to be the creation and application of a new genre of wireless sensing systems that will provide real-time, or near-real time monitoring capabilities of chemical, physical and biological parameters in freshwater and coastal ecosystems. These systems will enable the generation and testing of novel hypotheses about the processes that control the distribution, growth and demise of aquatic microbial populations. Our primary and continuing long-term scientific goals are to understand, model and ultimately predict the conditions under which specific populations of marine microorganisms develop and persist in nature. A fundamental requirement for attaining those goals is to correlate environmental driving forces with microorganismal abundances at spatial and temporal scales that are relevant to the microorganisms. In turn, this requirement calls for in situ sensing systems that can rapidly report emerging environmental events, and respond to and characterize ephemeral or emerging biological events in space and time.

Our work combines laboratory development and field deployment of technology for in-situ, real-time studies of microbial assemblages and concomitant environmental parameters. Laboratory studies provide a testbed for the development and testing of hardware and software for novel sensing/sampling approaches, and for detailed experimental studies of plankton behavior (growth, vertical migration, trophic interactions). Our unique approach to aquatic sensing and sampling, Networked Aquatic Microbial Observing Systems (NAMOS), employs coordinated measurements between stationary sensing nodes and robotic vehicles (surface robotic boat and more recently autonomous underwater vehicles) to provide in-situ, real-time presence for observing plankton dynamics (e.g. chlorophyll concentration, dissolved oxygen), and linking them to environmental variables (e.g. temperature, light, nutrients, etc.). Sensing and sampling capabilities of the autonomous vehicles are carried out through the development of adaptive protocols, directed through the network.

A new development within our wireless networked coastal sensing program has been the development of hardware and software for coordinated activities of underwater robotic vehicles (see Multi-scaled Actuated Sensing). The goal of this work is to develop algorithms and approaches for transmitting sensed information to shore-based facilities, assimilating the information into predictive models of coastal ocean physics, and using the resulting predictions of feature dynamics to re-task the underwater vehicles to optimize their activities (setting new tasks, way points, etc.). This work is being realized through attempts to characterize high-nutrient freshwater discharges into the coastal ocean, and the blooms of planktonic algae that are often stimulated by these inputs.

The development of new sensors, or new detection protocols, has been a minor component of this project. This work has largely been performed in coordination with other CENS groups whose primary objective is the development of innovative sensors. The development of a culture chamber on a chip has been pursued by the research group of Tai at CalTech, while the development of a single-cell approach for measuring domoic acid.
production by toxin-producing algae has been conducted by Ho’s group at UCLA. The aquatic group has provided cultures of algae and toxin for those projects as well as guidance and laboratory assistance.

Three specific applications have been developed during the past year that have involved the development and deployment of sensor networks to examine microbial plankton dynamics in the coastal ocean of southern California:

Marine coastal deployments of autonomous surface and underwater vehicles.

- Deployment of NAMOS (Networked Aquatic Microbial Observing Systems) in support of observational and experimental studies of the harmful algal bloom-forming species, *Heterosigma akashiwo* that causes fish kills.
- Use of NAMOS for studying vertical migration and photoadaptation in phytoplankton bloom formation and persistence.

**AQU 01.3 Approach**

During the center’s initial years, we began by examining network designs and components in a laboratory testbed. In 2005 and 2006, we constructed and deployed a full-scale distributed sensing system in Lake Fulmor on the James Reserve. We subsequently designed and constructed a unique ‘hybrid’ system, NAMOS (Networked Aquatic Microbial Observing Systems), which comprises a wireless buoy sensing system (or pier-mounted sensing system) and a robotic surface vehicle capable of sensing and/or sampling. This system represented a conscious effort to obtain both high-resolution temporal information on pertinent environmental parameters (information provided by the network of static sensor packages on buoys or piers) and high-resolution spatial data collected during periods of interest such as microalgal bloom events (using the capabilities of the robotic boat).

Our systems generate contextual information on a variety of physical, chemical and biological features of a water body and intensively observe particular locales during interesting transient events. The importance of these types of measurements is essential in trying to understand the highly dynamic nature of aquatic ecosystems and the rapid response of microbial communities to these driving forces. This is only possible because we use information streaming from the buoys to guide the boat. This distributed system was deployed multiple times in Lake Fulmor (James Reserve) to study plankton dynamics. The development of NAMOS and its successful use in Lake Fulmor resulted in a template for the design and construction of sensing systems that have now been employed in other settings.

Our goal for the field component of Networked Aquatic Microbial Observing Systems is to develop robust, decentralized algorithms and supporting hardware that enable a wireless sensor network consisting of sensor-equipped buoys (or pier-based sensor packages) and a sensor/sampler-equipped autonomous vehicle (robotic boat) to perform adaptive hydrographic and biological sampling using the information provided by the network. Until 2007, field studies had focused on the small Lake Fulmor ecosystem at the James Reserve in the San Jacinto Mountain. A subsequent, short deployment in Arrowhead Lake during a recent CENS retreat there presented a test scenario for rapid deployment of NAMOS, as well as the establishment of a collaborative effort with the Arrowhead Lake Association for studying water quality within the lake (see Partnerships and Knowledge Transfer below). These initial deployments provided an interesting natural testbed for our work, the acquisition of novel data sets and interpretations of these freshwater ecosystems, and an excellent opportunity for interacting with other components of the CENS community. Our most recent applications involving NAMOS include build-outs into two coastal marine ecosystems; King Harbor of the City of Redondo Beach, and Marina Del Rey, CA.

