AQU 01 Aquatic Observing Systems

AQU 01.1 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 autonomous underwater vehicles) to provide in-situ, real-time presence for observing chemical and physical parameters (e.g. temperature, light, nutrients, etc.) and linking them plankton dynamics and surrogates or indicators of biological activity (e.g. chlorophyll concentration, dissolved oxygen). Sensing and sampling capabilities of the autonomous vehicles are carried out through the development of adaptive protocols, directed through the network.

This research has included the development of hardware and software within our wireless networked coastal sensing program 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 retask 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.

Specific applications that have been the focus of the past year have involved continued development of our sensor networks to examine microbial plankton dynamics in the coastal ocean of southern California:

• The augmentation of our marine coastal deployments of autonomous underwater vehicles through collaboration and independently-funded projects.
• Use of NAMOS for documenting spatial and temporal distributions of toxic algal blooms (blooms of the microalga Pseudo-nitzschia and outbreaks of domoic acid poisoning) along the coast of southern California.
• In-depth analyses of sensor data for understanding phytoplankton biomass dynamics in nearshore coastal harbors.
• Establishment of a collaborative website for the presentation of coastal observational and monitoring information generated by NAMOS and other coastal monitoring programs: Center for Integrated Networked Aquatic Sensor PlatformS (CINAPS).

AQU 01.2 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. Through 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) 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 relationship with the Arrowhead Lake Association has recently evolved into a graduate level course taught by Caron and co-workers involving instruction of University of Southern California students in aquatic sensing and plankton biology. Our most extensive applications involving NAMOS research include build-outs into two coastal marine ecosystems (King Harbor of the City of Redondo Beach and Marina Del Rey), and an extensive monitoring/observing system within coastal waters of southern California.

Deployments in King Harbor of the City of Redondo Beach in 2007-2009 have comprised our most expansive ‘build out’ of NAMOS in a marine ecosystem, and the development of a long-term 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. This work, and the operation of the sensor network, has continued to the present with as many as six, fixed (pier-mounted) sensor nodes within the harbor operating simultaneously. The observations provided by this sensor network have yielded fundamental contextual information for understanding short-term, small-scale dynamics of the plankton assemblages in this protected marina/harbor (see below).

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 has been implemented in Marina Del Rey through the establishment of two pier-mounted sensor nodes within the harbor. A new data output and web portal have been developed for the Marina Del Rey and King Harbor sensor data (as well as data streaming from other build-outs) during 2009 (see CINAPS below).

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). In this ongoing project 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 2007-2009, 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 01.3 Systems/Experiments**

Field deployments conducted to date have included studies of the freshwater plankton communities of Lake Fulmor, near the James Reserve in the San Jacinto Mountains of Southern California, Lake Arrowhead in the San Bernadino Mountains. From the data collected by static buoy system and sensor-equipped robotic boat in Lake Fulmor, 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. An additional paper is near completion 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. Studies of Lake Arrowhead have been incorporated as a field component of a graduate level course in the Department of Biological Sciences at USC.

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 chose 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. We have been developing a web-based portal for presentation of the data streaming from the sensor network in near-real time (see below: CINAPS, USC Center for Integrated Networked Aquatic Platform(S)).

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 has been the design, construction, implementation and continual improvement of 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 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 DS5 multiparameter sondes. These sensors measure depth, temperature, salinity, dissolved oxygen, chlorophyll a fluorescence, and turbidity. We have maintained as many as three buoys with sensor nodes at two depth (near-surface and near-bottom) 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. We have also employed sensor packages tethered directly to the dock. The data is streamed back to the onboard buoy computer. Through a collaborative research project the West Basin Municipal Water Facility, we have established a communication system for real-time streaming of information from the buoys to the internet during the past year (see CINAPS). West Basin will soon be operating a pilot desalination project at Redondo Beach and we have collaborated with that group to establish a sensor-equipped coastal ocean buoy just outside the breakwater surrounding King Harbor (Figure 1).

We have significantly increased our ability to characterize short- and long-term changes in environmental parameters in the water column of King Harbor as a consequence of the establishment of the sensor network, and to relate changes in these environmental parameters 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 2). These data

![Image](image_url)
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 2A, 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 the Harbor Patrol location (Figure 2C). 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.

Figure 3. (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).

The fixed spatial and depth distributions of the sensors attached to buoys or attached to piers provide a high-resolution understanding the temporal progress 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 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 3; 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. 3A). 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).

Other tools 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 4). The system employs a small winch (white box in center of Fig. 4) 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 has been 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 have indicated significant differences in this biologically-determined parameter. Concentrations of oxygen differed on different days (Figure 5; 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 6). Sensor packages deployed at two depths at the same location in the harbor and equipped to measure temperature, chlorophyll fluorescence, dissolved oxygen, turbidity.

Figure 5. Concentrations of dissolved oxygen in the water of King Harbor Marina on four days in 2007. Note the differences in oxygen profiles on the different days, and also between the different depths on three of the days. Only the profile on 7 January showed a relatively uniform concentration of oxygen throughout the water column.

