AOSN II: Integration and Demonstration of Observation and Modeling

1 Objective

This program will integrate observational and modeling components to create and demonstrate an adaptive, coupled observation/modeling system in the context of a study of episodic iron fertilization driven by coastal upwelling. Previous AOSN development created and demonstrated individual platforms, communication systems, and preliminary integration of modeling systems. This work will focus on the integration of the broad array of elements into a functioning system. Collaborating groups at WHOI, Harvard, NPGS, Princeton, UCSB, CalPoly, CalTech, and NRL bring a strong suite of capabilities, both observational and computational, from which a powerful observation system can be constructed. MBARI efforts will be directed towards a) leadership of the AOSN II effort, b) system engineering to optimize individual elements with overall AOSN performance as the driving criteria, c) development of key infrastructure elements to support system operation, d) hosting the AOSN II field program in summer of 2003, and e) observation system contributions of AUVs, drifters, and existing moorings.

2 Motivation

The proposition that the ocean is under-observed is one with which most oceanographers would instantly agree. However, aside from simply spending more money and deploying more ships, how can we do better? The Autonomous Ocean Sampling Network, AOSN, concept is an approach that seeks to bring a host of new technologies to bear on the observation problem, from AUVs, to gliders, to acoustic communications [Curtin, Bellingham, 1993]. By linking these systems to assimilation and modeling systems, we provide a more effective tool for combining measurements into a single 'picture' of the ocean, or part of the ocean, and to develop some quantitative methods to plan more effective sampling strategies. Work towards this goal of integrating an adaptive, mobile observation system with assimilation-modeling tools has now been underway for over seven years. This proposal carries individual AOSN elements to the next level of integration.

Field experience and analysis have generated a number of critical insights that guide development of the proposed system:

- *Multiple vehicle survey strategies are extremely attractive.* An analysis of various investments in vehicle technology [Willcox et al., 2001] compared the consequences for survey effectiveness of improved battery capacity, improving propulsion efficiency, reducing hotel load, and operating multiple AUVs. The results unambiguously demonstrated the greatest reduction of survey error comes from increasing the number of platforms.

- *Adaptive sampling can multiply the effectiveness of mobile assets.* This is because the net effect of adaptive sampling is to reduce the distance traveled to achieve a given observational goal. For example, if the relationship between resolution and survey distance is $d = f A/2\lambda$, where A=observed area, λ=spatial survey resolution, and f =vehicle path length reduction, is less than one, then the effective survey speed increases by 1/f, for no additional cost of energy. Achieving the same acceleration of the survey by increasing vehicle speed would raise power consumed by propulsion (usually the dominant power draw) by $1/f^3$. This observation strongly motivates the development of adaptive sampling techniques [Bellingham et al., 1996].

- *Models may provide a relief from temporal decorrelation.* Techniques that employ models to assimilate data provide the potential for ameliorating the decorrelation of survey data that otherwise occurs as a survey proceeds. If a process has a temporal correlation interval of τ, then surveys longer than τ effectively provide no additional useful information. However, if by assimilating the data into a model one can effectively 'propagate' measurements forwards or backwards in time, then the time constraint on survey completion can be relaxed. This in turn can be leveraged to achieve high resolutions or reduce energy demands by reducing vehicle speed.

- *Models may allow benign scaling to larger observational domains.* Dramatic improvements can be realized if the fundamental scaling relationship between survey distance and observational area can be modified. For example, if one can survey the perimeter of an area and use the model to derive the interior conditions, the distance the vehicle must travel no longer scales as the area but rather as the square root of the area. The much more benign scaling law is possible because the path for a boundary survey encloses an area rather than physically interrogating each point in the interior. The consequences could have profound implications for scaling small domain experiments to larger observational problems.

The attractiveness of coupling models to observational assets creates a demanding mode of operation in which a fast-turn around cycle of activities carries observations through analysis to the planning of the subsequent surveys again and again (figure 2.1).

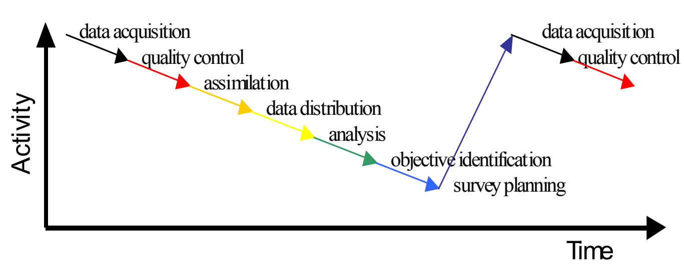


Figure 2.1: Activity cycle for coordinating surveys of an evolving process.

Minimizing the cycle time of this loop is critical since the value of the measurements accomplished in the early phase of the cycle deteriorate with time for the purposes of survey planning due to temporal evolution of the process. The comparatively simple task of working out a CTD plan for a single ship can be difficult and time consuming. AOSN, by integrating the use of a wide range of operational tools, increases this complexity dramatically.

While the technical demands of engineering adaptive coupled observation/modeling systems are imposing, specific examples of the approach are proliferating. Recent applications of advanced sampling platforms in Monterey Bay have demonstrated the importance of adaptive, high-resolution sampling to understand complex, rapidly evolving processes that influence the generation and fate of productivity. The scientific objectives of the proposed experiment fundamentally relate to transports and their consequences: 1) vertical transport of iron-bearing sediments from the deep shelf into the upper water column, 2) influence of eddy, filament, and frontal dynamics on lateral and vertical transports of upwelled nutrients and resultant productivity, and 3) response of transports to wind relaxation and reversal. These processes all have significant consequences for the generation and fate of upwelling system productivity. Study of these transport processes in the past has demonstrated our ability to resolve them (MUSE 2000). Application of adaptive research strategies will greatly augment our understanding of the processes and their consequences and will advance marine research methods.