Deployments in King Harbor of the City of Redondo Beach in 2007-2008 represented our first full ‘build out’ of NAMOS in a marine ecosystem, and a new and potentially far-reaching beginning of a relationship with the City to address issues of coastal water quality. Coastal municipalities nationwide have struggled to maintain high levels of water quality in their harbors and on their beaches in the face of an onslaught of chemical and biological contaminants originating from the activities within their own communities, or via the transport of various contaminants from inland sources via storm drains, rivers or effluent pipes. The threat of anthropogenic inputs to the coastal waters of urbanized regions of the country, in particular, has increased dramatically in recent decades.
Efforts by municipalities to provide responsible environmental stewardship of their coastal waters are often thwarted by a lack of water quality data and inadequate scientific understanding.

King Harbor of the City of Redondo Beach suffered microalgal blooms and consequent fish kills in 2005. Algal blooms recurred in 2006 without fish kills. City officials hypothesized that low oxygen levels, resulting from a rapid & intense accumulation of algal biomass, were responsible for the fish mortality of 2005. During Spring 2007 we initiated the continuous deployment of an environmental sensor network at several locations throughout the harbor to test this hypothesis.

While the work performed in King Harbor is addressing an important and specific issue of water quality, we feel that this project is actively generating a ‘template’ that other coastal municipalities will be able to use to design coastal monitoring networks that are applicable to their particular situations. During 2008 we began to ‘export’ this technology and the NAMOS approach developed in King Harbor into Marina Del Rey, another highly urbanized harbor region within the greater Los Angeles area. The network design employed in King Harbor is presently being implemented in Marina Del Rey. The data output and web portal developed for the Marina Del Rey build-out will be incorporated into the output for King Harbor during 2009.

A larger-scale implementation of a distributed sensing system in the coastal ocean is being conducted in conjunction with a NOAA-funded Monitoring and Event Response for Harmful Algal Blooms (MERHAB) program entitled Rapid Analysis of _Pseudo-nitzschia_ & Domoic Acid, Locating Events in near-Real Time (RAPDALERT). Here, we have used CENS hardware, software, and overall approaches in coastal waters near LA Harbor to study the environmental factors leading to toxic algal blooms caused by phytoplankton species that produce the powerful neurotoxin domoic acid. This project brings together CENS- and non-CENS investigators to develop and deploy a network of coastal sensor buoys. The project also employs autonomous underwater vehicles (Webb gliders) whose movements and activities are controlled by information gathered by the static sensor buoys, in a manner analogous to the present control of the robotic boat in our NAMOS project.

During 2007-2008, this latter project has focused on the hardware and software issues associated with vehicle communications, coordination and retasking (see summary of accomplishments in Multi-scaled Actuated Sensing). Considerable biological information has been acquired within the process of the iterative experiments carried out in the coastal environment of the San Pedro shelf region. The advancements in vehicle control accomplished through CENS constitute major advancements in our ability to characterize rapidly evolving biological events in the coastal ocean.

These field projects in urbanized coastal ecosystems have multiple levels of relevance; firstly, the research provides important theoretical insights into both the design and implementation of environmental sensing systems and the environmental factors leading to harmful algal blooms. Secondly, the projects have practical importance in that they provide government officials in these coastal municipalities with the vital information that is needed to make informed decisions regarding remediation and/or prevention of future harmful events. A major unanswered question regarding recent increases of HABs and other contamination events in the greater Los Angeles region is how human activities on land affect the occurrence and severity of these events in the coastal ocean. Finally, we feel that our collaboration with these cities is an excellent template for how CENS can assist other coastal municipalities in using distributed sensing systems to address issues surrounding coastal water quality.

Our laboratory work continues to involve the development and testing of novel sensors/samplers, the development of supporting software and hardware, and the testing of these novel approaches in ‘artificial water columns’ used to simulate natural planktonic environments. We have also incorporated more field-based, hypothesis-driven studies into the roles of vertical migration, photoadaptation, and trophic interactions to further investigate the spatio-temporal dynamics of algal bloom formation, development, and persistence in the Redondo Beach ecosystem.
AQU 01.4 Systems/Experiments

Field deployments in previous years focused on the plankton community in Lake Fulmor, near the James Reserve in the San Jacinto Mountains of Southern California. From the data collected by the static buoy system and the sensor-equipped robotic boat, correlations were detected between the physical lake environment (i.e. wind-induced mixing) and the biological constituents (i.e. chlorophyll concentrations and depth distributions). The relationships between these parameters have now been published in the journal of Limnology and Oceanography, the flagship journal of the marine and aquatic sciences, in a special volume dedicated to advances in aquatic sensing platforms. Additional papers are in preparation based on related datasets, correlating environmental parameters to photoadaptive indices in the water column over diel cycles, as well as a more descriptive paper detailing the seasonal compositional changes in the plankton community in this small sub-alpine lake.

Experiments in coastal ecosystems during the last funding cycle have focused primarily on the King Harbor of the City of Redondo Beach, California, a heavily urbanized harbor with recurrent algal blooms, and the larger-scale build-out of a more oceanic sensor network throughout the Southern California Bight as described below.

Marine Coastal Deployments

The Aquatic research group of CENS has been involved in a joint project with the City of Redondo Beach since 2006. The goal of our research is the design and implementation of an ‘environmental sensor network’ that will vastly increase our ability to make observations in nature, and thereby identify linkages between environmental forcing factors and ecosystem response. We have chosen King Harbor of the City of Redondo Beach as our test site with the overall goal of understanding the factors leading to recurring algal blooms and recent fish kills in the harbor. King Harbor is an enclosed series of basins housing three marinas, and is contiguous with the Redondo Beach Pier and Esplanade. Unprecedented algal blooms in King Harbor resulted in massive fish kills in 2005 and recurring blooms during 2006. Our on-going research project has been focused on developing and applying sensor networks to monitor the chemical, physical, and biological environment within the harbor and their relationship to algal blooms and fish kills. In addition, we have been developing a web-based portal for presentation of the data streaming from the sensor network in near-real time.