Figure 6. Environmental parameters collected over a four-day period in King Harbor from sensor packages deployed at two depths. Note the cyclical daily pattern in most parameters and depth-related differences in the ranges of these parameters.
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.

Figure 7. Marked periodicity (particularly in biological parameters; chlorophyll fluorescence and dissolved oxygen) observed in King Harbor water column.

Figure 8. Wavelet analysis allows for temporal localization of the dominant constituent periods. A wavelet is a function with mean of zero, resembling a short wavelike oscillation (B; Grinsted, et al., 2004) which can be crafted to have specific properties. In the figure above, the time-series of a 10-day tidal signal from King Harbor is shown (A). The time-resolved wavelet power spectrum (C) and the time-averaged Global Wavelet Spectrum (D) both show the changing contributions of the diurnal (period = 1d) and semidiurnal (period = 0.5d) constituents over time1. The 95% significance level of these contributions is also shown in the GWS (D; dashed line).

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Analyses of the short-term temporal variations of phytoplankton biomass (chlorophyll fluorescence) and environmental parameters have indicated strong periodicity (see chlorophyll fluorescence and dissolved oxygen patterns in Figure 7). These patterns are presumably a result of physical features of the environment that also undergo regular cycles, such as light availability and/or the tidal cycle. The underlying controls observed for the

Figure 9. The signal of chlorophyll fluorescence over time is often noisy (A, showing the normalized [by mean and standard deviation] time-series), but there is often some level of periodicity. Surface chlorophyll time series from Spring, Summer, and Winter of 2008, all displayed a strong signal in the diurnal period (dark red color appearing with a period of 1 day). While the Spring dataset exhibited a non-significant contribution in the semi-diurnal period (B), the Summer dataset revealed distinct diurnal and semi-diurnal periodicities in the chlorophyll signal with periods of 1 and 0.5 days, respectively (C). Similar to the Spring dataset, Winter chlorophyll (D) is dominated mainly by the diurnal signal. These differences may be indicative of a period of heightened influence of the tidal cycle (which also has semi-diurnal constituents) over that of the solar cycle and vertical migration during the Summer months.
biological parameters have been examined use wavelet analysis of the physical parameters to determine how much of the biological variability can be explained by the physical components of the system (Figure 8, 9). The unexplained variability might be related to biological factors such as behavior (e.g. diel vertical migration), physiology (growth or changes in fluorescence characteristics due to photoadaptation) or possibly predation.

While wavelet analysis is being used to examine the importance of physical forcing factors for explaining major patterns in phytoplankton biomass, biological composition of the microalgal community is also being analyzed to determine if behavior (such as vertical migration) of dominant taxa may play a significant role in generating high-resolution temporal or spatial patterns or periodicities of these organisms (Figure 10). Certain microalgal species such as dinoflagellates (e.g. important taxa in Figure 10 such as Prorocentrum, Akashiwo, Scrippsiella) are known to migrate vertically in response to light and nutrient status. Patterns and periodicities at particular times of year may be affected by the dominance of taxa that are capable of extensive vertical migrations.

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 approximately two years in different regions of King Harbor (Figure 1). A month-long record of chlorophyll fluorescence (a proxy for phytoplankton biomass) at the three locations is shown in Figure 11 during 2008. Two substantial phytoplankton blooms were observed within King Harbor Marina during this month-long observational period (Fig 11A). 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. 11C).

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.

Figure 10. Relative abundances of the major phytoplankton taxa in King Harbor of Redondo Beach. Large dinoflagellate taxa (e.g. Akashiwo) are known to undergo vertical migrations of tens of meters in response to light and nutrient conditions.
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 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. Surface concentrations of nitrate (NO3-) 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 and 2009 expanded on the finding from 2007, and have further examined 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 12), which may be related to the difference in the dominant phytoplankton during these studies (H. akashiwo and A. sanguinea/C. fulvescens, respectively) or to the fundamental differences in the physical or chemical environments between these times (i.e. overall lower water temperature, light in November).

Experiments carried out during 2008 addressed the influence of tidal cycle on nutrient concentrations and phytoplankton population response in King Harbor. Nutrients in surface waters of the harbor revealed a significant relationship with the tidal cycle (Figure 13). Elevated nutrient concentrations were observed during high tides,
indicating the advective input of nutrients to the water column from waters outside the harbor. Further experiments are planned.

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 14). Given that nutrient concentrations correlated with tidal height (Figure 13), the latter feature appears to represent a proxy for overall nutrient status in the harbor. Phytoplankton responses to the rapidly changing physical and chemical structure of the harbor are considerable (Figure 15) as well as periodic (Figure 7). Phytoplankton communities within the harbor are dynamic in terms of species composition of the assemblage and in terms of behavior. Phytoplankton physiological response and vertical migratory behavior resulted in pronounced, short-lived subsurface maxima in abundance during the diel studies (Figure 15).

Figure 12: 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.

Figure 13. Data from two-day study in King Harbor in August 2008 indicate a relationship between tidal cycle and nutrient concentrations (ammonium) in surface waters.
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, our NAMOS group has been modifying the capabilities of these vehicles to allow (1) retasking of vehicles during a mission, (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, and Publications arising from this project), and (3)

Figure 14. 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. 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.