3 Background

3.1 Field Experience

The strategy employed for developing AOSN, continued in this effort, has been to couple incremental technology developments to science-driven field programs. Science experiments have been chosen to exploit new capabilities, as they are available. This serves a variety of goals, providing: near-term focus for technology development, field verification of technology, opportunity for testing new operational techniques, feedback on the scientific utility of the technology, and exposure of new technology to the scientific community. The experience gained though these field programs has had the benefit of allowing the identification of new scientific opportunities, and providing important results necessary for the system-level engineering of AOSN.

Haro Strait Primer (1996) – The Haro Strait experiment focused on studying the dynamics of tidally driven mixing in Haro Strait, British Columbia. Here, fresh water from the Fraser river mixes with salt water carried north from the Strait of Juan de Fuca. The AUV component of this experiment focused on characterization of frontal processes via a variety of techniques: multi-vehicle operations, vehicle-drifter operations, model-guided sampling, and moving-source tomography.

Labrador Sea Deep Oceanic Convection (1998) – This experiment was an ambitious effort to characterize small-scale structure of deep convection processes during winter in the Labrador Sea. Two types of AUVs operations were attempted: ship attended operations from the R/V Knorr, and docking station based operations from a deep-water mooring. Ship-based Odyssey operations detected and mapped convection processes [Zhang, 2001]. Critical elements of a fully autonomous docking capability were demonstrated in extremely demanding conditions, although the full system functionality remains a work in progress.

Littoral Ocean Observation and Prediction System (1998) – The LOOPS experiment focused on understanding horizontal scales of variability of the biology of Massachusetts Bay. Odyssey class vehicles were employed as an element of a multi-ship, multi-AUV, coupled observation-modeling system. Concurrent operation of the Harvard Ocean Prediction System (HOPS) provided the assimilation and modeling component. Numerous vertical oceanographic sections characterizing horizontal and vertical extents of plankton patchiness were obtained [Yu et al., 2002]. Acoustic communications were employed to control AUVs during survey operations. Model directed sampling guided AUV observations of upwelling processes.

Generic Oceanographic Array Technology (1998) – The GOATS experiment used an Odyssey class vehicle to test the viability of multi-static sonar techniques for sensing buried mines.

Synoptic Internal Tide Experiment (1999) – SITE used a variety of autonomous platforms in an attempt to characterize interactions of internal tides with the Monterey Canyon. The first multi-day deployment of glider vehicles (Spray) was demonstrated. Acoustically controlled operations of AUVs from shore via moorings equipped with radio and acoustic modems were also demonstrated.

Monterey Upper-water Column Science Experiment (2000) - MUSE 2000 employed a variety of platforms and advanced sensors in an experiment designed to understand the bio-geo-chemical response of Monterey Bay to episodic iron fertilization driven by coastal upwelling. MUSE was characterized by a large number of autonomous platforms, ships, aircraft, and satellite systems, all linked by various communications systems (see figure 3.1). Coordinated operations with these platforms generated a highly interdisciplinary, multi-scale data set. The MUSE experiment demonstrated many of the observational elements that will be employed in AOSN II, and provides a scientific foundation for planning the AOSN II field program.

MUSE focused on the response of Monterey Bay to a naturally occurring impulsive injection of iron-bearing sediments. Wind events in late summer drive upwelling along the California coast to the north of Santa Cruz, bringing sediment-bearing water from the seafloor to the surface. This iron-rich water enables the growth of various phytoplankton species that in turn provide grazing for organisms higher in the food chain. The observational needs of MUSE were tremendous. Not only are nutrients introduced through the interaction of a host of physical processes acting on different time and space scales, the nutrients also trigger a cascade of transformations throughout the ecosystem.

Figure 3.1: Cartoon of MUSE Experiment, August 2000.

To answer the demands of the MUSE experiment, a large number of assets were employed, including:

- R/V New Horizon: continuous measurement of physical, chemical, and biological parameters.
- R/V Pt Sur: AUV operational platform.
- R/V Pt Lobos: ROV Ventana operational platform (MBARI).
- R/V Shana Rae, R/V John Martin, and R/V Ed Ricketts for mooring deployments, logistical support, and some near-shore sampling (UCSB).
- 2 Odyssey IIb AUVs: CTD, fluorescence, bioluminescence, oxygen, optical backscatter (MBARI/MIT).
- 4 gliders (‘Seaglider’)from University of Washington and 2 gliders (‘Spray’) from SIO/WHOI (2 UW vehicles deployed): CTD.
- 2 instrumented drifters: temperature, salinity, pCO_2, optical backscatter, fluorescence, and irradiance (MBARI).

- 6 moorings: wide range of physical, optical, meteorological, and biological sensors, including the Environmental Sample Processor (ESP) configured for in situ genetic identification of micro-organisms (MBARI, NPS, WHOI).
- Twin engine Navajo aircraft: sea-surface temperature and meteorological measurements (Naval Postgraduate School)
- C-130 aircraft: sea-surface salinity (NASA).
- HF Radar: surface winds and currents (Naval Postgraduate School).

The large number of platforms and complementary nature of their instrument suites provided opportunities for synergistic sampling programs. However, the evolving nature of the iron fertilization event and its aftermath imposed the requirement that survey plans be rapidly adapted to changing conditions. Each system was tuned to address a part of the observational problem, and coordination of these assets was central to extracting a more complete picture. A wide range of combined operations was carried out, including multiple ships, ships and AUVs, ship and AUVs and aircraft, and ships and AUVs and drifters. Many of these operations focused on frontal processes, which evolved significantly in the course of a single day. Planning for the coordinated operations therefore occurred on a short time-scale, and imposed heavy demands on rapid data processing, communication systems, and manpower.

MUSE experiment demonstrated that for an ocean observation system to be more than the sum of its parts, the elements must function as integral parts of a larger system. For the full power of the multi-platform sampling system to be realized, the observational assets must function within a fast-turn around cycle of activities that carries observations through analysis to the planning of the subsequent survey again and again. Since these elements are complex devices in their own right, the infrastructure demands are daunting. This effort will provide the larger framework to integrate observation/modeling system components.

3.2 Observational Elements

3.2.1 Mobile Platforms

At the heart of AOSN are mobile platforms. Two classes of systems have been the focus of development: faster propeller driven AUVs, and longer endurance buoyancy driven ‘gliders’ (figure 3.2). The focus has been on creating small, high-performance systems to support multiple vehicle operations.