The short-term goals of applying sensor network technology in King Harbor are to (1) determine the immediate cause of the fish kills, and (2) evaluate approach(es) to mitigate these events. The long-term objective is to develop an understanding of the factors leading to fish kills, with the ultimate goal of preventing these harmful events. The ‘CENS related’ goal of this project is the design, construction and implement a sensor network that will have practical and specific application to a societally relevant issue involving water quality in a coastal ecosystem. We envision this project as addressing an existing environmental issue, but also as a means of developing a ‘template’ that can be adapted in the future to provide sensor networks for applications in other coastal environments with other water quality issues.

The static components of the network (sensor-equipped buoys and pier-mounted sensors) constitute a ‘sentinel’ activity to monitor constantly for signs of an emerging environmental issue (in this case, a ‘red tide’ of other harmful algal bloom). Since 2006, the sensors on these buoys have been upgraded to include Hydrolab DSS multi-parameter sondes. These sensors measure depth, temperature, salinity, dissolved oxygen, chlorophyll a fluorescence, and turbidity. Three buoys are located throughout the harbor in sites representative of the two marina basins (King Harbor and Port Royal) and near the entrance to the southern basin (Harbor Patrol dock [HP]), as illustrated in Figure 1.
Each buoy (Figure 2) is outfitted with 2 sondes, deployed near surface (0.5m) and near-bottom (4.5m). We have also employed sensor packages tethered directly to the dock. The data is streamed back to the onboard buoy computer. We are working towards uploading the data in near-real-time to the internet. This last task has been delayed due to lack of internet connection. We have recently begun a collaborative research project with the West Basin Municipal Water Facility located in El Segundo, CA. This facility will soon be operating a pilot desalination project at Redondo Beach. As a part of that collaboration, we are establishing a coastal ocean buoy just outside the breakwater surrounding King Harbor (Figure 1). This buoy will allow (1) additional sensor measurements in this coastal ocean region, (2) an internet hub for uploading the offshore and harbor sensor data, and (3) a common web portal for display of the data in near-real time.

We have significantly increased our ability to characterize short- and long-term changes in environmental parameters in the water column of King Harbor, and relate these changes to alterations in the composition and dynamics of the plankton community. The ability of NAMOS to document changes in environmental parameters that are pertinent to phytoplankton growth are exemplified below for an unusual rain event in September 2007 (Figure 3). These data show decreasing water temperature and salinity following the rain event on 21 September at both the Harbor Patrol (red lines) and Port Royal (blue lines) locations (Figure 3A, B). There was spatial heterogeneity in the response of the phytoplankton population to the rain event, however, with surface chlorophyll concentrations at the Port Royal location showing a significantly greater increase than those at

Figure 3: Time-series plots of temperature (A), salinity (B), chlorophyll fluorescence (C), and dissolved oxygen (D) in King Harbor, Redondo Beach, during a rain event that began on 21 September 2007. Red lines the Harbor Patrol dock location (HP), near the entrance to the lower marina basin. Blue lines are data from a sensor placed in the Port Royal marina (PR), in the back corner of the lower basin. The light blue rectangle denotes the approximate period of rainfall.
the Harbor Patrol location (Figure 3C). This is most likely due to the enclosed location of Port Royal (see Figure 1) that serves as an “incubator” compared to the well-mixed and open area of the Harbor Patrol site. The increase in algal biomass did not necessarily translate to an immediate change in dissolved oxygen concentrations, although a slight downward trend was somewhat apparent.

The fixed spatial and depth distributions of the sensors attached to buoys or attached to piers provide a high-resolution understanding of processes controlling algal blooms throughout the larger harbor and water column. However, typical deployments lack the density of sensors necessary to fully characterize the spatial distribution of plankton and forcing factors. The use of the static buoys in combination with the mobile robotic boat equipped with a vertically profiling sensor is the approach we have taken to amplify our sensing power. A significant goal of the NAMOS project has been the development and application of algorithms that use sensed data to respond rapidly to changing environmental parameters, thus maximizing the use of limited and valuable sampling/sensing resources. This has been accomplished up to recently using a robotic boat (in combination with stationary sensors on buoys and piers) for synoptic measurements of pertinent environmental and biological parameters (including chlorophyll concentration and dissolved oxygen) to characterize an emerging event and its possible driving factors (Figure 4; also see ‘Roles of Vertical Migration and Photoadaptation in Bloom Formation and Persistence’ below). The combined buoy/boat data has been used to direct manual and/or automated sample collection and also experimental field work by the research team. This work is enabling a ‘system-level’ analysis and modeling effort of the harbor, and the use of our robotic boat within the harbor in conjunction with the sensor buoys has allowed us to begin to fully characterize the harbor water column (Fig. 4A).

![Figure 4. (A) Vertical profile of sensed parameters in Redondo Beach (temperature, salinity, dissolved oxygen, chlorophyll fluorescence) obtained using the robotic Q-boat, as pictured in (B).](image)

During the present funding cycle, this approach has been expanded to include retasking of autonomous underwater vehicles (gliders) to optimize feature-following such as freshwater plume discharges into coastal ecosystems (see Multi-scaled Actuated Sensing).