Figure 15. 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.

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use of an existing, regional ocean model for accepting input from the glider and generating predictions of the movement of features of interest. This work is enabled by coordinating NAMOS objectives with the overall objectives of a NOAA-funded project led by Caron and Sukhatme (RAPDALERT: Rapid Analysis of Pseudo-nitzschia & Domoic Acid, Locating Events in near-Real Time; funded by NOAA’s Monitoring and Event Response for Harmful Algal Blooms, MERHAB program).

We have used the gliders to characterize water structure prior to and during upwelling events, periods when cool, nutrient-rich deep waters are injected into surface waters in our study area located between the LA-Long Beach Harbor and the city of Newport Beach (Figure 16). Significant winter rain and wind events in southern California are known to trigger the development of phytoplankton blooms in nearshore waters via upwelling events or the direct injection of nutrients from river plumes flowing into coastal ecosystems (Figures 17, 18).

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 improve the glider’s capabilities as noted above.

This work represents a contribution of CENS approaches, and an extention 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.
Figure 19. Cross-sectional pictures of temperature, and chlorophyll fluorescence on March 23 (left panels) and March 25 (right panels) showing changes along an onshore-offshore transect in the vicinity of Newport Beach, CA. The ovals indicate the presence of a subsurface maximum in phytoplankton biomass (i.e. chlorophyll fluorescence) that is brought to the surface during the upwelling event.

Figure 20. Cross-section of chlorophyll fluorescence off Newport Beach in March 2009 obtained using a Webb glider. The presence of a subsurface algal bloom offshore becomes a surface feature onshore due to lifting of deeper water due to upwelling. Directed sampling from ships of the deep chlorophyll maximum offshore prior to this event indicated the presence of high abundances of the Pseudo-nitzschia. Laboratory analyses confirmed that these algae were producing the neurotoxin.
A glider mission conducted in March 2009 documented an upwelling event, and the appearance of an increase in chlorophyll concentration in the wake of storm and wind events (Figures 19, 20). One remarkable feature revealed by this sensing and surveillance study was that the upwelling event, which is known to inject nutrients into surface waters, may also be an important mechanism for inoculating surface waters with high abundances of microalgae present in subsurface waters (Figure 20). The vertical patterning of chlorophyll concentration during this event indicates that the subsurface maximum in microagal biomass was brought to the surface during the event and advected away from the short. However, one glider transect (Figure 20) clearly demonstrated that the movement of surface waters seaward during the upwelling event brought the abundant microagal population situated at 20 m in the water column to the surface during the event (note the general slope of the deep chlorophyll maximum towards the surface in nearshore waters in Figure 20).

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 confirmed that the bloom was composed of neurotoxin-producing algae.

**CINAPS (Center for Integrated Networked Aquatic Sensor Platforms)**

Data management and dissemination of our NAMOS study sites has continued to be a significant effort in our CENS program. As a result of these efforts, we have recently launched CINAPS, a web-based portal for information streaming from our stationary and mobile sensor network components (buoys, pier-based sensors, robotic boat, glider). This website incorporates our CENS activities as well as ancillary and complementary projects funded by the PIs (see Partnerships).

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 and collaborative projects. This work is now dovetailed with other coastal monitoring projects being conducted by the NAMOS research team, including the NOAA-funded RAPDALELT project mentioned above and a pilot study of desalination being conducted with the West Basin Municipal Water District.

The CINAPS website provides information on research projects in which the group is engaged, sensor platforms involved in the work (buoys, pier-based systems, autonomous surface and underwater vehicles), study locations, partners, outreach and personnel.

**AQU 01.4 Future Directions**

**King Harbor, City of Redondo Beach**

Our primary accomplishments in King Harbor during 2009 have involved the application of our sensor network to facilitate experimental studies of plankton dynamics (see sections above). The established network of static sensor locations have provided high resolution, temporal observations throughout the year, enabling new insights into the factors controlling phytoplankton abundances in this small, complex ecosystem. The design, construction and deployment of an automated winch system has provided 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. 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.

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.

**Marine Del Rey**

During the past year we extended 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, two locations (in the southeastern region and the northeast region of the marina)
have been outfitted with a pier-based sensor platforms. The overall approach is similar to the one that we have
developed and described for King Harbor, City of Redondo Beach. We have tied the data now-streaming from these
sensor platforms into web portal established by CINAPS for the King Harbor network and other locations. The goal for
the coming year will be to establish a real-time download capability for these platforms (presently information is
manually downloaded and entered into the database), and begin to analyze the long-term data streaming from this
location.

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. This work will continue as a major effort
within this CENS project. 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 are being 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 dovetails closely with a MERHAB-funded (NOAA) project (Rapid Analysis of Pseudo-nitzschia & Domoic
Acid, Locating Events in near-Real Time: RAPDALERT). 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 is playing an important role with the Southern California Bight study just
beginning at the present time (periods of intensive observation are February-June 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 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 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. It is getting underway at this time to document the Spring 2010 event. 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.