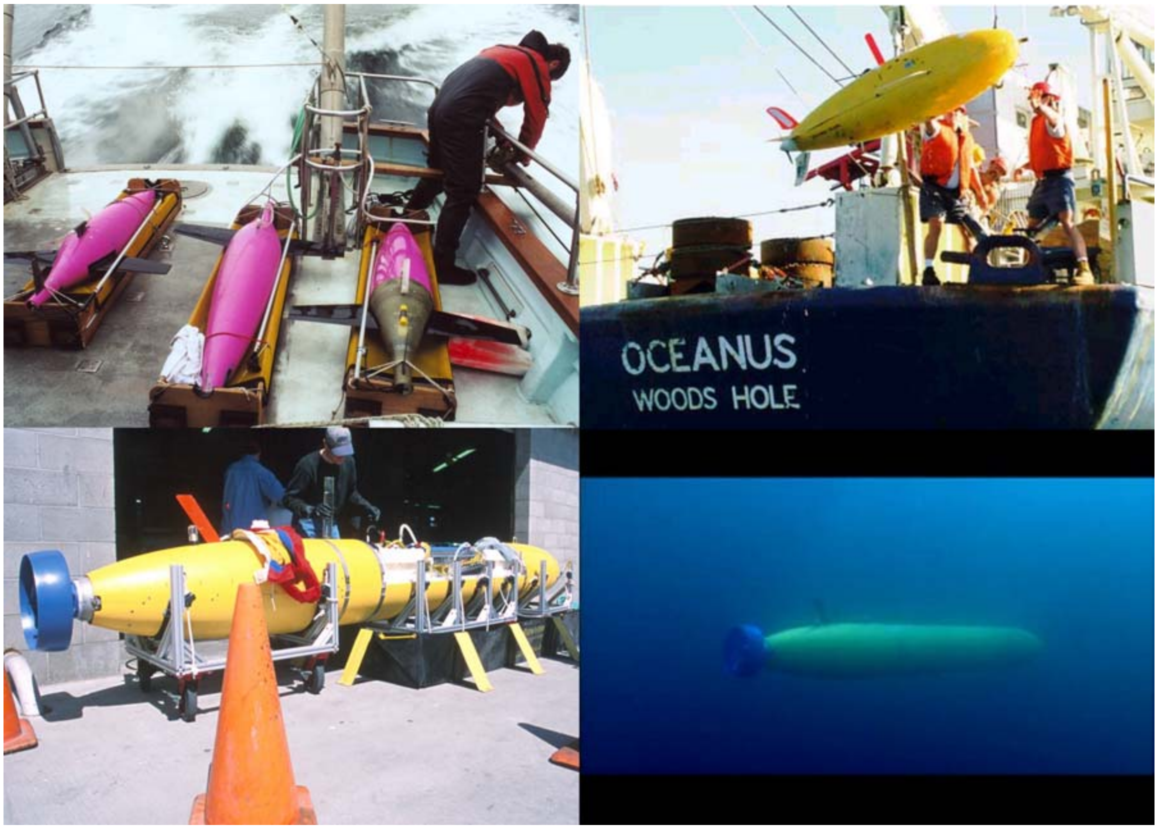


Figure 3.2: Pictures of various Autonomous underwater vehicles. Starting with upper left and going clockwise: a) Seaglider buoyancy-driven AUVs developed at University of Washington being deployed in Monterey Bay, b) Odyssey IIb class AUV being deployed during the LOOPS experiment in Massachusetts Bay, c) Dorado AUV operating underwater in Monterey Bay, and d) Dorado AUV, developed at the Monterey Bay Aquarium Research Institute, shown here in an ALTEX configuration with a 60 kW-hr semi-fuel cell.

The AOSN II experiments will emphasize the use of gliders. Gliders are vehicles capable of varying their buoyancy, and using wings to translate vertical into forward motion (see figure 3.2a). Gliders typically operate at low speeds (under 0.5 m/s) and consequently expend little power on propulsion. They are constrained to profiling trajectories, and typically fly saw-tooth trajectories to obtain vertical sections although station-keeping capability is possible as well. For AOSN II, a group from WHOI (Fratantoni et al.) will deploy 10 Webb Coastal gliders (http://www.webbresearch.com/slocum.htm) to provide an effective combined survey rate of 10 kts for approximately two months. These are not the first gliders to be deployed in Monterey Bay, but they will be the most numerous, and the first to be integrated into an observation/modeling system. The Spray glider was operated in the SITE 99 experiment [Sherman et al., 2001] while several Seaglider vehicles were operated during MUSE [Eriksen et al., 2001].

The Dorado AUVs will provide faster moving, more heavily instrumented, mobile platforms for survey and response activities. These systems are based on the Odyssey series of AUVs [Bellingham et al., 1992, 1994] that were heavily employed for developing and demonstrating AOSN capabilities (figure 3.2b). In the MUSE experiment, Odyssey vehicle carried CTD, optical backscatter, oxygen, pH, bioluminescence, and ADCP sensors. The most common AUV configuration consists of a torpedo-like vehicle with a streamlined body and propeller and control surfaces at the stern. The Dorado propeller is shrouded in a duct, and the entire tail articulated [Kirkwood, 2001]. The articulated tail, offers a higher degree of robustness to impact, a useful characteristic for launch and recovery.

Propeller-driven AUVs have been used to carry a wide variety of sensor systems. Bottom mapping sensors include side-scan sonar, mechanically scanned sonar, multi-beam bathymetric sonar, laser-linescan imaging systems, still and video imaging, and sub-bottom profilers. Measurements made in the water column include temperature, salinity, chlorophyll fluorescence, optical backscatter, pH, oxygen, bioluminescence, and a wide range of inherent optical properties. Specialized uses of AUVs include use as mobile acoustic arrays, and mobile sources for acoustic tomography. This list covers just a portion of the sensor systems operated on AUVs. Given the rapid increase in organizations operating and employing AUVs, the variety of sensors is likely to increase for some time to come.