New developments for increasing our ability to characterize the spatial and temporal dynamics of chemical, physical and biological parameters include the design and construction of a pier-mounted vertical profiling system (Figure 5). The system employs a small winch (white box in center of Fig. 5) that is used to raise and lower a sensor package (cylindrical package just below the water surface) in a water column according to a programmed schedule. The large plastic container houses batteries and the computer running the software that controls the vertical movement/positioning of the sensor package, and also collects the data streaming from the sensor package. The winching system was recently employed to study the dynamics of microalgae in the water column of King Harbor over a diel (24 hr) cycle. The collection of ancillary data on ecologically important environmental parameters
greatly enhances the ability to understand the forces affecting algal abundances and dynamics in the water column (see ‘Roles of Vertical Migration and Photoadaptation in Bloom Formation and Persistence’ below).

Fine-scale spatial patterns of chemical or physical parameters derived from the network of sensor buoys have indicated the relevance of these measurements for explaining the dynamics of phytoplankton biomass (i.e. chlorophyll fluorescence), or chemistry that is dependent upon biological activity. For example, fine-scale vertical patterns of dissolved oxygen in the water column on different days indicated significant differences in this biologically-determined parameter. Concentrations of oxygen in a recent study differed on different days (Figure 6; four colors) and also with depth on any given day (each color; indicating a single profile) over the relatively short water column.

The stationary NAMOS sensor platforms have also been employed to collect exceptionally high resolution temporal data at specific depths and locales with King Harbor (Figure 7). Sensor packages deployed at two depths at the same location in the harbor and equipped to measure temperature, chlorophyll fluorescence, dissolved oxygen, turbidity and salinity have recorded significant differences in these parameters that are related to tide, depth, and time of day. Populations of phytoplankton integrate the effects of these complex temporal patterns in chemical and physical parameters. Thus, understanding their population dynamics in these coastal ecosystems must take the variability associated with these forcing factors into account.

Considerable horizontal variability in sensed parameters has also been recorded by the stationary sensors within the relatively narrow spatial extent of King Harbor. Sensor packages have been located for more than a year in three regions of King Harbor (King Harbor Marina, Port Royal Marina, and the Harbor Patrol facilities (Figure 1). A month-long record of chlorophyll fluorescence (a proxy for phytoplankton biomass) at the three locations is shown in Figure 8 during 2008. Two substantial phytoplankton blooms were observed within King Harbor Marina during this month-long observational period (Fig 8A). In contrast, only a minor bloom occurred at the Harbor patrol station, and no significant increase in phytoplankton biomass was observed at the Port Royal Marina location. These differences were mirrored by increased concentrations of dissolved oxygen during the phytoplankton bloom in King Harbor Marina (Fig. 8C).
Characterization of both the vertical and horizontal distribution of biomass and environmental parameters in King Harbor is essential for resolving the cause of fish kills there. Present assumptions are that (1) the immediate cause of the fish kills is the depletion of dissolved oxygen in the water during blooms (temporal and horizontal variability in dissolved oxygen concentrations have been measured by the buoys and boat, respectively), and (2) these blooms...
are not produced within the harbor but rather develop in coastal waters and are advected into the harbor. The latter issue is being addressed by examining the appearance of the bloom across the coarse spatial (horizontal) grid provided by the network of buoys, with increased resolution provided by the robotic boat and, ultimately, outer harbor and Santa Monica Bay Webb glider deployments.

Experimental Studies of Heterosigma akashiwo populations employing NAMOS technology and approaches

The NAMOS sensor network and robotic vehicles have greatly facilitated investigation of the roles of environmentally-driven conditions, or ‘bottom-up’ controls, on the dynamics of microalgal populations in King Harbor. When combined with cutting-edge genetics approaches for identifying and enumerating microalgae, NAMOS approaches have supported investigations of the dynamics of potentially harmful algal species. These investigations have provided unique insight into (1) the species causing fish kills and other harmful environmental impacts in King Harbor and (2) the environmental conditions conducive to these harmful events. Towards that end, we have combined the use of microscopy and genetics with NAMOS sensing technology to investigation the ecology of the raphidophyte alga Heterosigma akashiwo, a species known to cause fish kills in other parts of the world and known to be present in King Harbor. We have performed experimental studies to follow the seasonal changes in species composition of King Harbor, and to estimate ‘top-down’ control on H. akashiwo specifically in order to estimate the effects of grazing pressure on this microalgal species. Studies of grazing pressure have been undertaken through a series of field-based experiments to investigate the relationship between grazing and bloom formation.

Many species of harmful phytoplankton have been detected in King Harbor (Figure 9); among these are several dinoflagellate species and the raphidophyte Heterosigma akashiwo, which was observed blooming to high abundance on more than one occasion. Raphidophytes are difficult to identify using classical microscopical techniques due to their relatively soluble cell walls which do not preserve well. We have therefore developed and utilized a molecular-based quantitative real-time PCR method for the detection and enumeration of H. akashiwo in the natural samples.

The qPCR method, which detects and counts multiple raphidophyte species, was applied to a set of natural samples collected from King Harbor over the course of a year. The analysis demonstrated the presence of three potentially harmful raphidophyte species including Chattonella marina, Fibracapsa japonica, and H. akashiwo (Figure 10).

Weekly sampling of surface water in King Harbor Marina has been conducted since mid-2006. H. akashiwo has been present at least at low abundances (<25 cells ml⁻¹) throughout this period. Two blooms were observed in June 2006 and 2007, when cell densities reached 21,000 cells ml⁻¹ and 2,500 cells ml⁻¹, respectively. Both C. marina, F. japonica have also detectable been during the study.

The impact of microbial consumers on H. akashiwo population dynamics, has been examined through experiments carried out during a bloom in June 2007 and periodically thereafter. Results of these studies have revealed significantly higher growth rates in seawater that was prefiltered through <20µm screening (excluding potential microbial predators) that were present in the unfiltered seawater (Figure 11). These results indicate that significant

Figure 9: Time-series of extracted chlorophyll levels at weekly intervals. Arrows and photos indicate dominant phytoplankton during bloom periods (A, clockwise from top) Akashiwo sanguinea, two Prorocentrum species, and (B) Heterosigma akashiwo, Cochlodinium fulvescens, and Ceratium lineatum.
grazing pressure on *H. akashiwo* exists in the surface waters of King Harbor, a situation that may keep algal blooms in check for most of the year. Among the six experiments shown in Figure 11, four of them showed negative growth rates even after removing grazers, suggesting that nutrients may also be limiting *H. akashiwo* growth during much of the year.

**Roles of Vertical Migration and Photoadaptation in Bloom Formation and Persistence:**  
Experimental studies of phytoplankton dynamics in King Harbor, supported by NAMOS approaches, have been conducted since 2007. Initial work included bathymetric characterization of the harbor (Figure 12A) collected using profiling sonar mounted on the robotic QBoat, combined with current speed measurements from an acoustic Doppler current profile (ADCP), and measurements of tidal height. This work established that the entire volume of King Harbor has a turnover time on the order of 12 hours. Investigations into biological parameters contributing to bloom formation and persistence have focused on vertical migration and photoadaptation trends over diel cycles in King Harbor. Studies undertaken in June 2007 during a *H. akashiwo* bloom noted a relationship between nutrients and the tidal cycle (Figure 12B,C). Surface concentrations of nitrate (NO$_3^-$) were higher at lower-tide points in the tidal cycle, and lower during the peak of the high tide. These data suggest the intrusion of more oceanic (and lower nutrient) Santa Monica Bay water during high tides and the potential flushing of stormwater drains (many of which are present in the harbor) or input of other higher nutrient water during low tides. Overall, there appears to be very strong tidal flushing of nutrients into and out of the King Harbor system.
Experiments during 2008 expanded on the finding from 2007, and have further resolved some of the complex relationship between tidal cycle, nutrient inputs, and the resulting phytoplankton abundance and physiological condition in the water column. The ability of planktonic organisms to maintain photosynthesis despite physiological stresses, such as photo-oxidative damage resulting from excess or poor quality light or nutrient limitation, may afford a selective advantage to some species over others and thus help explain the succession of bloom-forming species we have observed in King Harbor. To investigate this, we have measured photosynthetic yield using an active fluorometer from Turner Designs. Yield is a measure of the proportion of photosystem II (PSII) reaction centers that have been closed due to stress (lower yield = more closed reactions centers), and gives a general indication of overall photosynthetic health. Data from the diel studies conducted in June and November show different patterns of yield in the field population with depth and over time (Figure 13), which may be related to the difference in the dominant phytoplankton during these studies (H. a k a s h i w o and A. sanguinea/C. fulvescens, respectively) or to the fundamental differences in

Figure 12: (A) Bathymetric map of the lower basin in King Harbor, measured by QBoat-mounted profiling sonar. Scale is below the map. (B) Tidal cycle (in meters), taken from a NOAA buoy in Santa Monica Bay, over the June 2007 diel study. (C) Nitrate (NO3-) concentrations, measured at several timepoints (colors) and multiple depths (y-axis, in meters) during the June study. Arrows indicate timepoints of nutrient samples on the tidal cycle.

Figure 13: Extracted chlorophyll (blue lines) and photosynthetic yield (red diamonds) for populations in June (A, B) and November (C, D) in King Harbor. Y-axis is depth in meters.
the physical or chemical environments between these times (i.e. overall lower water temperature, light in November).

Diel experiments carried out during 2008 have addressed the influence of tidal cycle on nutrient concentrations and phytoplankton population response in King Harbor. Nutrient concentrations in surface waters of the harbor revealed a significant relationship with the tidal cycle (Figure 14). Elevated nutrient concentrations were observed during high tide periods, perhaps indicating the advective input of nutrients to the water column from waters outside the harbor.

In turn, nutrient concentrations in the surface waters of the harbor affected the total amount of phytoplankton biomass (i.e. chlorophyll concentration) observed in this enclosed ecosystem. A positive correlation was observed between the amount of algal biomass at the depth of the algal maximum in the water column and the tidal height (Figure 15). Given that nutrient concentrations correlated with tidal height (Figure 14), the latter feature appears to represent a proxy for overall nutrient status in the harbor.

Figure 14. Data from two-day study in King Harbor in August 2008 indicate a relationship between tidal cycle and nutrient concentrations (ammonium) in surface waters.

Figure 15. The concentration of phytoplankton biomass (as shown by chlorophyll concentration) in the water column of King Harbor correlated with tidal height during observations made during two diel (day-long) experiments in the harbor during August 2008. Nutrient input occurring during the incoming tide apparently is responsible for the close relationship. Tidal advective processes and perhaps mixing constitute important driving forces for the biology of this small, enclosed embayment.
Phytoplankton responses to the rapidly changing physical and chemical structure of the harbor are considerable. Phytoplankton communities within the harbor are dynamic in terms of species composition of the assemblage and it terms of behavior. Phytoplankton physiological response and vertical migratory behavior resulted in pronounced, short-lived subsurface maxima in abundance during the diel studies (Figure 16). Characterization of these features was made possible by the application of NAMOS technology and approaches.