3.2.2 Moorings

MBARI has maintained two moorings since 1989 (M1 and M2). More recently, additional moorings have been deployed for shorter time periods by MBARI (M3, S2, S3) and NPS (M4). The M moorings are equipped with meteorological, physical, chemical, and bio-optical instrumentation. The S moorings have current meters and sediment traps. Continuous monitoring from moorings is essential to understanding regional variability and providing context for process studies that occur over more limited periods (e.g. process studies). MBARI has a proven track record in the deployment and maintenance of moored systems.

A major development emphasis at MBARI has been a new generation mooring system capable of providing observations of water-column and benthic processes in near real-time [Chaffey and Mellinger, 2001]. The mooring system will support power and communications between the surface float and benthic nodes through an electro-optical-mechanical cable. Radio and satellite based communications between shore and the mooring will enable instrument query, control, event detection, and response. The mooring is designed to be deployed from regional class vessels in waters up to 4000 m. The existing moorings of the MBARI array and the near-term advancements in mooring technology will provide a tremendous resource for providing time-series data in the AOSN II experiment.

3.2.3 Drifters:

Drifters are widely used in oceanographic field programs, and provide a powerful tool for tracking the drift of surface water and detecting downwelling. Heavily instrumented drifters provided an important tool for tracking and monitoring the evolution of patches of upwelled water during the MUSE experiment. Drifters were equipped with Seabird SBE37 Microcat CTD, Hobilabs Hydroscat-2 (HS2), and a Satlantic OCR-100 radiometer. Since the drifters were equipped with GPS and were in constant radio contact, both the drifter path and sensor data could be recovered in real-time.

Several Odyssey frontal surveys were centered on drifter locations during the MUSE experiment to characterize convergence fronts. Convergence fronts tend to concentrate floating debris. AUV surveys were set up to run roughly orthogonal to the direction of drifter motion, and to intersect the drifter location. Such techniques resulted in a number of AUV oceanographic sections capturing downwelling at convergence fronts. AOSN II will also make heavy use of drifters, both to characterize surface circulation, and to help guide AUV operations (Chavez, MBARI; Fratantoni, WHOI).

3.2.4 Aircraft:

In the MUSE experiment, aircraft-born SST was used to map Monterey Bay on a daily basis [Paduan et al., 2001]. Since the aircraft can fly under the cloud cover typically found over Monterey Bay in late summer and early fall, the aircraft surveys provided a much more reliable and high-resolution SST than could have been obtained from satellite remote sensing. The resulting maps were extremely useful for planning survey operations. The twin engine Navajo aircraft equipped to measure sea-surface temperature and meteorological parameters is expected to be operated by the Naval Post Graduate School again for AOSN II (Prof. Steve Ramp).

3.2.5 CODAR:

CODAR (COastal raDAR), uses multiple 10 m wavelength radars to interact with ocean surface waves permitting measurement of surface currents. The CODAR system currently observing the Monterey Bay is owned and operated by the Naval Postgraduate School (Prof. J. Paduan). The system has a range of up to 50 Km offshore using radars located at the MBARI facility in Moss Landing, Long Marine Lab in Santa Cruz, and at Point Pinos in Pacific Grove.

3.2.6 Communications:

The AOSN paradigm demands that mobile systems at sea operate as elements of a networked observation system. For this and other reasons, communications play a central role in AOSN. Communication is essential for connecting observational assets to modeling and assimilation systems. Communications is also highly useful as a mechanism for enabling coordinated sampling strategies by mobile systems. The ideal is the extension of Internet to instruments and vehicles deployed in remote regions of the ocean.

A variety of communications technologies are relevant to AOSN. Above water, radio communications are employed in both line-of-sight and satellite communications schemes. Below water, acoustic communications can be used, although the performance depends greatly on the complexity and variability of the acoustic environment. Radio links between ship and shore, ship and surfaced AUV, ship and mooring, and shore and mooring are routine. Acoustic communications capabilities have progressed substantially in the last decade. Ship to AUV, mooring to AUV, and AUV to AUV communications have all been demonstrated. However, acoustic communication is more difficult to implement, and is more limited in range and bandwidth.

Remote interaction with AUVs during operations requires flexible supporting software and communications capabilities. A two-tier system has been demonstrated: radio communications provides a long-range link with a communication mooring, which in turn acoustically communicates with underwater platforms [Frye et al., 2001]. In SITE 99, an array of communications moorings were deployed in the upper Monterey Canyon and employed to control submerged AUVs in real-time. The moorings allowed an operator, sitting at MBARI, to receive data from, and send commands to, AUVs operating in the Monterey Canyon [Kreamer, 2000]. While this capability is unlikely to be implemented for AOSN II, ocean observatory efforts such as MOOS and MARS will provide the necessary infrastructure to support such communication systems in the future.

3.3 AOSN: Modeling and Control:

3.3.1 Modeling:

Coupling models directly to observation systems is a cornerstone of AOSN. Figure 3.3 shows a sequence of prediction, survey paths, survey data, and assimilated data for coupled observation-modeling system experiment during the Haro Strait experiment [Bellingham, 1997]. The predictions were generated by an implementation of the Harvard Oceanographic Prediction System (HOPS) and delivered to the AUV operations team at 6am. The AUV team used the predictions to identify frontal locations, and the resulting surveys are shown in plan view. The AUV vertical section is shown for a survey that ran across the front and back again. Finally, the result of assimilating AUV back into the model is shown in the final panel. This example demonstrated the two great strengths of an intimate integration of modeling with the observation system: more efficient surveys, and improved estimates of the environment.

The Harvard Ocean Prediction System (HOPS) [Robinson, 1999] is a system of interacting software elements that permits:

a) Setting-up modeling domains
b) Preparing data
   - Gridding data
   - Preparing fields for dynamical models
c) Running dynamical models
d) Visualizing results

The dynamical model usually employed in HOPS is a primitive equation physical dynamical model. A wide range of spatial scales can be supported, from 10m to to several kilometers. A number of data assimilation schemes are supported. Since HOPS is designed to be modular, it is possible to incorporate other circulation models and assimilation techniques. HOPS has been used to support forecasting operations at sea since the mid 1980s. HOPS will form the heart of the modeling and assimilation system for the AOSN II experiment.