Marine Coastal Deployments of Autonomous Vehicles

The build-out of the NAMOS approach into open coastal oceans has required the use of more robust robotic vehicles than have been used in the freshwater bodies and protected embayments in past CENS Aquatic Application campaigns. However, the same overall approach and software developed for controlling smaller vehicles, winches, etc. has proven applicable to the larger, more robust systems. For our research along the open coast of southern California, we have employed a Webb SLOCUM glider as the primary mobile vehicle for autonomous sensing. While the unmodified version of this vehicle is capable of autonomous, preprogrammed flight (Figure 17), our NAMOS group is in the process of modifying the capabilities of these vehicles to allow (1) retasking of vehicles during a mission and (2) coordinated activities of multiple gliders to enable gliders to follow features that change in space and time thus making more efficient use of mission time (see Multi-scaled Actuated Sensing). This work is enabled by coordinating NAMOS objectives with the overall objectives of a NOAA-funded project.

Figure 16. The vertical distribution of algal biomass in the water column of King Harbor during a two-day observational period in August 2008. A pronounced subsurface maximum in abundance (red color) was observed throughout the study period, but the absolute magnitude of the maximum changed dramatically during the examination period.

Figure 17. Cross-sectional pictures of temperature, salinity, backscatter and chlorophyll fluorescence (top to bottom) in an onshore-offshore transect along the California coast in the vicinity of Newport Beach, CA. The purple oval indicates the presence of a subsurface maximum in phytoplankton biomass (i.e. chlorophyll fluorescence) that indicates the presence of a subsurface algal bloom.
The RAPDALERT grant focuses, in part, on the application of wireless sensor networks in the coastal ocean for the detection and study of toxic phytoplankton blooms. Coordination with that project allows access to a SLOCUM glider that has been used for hardware and software modifications that will improve the glider’s capabilities as noted above.

This work represents a contribution of CENS approaches, and an extension of NAMOS technologies, that will have a very significant impact on design and implementation of coastal Ocean Observing Systems (OOS) that are now developing along our coastlines. Moreover, this work provides a direct link between the study of harmful algal blooms and a regional OOS, the Southern California Coastal Ocean Observing System, with whom we work collaboratively on this aspect of the research.

Most recently, the glider has been employed to characterize an emerging phytoplankton bloom off the southern California coast in the vicinity of Newport Beach (Figure 18). Significant winter rain events in southern California are known to trigger the development of phytoplankton blooms in nearshore waters. These phytoplankton blooms are often dominated by harmful algae that are capable of the production of the powerful neurotoxin domoic acid. A glider mission conducted in February 2009 has documented the appearance of a subsurface increase in chlorophyll concentration in the wake of these winter storms. The ability to retask the glider while it is in the water, a capability that is a direct result of technological and computer software advancements enabled by NAMOS (see Multi-scaled Actuated Sensing), constitutes a major improvement in our ability to follow and study these highly dynamic and ephemeral events. Directed sampling of the subsurface feature from ships has confirmed that the bloom is composed of neurotoxin-producing algae.

![Figure 18. Cross-section of chlorophyll fluorescence off Newport Beach in Feb 2009 obtained using a glider. The purple oval indicates the presence of a subsurface algal bloom close to the shore. Directed sampling of this feature from ships indicated the presence of high abundances of the alga Pseudo-nitzschia. Laboratory analyses confirmed that these algae were producing the neurotoxin. The subsurface bloom was not apparent at the ocean surface, and thus detection and sampling was enabled by the information provided by the robotic vehicle.](image-url)
**Networking NAMOS study sites**

A significant effort during 2007-2008 has been the development of a web-based portal for information streaming from our stationary and mobile sensor network components (buoys, pier-based sensors, robotic boat, glider). At this time we have a prototype webpage that collates and organizes the various data streams (Figure 19).

The development of an appropriate and functional web page has been a nontrivial task because of the constantly increasing number of platforms/vehicles in the NAMOS portfolio. Also, acquiring connectivity to the internet for these study sites has been problematic. This aspect of the project is now being dovetailed with other coastal monitoring projects being conducted by the NAMOS research team, including the NOAA-funded RAPDALERT project mentioned above and a pilot study of desalination being conducted with the West Basin Municipal Water District (see Partnerships and Knowledge Transfer).

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**Figure 19.** A ‘screen capture’ of the design and look of the web portal for displaying Networked Aquatic Microbial Observing Systems data. Locations of two NAMOS study sites (King Harbor, City of Redondo Beach and Marina Del Rey) are shown to the left in a Google style map. Recent and archived data collected by the sensor network can be queried and displayed using the interactive website. An example (using only fictitious data) is shown on the right side.
Partnerships and Knowledge Transfer

Southern California Coastal Water Research Project

A primary means of knowledge transfer within the aquatic application area exist through our partnership with the Southern California Coastal Water Research Project (SCCWRP). SCCWRP plays a pivotal role in southern CA by examining the linkages between human activities and natural events in the coastal CA environment, and through their activities to communicate this information to decision makers and stakeholders. Its stated mission of providing a sound scientific foundation for management decisions affecting strategies for protecting the ocean for this and future generations make it an ideal mechanism for the dissemination of the scientific information arising from NAMOS applications in coastal waters. Knowledge transfer through SCCWRP is facilitated by a CENS-enabled grant from the National Oceanic and Atmospheric Administration’s program on Monitoring and Event Response for Harmful Algal Blooms (MERHAB). The grant (RAPDALERT: Rapid Analysis of Pseudo-nitzschia & Domoic Acid, Locating Events in near-Real Time) focuses on the application of wireless sensor networks in the coastal ocean for the detection and study of toxic phytoplankton blooms. Co-principal investigators on the project include D. Caron, G. Sukhatme, B. Jones (USC), D. Estrin (UCLA), S. Weisberg (SCCWRP), P DiGiacomo (JPL, CalTech), P. Miller (UCSC).

SCCWRP is a public agency charged with assessing the condition, and factors that affect the condition, of a 500 km section of southern California’s coastal environment. SCCWRP is governed by a ten-member commission composed of a partnership of municipalities that discharge to the ocean, and government organizations that regulate the discharge. Partnering with this agency provides an essential connection to the application of CENS (NAMOS) technology to coastal marine ecosystems.

Southern California Coastal Ocean Observing System

The Southern California Coastal Ocean Observing System (SCCOOS) is a NOAA-funded member of the regional association of Ocean Observing Systems (http://www.sccoos.org/). Caron (together with Burt Jones) have an active collaboration within SCCOOS to examine the occurrence of harmful algal blooms near the Newport Beach, CA through a weekly pier-based sampling project. The Newport Beach coastal site is also the location of the glider work being conducted as a part of the CENS Marine coastal deployments of autonomous surface and underwater vehicles within the Aquatic application. The collaboration with SCCOOS allows direct knowledge transfer of algorithms derived from CENS for glider coordination and retasking. That information will significantly improve the capacity of the Ocean Observing Systems to task their own vehicles. In addition, the dissemination of information on algal blooms derived from CENS studies through the SCCOOS web portal. Jones has recently been appointed as the Chair of the Executive Steering Committee of SCCOOS.

Figures 20 (left) and 21 (right): The CENS NAMOS exhibit at the Redondo Beach Clean Waterfront Festival showcased state-of-the-art sensing equipment for water quality monitoring, and description of network-based approaches for its application. The public examined sensor instrumentation (Fig. 20), and got a chance to direct the robotic boat (Fig. 21) inside the lagoon.
City of Redondo Beach, CA

We began a partnership with the City of Redondo Beach during 2007. King Harbor of the City of Redondo Beach has been the site of repeated nuisance phytoplankton blooms or “Red Tides” that have resulted in fish kills within the harbor. These events are presumably caused by reduced oxygen levels in the harbor’s water. We have begun a collaborative effort between the City and CENS with the short-term goals of applying sensor network technology to (1) determine the immediate cause of the fish kills, and (2) provide information to the City to aid its evaluation of approach(es) to prevent or mitigate these harmful events.

Our partnership with the City of Redondo Beach provides the City with vital information on the factors that have led to fish kills in King Harbor. This knowledge transfer will significantly influence and improve the City’s abilities to decide on an appropriate course of action to prevent or ameliorate these harmful events. The information obtained by the NAMOS set-up within the harbor will be made freely available to city officials and to the public.

We have also participated in public outreach and education programs hosted by the City of Redondo Beach. The Redondo Beach Clean Waterfront Festival was held at a favorite local community recreational area, Seaside Lagoon on October 11, 2008. The all-day event focused on coastal ocean stewardship. It was open to the public and featured invited speakers (including Caron), booths by local schools, environmental and governmental groups.

West Basin Municipal Water District

A collaborative effort has been established with this municipal agency to examine the impact of harmful algal blooms on water desalination processes. The District is involved in pilot studies to investigate desalination, and members of our NAMOS group are collaborating with the District to characterize desalination issues relating to coastal algal blooms. This collaboration will provide funds for a large, coastal ocean buoy that will be located just outside the breakwater of Redondo Beach. The wireless network that is being enacted for the West Basin project will be folded into the network now working in King Harbor of Redondo Beach. Moreover, the desalination project will provide a high gain antenna and an internet connection that has been lacking in the NAMOS build-out of King Harbor for uploading sensor data to the internet.

Marina Del Rey, CA

We began a build-out of a second NAMOS in this harbor, situated approximately 20 km north of the City of Redondo Beach during 2007 (Figure 19). Like King Harbor, Marina Del Rey is another highly urbanized harbor within Santa Monica bay that is a potential site for harmful algal blooms and poor water quality due to discharges within the harbor, and due to the proximity of the marina to Ballona Creek. The goals of the Marina Del Rey project are (1) to establish a NAMOS within the marina that will relay information on water quality to a web-based portal in real-time.
time, (2) integrate this system with the NAMOS presently established in King Harbor, and (3) employ the system to characterize environmental conditions that lead to algal blooms within the marina. The information obtained by the NAMOS set-up within the marina will be made freely available to city officials and to the public.

OceanScience, Oceanside, CA

OceanScience is a private corporation involved in the development and manufacture of oceanographic and hydrologic field deployment equipment, for freshwater and marine applications. We have established a collaborative relationship with this company to bring NAMOS-based technology to the commercial sector. In turn, OceanScience has provided design advice and custom building of some of the NAMOS component hardware. Collaboration with OceanScience Corp. provides a direct conduit for the movement of CENS (NAMOS) technology to the private sector.

Arrowhead Lake Association, Lake Arrowhead, CA

As a result of a past deployment of NAMOS within Arrowhead Lake, we have established a relationship with the Arrowhead Lake Association (ALA), a group that is charged with monitoring water quality within the lakes. We have continued discussions with the ALA with the intent of designing a simple monitoring program for lake water quality that would incorporate NAMOS approaches. This partnership will be conducted as a part of an on-going graduate course in plankton biology offered by Caron within the Graduate Program in Marine Environmental Biology at USC. The project will provide the ALA additional monitoring effort to on-going studies in the lake, and it will serve as graduate research training for students in the USC program.