A highly complimentary effort is the development of a state-of-the-art coupled physical-ecosystem model of the West Coast under a current NOPP award (see http://www.mbari.org/nopp). There is tremendous synergy between the ongoing modeling effort and this proposal. Clearly, the AOSN II effort can make use of what has already been learned by the NOPP modeling effort. In addition, the data set collected by AOSN II will be of tremendous value to NOPP model validation efforts. The NOPP Team will endeavor to have an "Operational" model by summer 2003. However, it is unlikely that by that date the model will have the necessary day-to-day accuracy to satisfy AOSN requirements.

3.3.2 Command, Control and Autonomy

AUVs are expected to be capable of carrying out a broad range of missions and supporting a range of autonomy. The need for flexibility ranges from simple modification of flight profiles to redefinition of mission objectives, including reconfiguration of vehicle sensor suites. Autonomous operations are enabled by software architectures that provide mission level control, navigation, subsystem management, and dynamic control while supporting reconfigurability. Such software approaches have enabled a large range of autonomous capabilities.

Straightforward autonomous capabilities include navigating to waypoints, flying grid surveys, flying saw-tooth vertical profiles, and maintaining constant altitude over bottom. Dorado AUVs encompassed such capabilities as *behaviors*. Several dozen behaviors have been developed and demonstrated, and missions are constructed by activating behaviors, setting their relative priorities, and providing values to behavior arguments. To achieve more complex tasks, behaviors can be combined, for example using a grid survey behavior with a bottom following behavior creates a bottom-following grid survey. Other examples of creating more complex behaviors from simple building blocks include demonstrating formation flight of two vehicles by using a homing behavior to cause one vehicle to follow another, and docking. This range of autonomous capabilities provides powerful building blocks for adaptive sampling techniques.

3.3.3 Adaptive Sampling

Adaptive sampling refers to the process whereby survey efficiency is increased on the basis of data acquired during the survey. Substantial savings can be realized in both energy consumed and time required for completing a survey. Relatively few examples of adaptive sampling exist, as most AUV surveys are accomplished by flying pre-determined tracks. Demonstrating adaptive sampling with the coupled observation-modeling system is a central objective of this project.

Adaptive sampling could be employed to improve application of the coupled observation/modeling system to achieving observational goals in a number of ways. One method would use the coupled observation/modeling system to identify observational opportunities for more targeted sampling. In this operation scenario, the results of the targeted sampling would not be designed for input into the model, but would instead respond directly to science goals. For example, the model might be used to track upwelling filaments as they propagate across Monterey Bay, which in turn might be targeted for characterization of turbulent mixing.

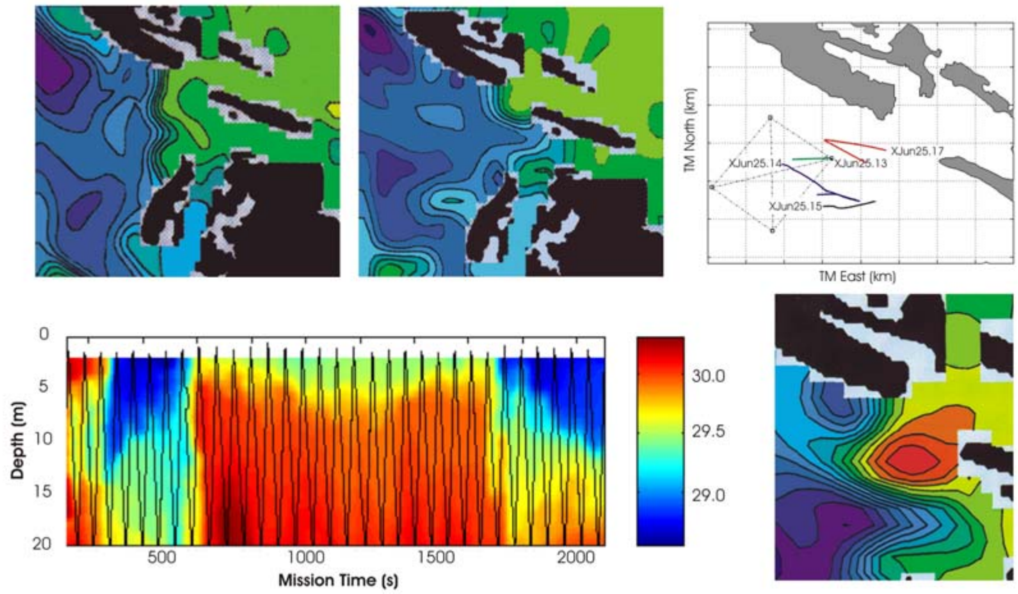


Figure 3.3: Coupled observation/modeling system operations during the Haro Strait experiment. HOPS predictions, shown for 10 meter depth at upper left, were employed to predict frontal locations. The front was clearly observed by the AUV, as demonstrated by the vertical plane section obtained by a run that crossed the front twice: once outbound and once returning. Finally, AUV observations were assimilated into the model to generate the resulting hindcast.

Use of adaptive sampling as an integral component of the coupled observation/modeling system imposes greater demands on the system infrastructure. Techniques such as those proposed separately by Prof. Naomi Leonard (Princeton) provide vehicles with the capability to coordinate their paths to more effectively sample ocean features. For example, gradient climbing techniques might be used to localize and characterize a frontal system. Simple rules at the individual vehicle level, and a means of communication enables these capabilities.

A more intimate integration of adaptive sampling to the coupled observation/modeling system is achieved by designing survey strategies to directly control model errors [Robinson and Glenn, 1999]. This is a nonlinear optimization problem, and is strongly constrained by the physical limitation of the assets available (e.g. vehicle speed). However, increasingly sophisticated tools are being developed to support model-driven adaptive sampling, and these are expected to play an important role in the development of AOSN capabilities.

4 Approach and Project Description

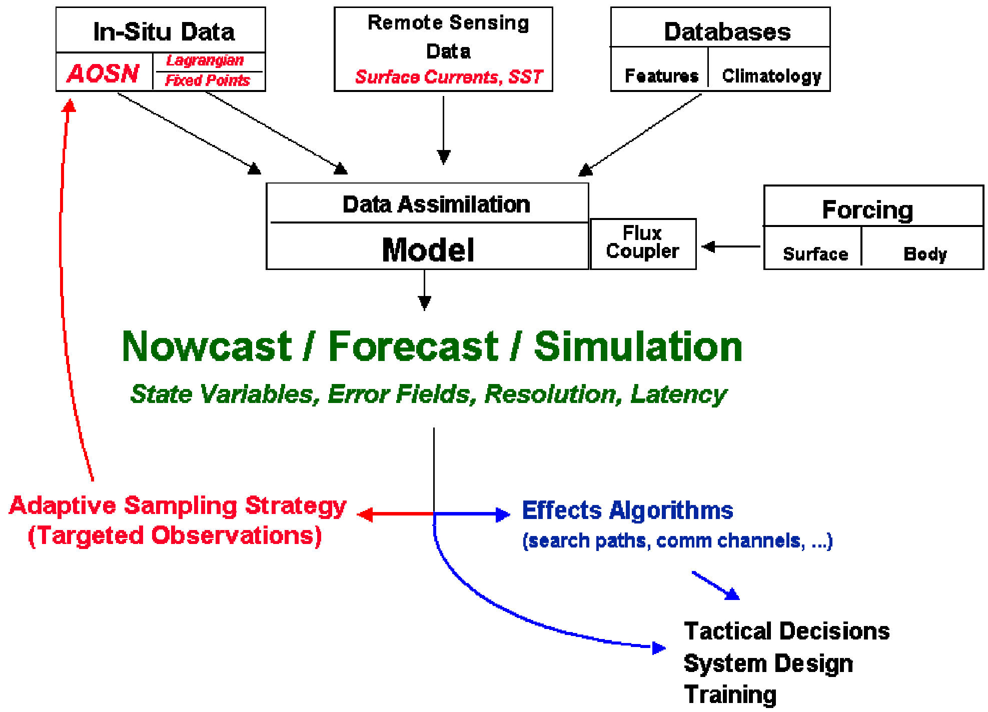


Figure 4.1: System Concept Diagram

4.1 Overview

Previous systems have suffered from weakly integrated ad hoc communications, independent operation of mostly experimental assets owned by various independent and often orthogonally motivated research groups, lack of software designed to interface system components, no real time data processing and assimilation tools, insufficiently quantitative physical models, and decentralized mission planning. These deficiencies, hallmarks of all ground breaking efforts, have limited the time and space scales measurable by previous systems, have confounded efforts to predict and account for the cascade of ecosystem transformations, and have placed heavy demands on available data processing, communication, and manpower assets.

The AOSN II Team will include many previous system contributors and will therefore benefit from the individual experiences gained while designing, building, and testing the earlier systems. The AOSN II project will address earlier deficiencies through focused system integration and design efforts, and will provide a framework within which the skill of each subsystem can be further evaluated and improved.

The potential list of AOSN II participants is listed in section 4.3 below. Each brings with them assets that can be grouped and summarized as seen below in Section 4.1.1. Discussions addressing the selection and integration of these assets have begun. Details will be worked out during a series of conversations and meetings conducted over the first three months of the project.

The envisaged AOSN-II System will function as follows (Figure 4.1): The Model will be initialized prior to Commencement of Experiment (ComEx) based on pre-determined science mission and initialization parameters. The initialized Model will be used to feed the Adaptive Sampling, Decision Making, and Mission Planning tools (Adaptive Sampling Strategy). Assets will be programmed and deployed according to the output from these tools. At ComEx, the observation assets will begin to collect in-situ data, will register with the local network (acoustic, line-of-sight, satellite), compress the data in a predetermined and asset specific manner, communicate the data to a central processing station (most likely ashore) for automated data processing, QC , and assimilation into the Model. The model will also have access to appropriate databases. The model will forecast environment evolution and then feed forecasted information to the Adaptive Sampling Strategy tools, thus closing the update loop. The system will continue to iterate this loop until Finish of Experiment (FinEx). Operators will maintain override control at all decision points.

Clearly, deficiencies in any of the subsystem listed above can lead to System inaccuracy, confusion, or failure. Great care will be taken during System development to identify the critical functions of each subsystem and ensure at least an adequate level of performance for these functions. Simulations of subsystems, their interactions, and possibly the entire system will be conducted prior to deployment for the purpose of further mitigating risk.

4.1.1 Asset Groups and Summaries

4.1.1.1 Autonomously controllable observation assets.

- Assets available to AOSN II will closely parallel those available during AOSN I. These include: Gliders for adaptive response, AUVs for targeted response, instrumented drifters, moorings, Sea Surface Fields (Aircraft), CODAR, and Satellite (SeaWIFS). AOSN II will upgrade these systems to incorporate an integrated data communications standard ensuring timely and reliable data transfer and readability between all assets and subsystems that need to share data.

4.1.1.2 Improved and system integrated communications

- While AOSN II emphasis will not be placed on advanced communications technologies, we will follow a path that permits integration and test of advanced technologies without placing the communications network at risk. A robust communications network will be established, and will serve as the fallback communications standard should more ambitious attempts at advanced communications strategies function below anticipated and required performance levels. Line-of-sight (Freewave), satellite, and acoustic communications networks will be considered.

4.1.1.3 Dynamic network technologies.

- Dynamic registration of assets with system networks will be investigated and integrated if and where the AOSN II Team determines sufficient performance can be expected.

4.1.1.4 Real time data processing and quality control tools.

- These tools serve as the front end to the Phys/Chem/Bio models. They track each asset on its assigned mission to ensure receipt of timely data. They accept data from the assets received through the communications network. They process data for input into the model, including the generation of delta vectors indicating deviations between planned and executed asset missions. These tools also hold the responsibility for data archiving.