AQU 01.5 Future Directions

King Harbor, City of Redondo Beach

Our primary accomplishments in King Harbor during 2008 have been the continued development of sensor network capabilities in King Harbor, Redondo Beach. The established network consisting of three static sensor locations have provided high resolution, temporal observations throughout the year. This network has been augmented with the design, construction and deployment of an automated winch system allowing round-the-clock measurements of chemical, physical and biological parameters throughout the water column. A major unanswered question regarding the recent increase of HABs and other contamination events in this region continues to be how human activities on land play a role in the occurrence and/or severity of these events. Anthropogenic sources of nutrients and contaminants may contribute to algal blooms and other environmental problems along our highly urbanized coastline where land runoff, river discharge, sewage outfalls and storm drains constitute multiple point potential sources. The relative importance of anthropogenic sources of contaminants, relative to natural sources of nutrients, for the proliferation and intensification of these phenomena is not clear to science at this time.

A major problem with characterizing pollution in harbors and beaches is the ephemeral nature of these events, and the factors leading to them. Because of the episodic nature of nutrient input to coastal waters (e.g. storm drain and river discharge during sporadic rainfall events in southern CA), it is difficult to link cause-and-effect for many environmental problems. The data we have collected from our NAMOS network in King Harbor suggest some anthropogenic input of nutrients to the system during the tidal cycle. It also appears that reduced grazing pressure has a significant effect on growth rate of some bloom-forming species. Our research summarizing this aspect of the project is now contained in a manuscript that is being revised for publication at this time (Bai et al. “Study of Raphidophytes population dynamics and the grazing pressure on the species of Heterosigma akashiwo using species specific qPCR in Los Angeles coastal waters”). It is likely that both bottom-up (e.g., nutrients, light) and top-down (e.g., grazing) processes contribute to the formation of blooms in Redondo Beach.

Our specific goals for the next year will focus on (1) continued and expanded studies to examine the behavior (specifically vertical migration), physiology and population dynamics of harmful algal species within the harbor, and (2) the construction of true real-time, web-based access to the streamed information. Most major equipment items are built out at this time, and the City continues to provide essential logistical support and local contacts to allow the study to take place. Protected space, an internet connection, and housing for the connection have now been acquired and the node linking our system to the internet is presently under construction.
Marina Del Rey

We have recently begun to extend our NAMOS technology to this location. External (non-federal) funding was secured in the last CENS funding cycle to support this project, and that funding has supported hardware purchases to build out the network. At this time, one location in the southeastern region of the marina has been outfitted with a pier-based sensor platform. The overall approach is similar to the one that we have developed and described for King Harbor, City of Redondo Beach. The goal for the coming year will be to fully deploy the Marina Del Rey network and link the resulting data stream into the real-time web portal now emerging for the King Harbor network.

Studies in Southern California Bight

The coastal ocean south of Redondo Beach is the location that we are employing as the study site for the development and deployment of strategies for the glider retasking and coordination work that is presently underway. This research is designed to examine the distribution and activity of phytoplankton that produce the powerful neurotoxin domoic acid. We have chosen this important environmental problem as a ‘model system’ 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 harmful algal blooms.

The goal of the Aquatic Application’s NAMOS project in the open coastal ocean 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 using wirelessly networked static sensor packages (buoys and pier-mounted sensor packages), and autonomous Webb gliders equipped with a suite of sensors. These instruments will be used to characterize and track water movement, and thereby direct the autonomous gliders (and human-assisted sampling for verification) to document the biological response.

This work will dovetail closely with a MERHAB-funded (NOAA) project (Rapid Analysis of Pseudo-nitzschia & Domoic Acid, Locating Events in near-Real Time: RAPDALERT). In fact, this project heavily leverages equipment purchased through that program (dock-based sensor packages and mooring, and autonomous gliders) as a platform for software and hardware design discussed below. Our efforts will also dovetail with the efforts of Southern California Coastal Ocean Observing System (SCCOOS). SCCOOS is a regional component of the Ocean Observing System that makes measurements of the scale of the Southern California Bight. Our scales of measurement fit well within the geographic breadth of SCCOOS. We already make use of SCCOOS surface current data to provide context and meteorological information for our work, and in turn our studies will provide a more fine-scale resolution of plume tracking and biological response than SCCOOS is capable of obtaining. Our relationship with SCCOOS is very strong, and we anticipate close cooperation from them.

Additionally, the work that we are undertaking will play an important role with the Southern California Bight study planned for Spring 2010. The Bight study is a regional (entire Southern California Bight from roughly Santa Barbara to the U.S.-Mexico border) study conducted once every five years. It is coordinated by 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 California’s coastal environment. It is governed by a ten-member commission composed of a partnership of municipalities that discharge to the ocean, and government organizations that regulate the discharge. A stated focus of the Bight study as planned at this time 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 harmful algal blooms of the bight region. The plume tracking studies conducted by our NAMOS group will constitute a significant contribution to the overall Bight effort. The study was originally planned for Spring 2009 but was postponed year due to statewide fiscal difficulties. The
participation of our NAMOS research program is highly beneficial to the entrainment of CENS-derived information and technology into the data available to coastal managers and regulators.

**AQU 01.6 External Partners and Collaborators:**

- Burt Jones, USC
- Southern California Coastal Water Research Project, Westminster, CA.
- OceanScience, Oceanside, CA.
- City of Redondo Beach, CA
- Southern California Coastal Ocean Observing System, San Diego, CA