4.1.1.5 Databases

- The AOSN II System will take advantage of useful databases where appropriate, such as Meteorological and bottom topography databases. Data needs and database availability will be reviewed early in the project.

4.1.1.6 Atmospheric Forcing

- COAMPS™ for targeted observations. COAMPS™, Targeted Observations: The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS™) is described fully at (http://stratus.nrlmry.navy.mil/, http://www.nrlmry.navy.mil/projects/coamps/). COAMPS™ provides a 3-D data assimilation system including quality control elements and predictive equations for important forcing functions.

4.1.1.7 Physical, Chemical, Biology models

- The HOPS model has been under development for many years. Its evolution is continuous and much experience has been gained through the LOOPS and Haro Strait studies, for example. The HOPS Team plans further improvements this year to, in part, address the needs of the AOSN II effort. However, the challenges these models face are substantial. We cannot, therefore, realistically expect to have a highly accurate quantitative model in hand by the summer of 2003. Recognizing that mission planning cannot succeed without sufficiently accurate input from the model, the AOSN II Team will conduct early evaluations of model skill when applied to selected scenarios, and will adjust scenarios and models until sufficient performance overlap is achieved to guarantee adequate Adaptive Sampling Strategy performance.

- Planned improvements to the HOPS model, in support of the AOSN II effort, have been submitted under a separate proposal, MBPSE-03, Robinson, et. al., describing their integrated system concept for real-time interdisciplinary forecasting with data assimilation and adaptive sampling. It proposes to study physical and interdisciplinary processes on multiple scales and to develop scale-interactive dynamical and advanced error models, which in turn depends on continuation of physical-acoustical-biochemical Error Sub-Space Statistical Estimation (ESSE) efforts. MBPSE-03 further proposes to carry out data driven physical simulations and associated dynamical process studies to identify the principal dynamical features of Monterey Bay on multiple scales. The remote influences from the California Current system, deep sea/coastal interactions, upwellings and coastally trapped waves will be investigated, and the impacts of boundary fluxes and remote forcings will be evaluated. Ecosystem simulations will be utilized to study the coupled biological-physical-chemical-sedimentological dynamical processes of Monterey Bay. In particular, empirical bioluminescence models will be developed and utilized, the dominant sub-regional dynamics for trophic enrichment and accumulation will be researched, and Eulerian and Lagrangian dynamics will be compared. For data assimilation and adaptive sampling, the ESSE framework will be employed to formulate dynamical control criteria for the quantitative and adaptive minimization of errors. Algorithms for adaptive and practical sampling strategies will be researched for the MBPSE-03 sampling network and more sophisticated Lagrangian data assimilation schemes will be implemented.

4.1.1.8 Adaptive Sampling

- Sitting between the Model and Decision Making and Mission Planning tools, will be an Adaptive Sampling Engine, designed to specify future data needs of the Model, based on Model current and forecasted state and error analysis.

4.1.1.9 Automated and centralized decision making and mission planning tools.

- Automated decision making and mission planning tools are essential to any system tasked to adaptively control more than about ten independent assets. The AOSN II System will support assets in excess of this number and must consider incorporation of automated decision making and mission planning tools. Careful selection/development of these tools will be undertaken following assessment of the input these tools can expect from the Phys/Chem/Bio models and the control these tools must provide to the observation assets.

4.1.1.10 Predictive Skill Quantification

- Tools will be developed and run to quantify the predictive skill of the remote adaptive coupled observation/modeling system for principal circulation trajectories, transport at critical points and nearshore bioluminescence potential in the Monterey Bay.

4.2 Target Scenarios

The following two challenging scenarios describe previously observed Monterey phenomena that occur on temporal and spatial scales believed to be consistent with the measurement capabilities of the planned AOSN II System. Final scenario selection will be made based on fit with the capabilities of AOSN II System components, in particular, based on the scenario's fit with anticipated skill of the Phys/Chem/Bio Model.

4.2.1 Scenario I: Upwelling Plume Detection, Tracking, and Characterization

In this operational research scenario, deployment of an array of shallow water gliders in the upwelling source region north of Monterey Bay will permit monitoring of a temporally variable upwelling process, specifically the location of the upwelling plume core where transport of deep particulate material to the surface occurs. The spatial scale for this glider network coverage is about 40 km alongshore and 10 km cross-shore. The observation assets will be used to survey the upwelling source region, characterize the transport pathways, and quantify the fluxes of deep waters and particulate material.

4.2.1.1 Influence of eddy, filament, and frontal dynamics on lateral and vertical transports of upwelled nutrients and resultant productivity

As upwelling filaments evolve in this region, their path and hence their transports are highly variable. Among the important physical phenomena influencing lateral transports are eddies. Adaptive multi-platform sampling methods have demonstrated the ability to resolve eddy processes and their influence on lateral transports in the Monterey Bay region. During the August 2000 MUSE field efforts, remote measurements of surface temperature and velocity revealed an eddy pair structure immediately outside Monterey Bay (Figure 4.2, left). A warm anticyclonic eddy was immediately seaward of a cold cyclonic eddy (the cyclonic eddy is pronounced in the CODAR velocities). An Acoustic Doppler Current Profiler (ADCP) section across the southern end of both eddies (Figure 4.1, right) showed that circulation influence of the paired anticyclone and cyclone extended to at least 400 m. ADCP observations further north (not shown) also revealed eddy circulations throughout the water column. The horizontal spatial scales of these eddies in the Monterey Bay region is about 30-70 km.

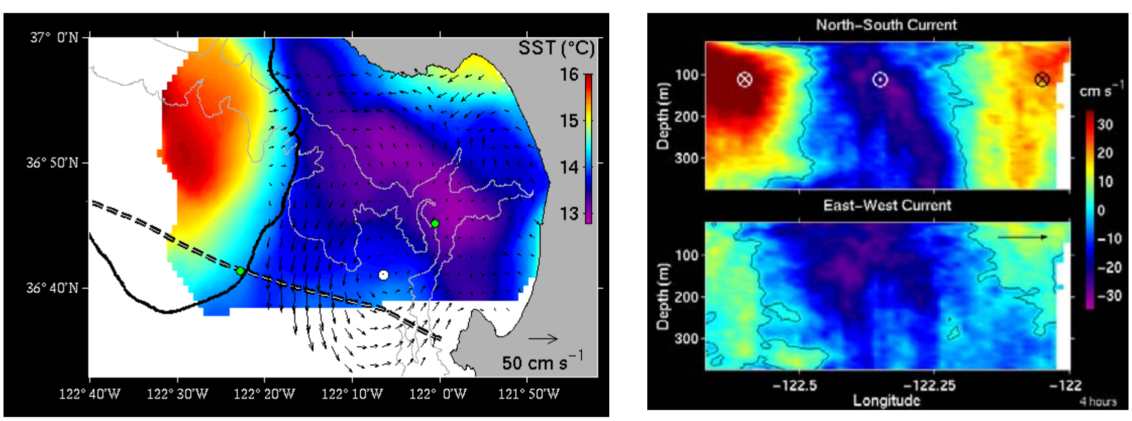
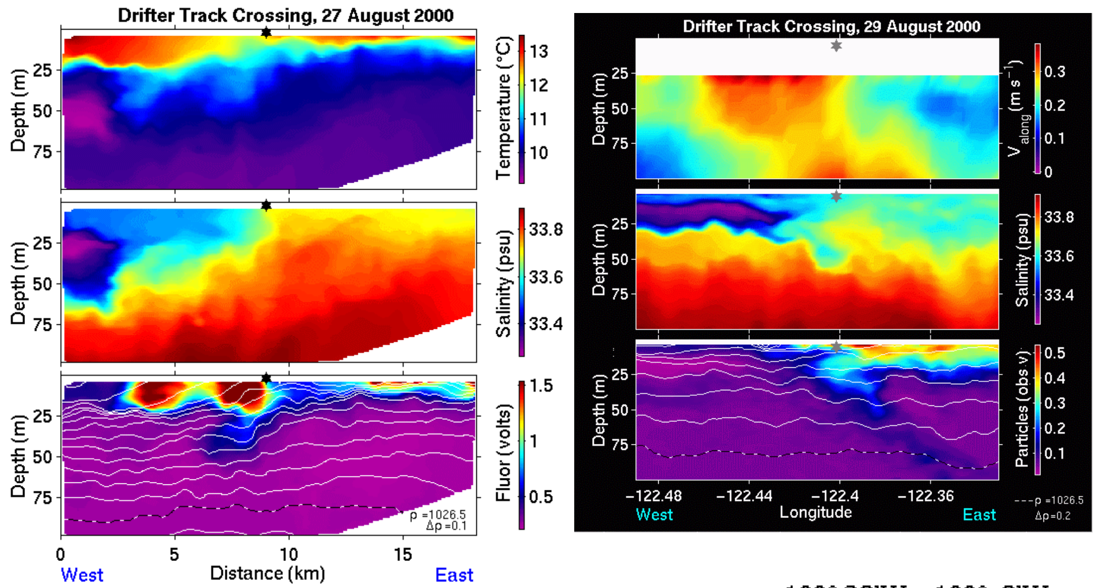


Figure 4.2: (Left) Surface SST and CODAR vectors from NPS (S. Ramp and J. Paduan), and an MBARI drifter track (black contour) illustrating the influence of the eddies on transports of upwelled waters. The transect line shows the surface track of the ADCP section across the eddy pair (right).

Filaments and eddies are associated with fronts that affect the ecological and biogeochemical energy transfer processes through various processes. Frontal jets and eddy circulations modify the spatial patterns and magnitudes of lateral transports. Instabilities along the fronts are associated with enhanced vertical transports [Washburn and Armi, 1988]. Convergence along fronts can concentrate upwelling system productivity to favor feeding of krill, fish, marine mammals and/or seabirds, or rapid subduction of material before degradation.

These dynamic frontal zones present a tremendous challenge to adaptive research strategies. In this research scenario, surface drifters may provide essential information for adaptive deployment of other sampling platforms, including AUVs and gliders. During MUSE, surface drifters were deployed north of Monterey Bay. One of the drifters was entrained into the periphery of the anticyclonic eddy outside the bay (the drifter track is shown with SST in Figure 4.2). Real-time drifter position obtained through satellite communications served as the basis for informed deployment of an AUV. The surface drifter track was used to guide the AUV survey across the filament and its frontal boundaries. AUV sections across the upwelling filament are shown in Figure 4.3.

The survey off Northern Monterey Bay showed concentration of phytoplankton within two lobes in the frontal zone west of the drifter (Figure 4.3, left column). Depression of the thermal field beneath these high fluorescence lobes is consistent with convergence zones within the front. Further, relatively high fluorescence extended deepest into the water column within eastern margin of the frontal zone beneath the drifter, which presumably marked the strongest convergence. This apparent subduction of phytoplankton in the front was aligned with frontal isopycnals (constant density layers). Off southern Monterey Bay, the drifter track crossing again showed enhanced penetration of surface particles down into the water column beneath the drifter (Figure 4.3, right column), however in contrast to the first section, penetration of surface particles extended across isopycnals, suggesting diapycnal (transverse to isopycnals) mixing between the northern and southern section. These processes were studied on different days with the same platform. Studying these processes with multi-platform adaptive sampling concurrently over a larger scale will help separate spatial and temporal variation in these processes and provide new information on how filament and frontal processes influence lateral and vertical transports of upwelling system plankton biomass.



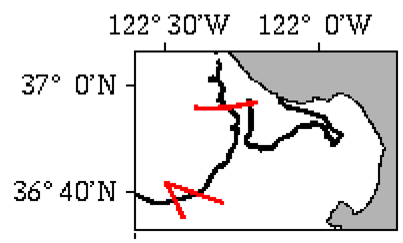


Figure 4.3: AUV sections across an upwelling filament off northern (left) and southern (right) Monterey Bay. Locations are shown in the map below (red lines) relative to drifter tracks (black contours).

4.2.2 Scenario II: Dynamic Frontal Zones with Wind Relaxation/Reversal

A second operational research scenario for adaptive sampling of dynamic frontal zones is to resolve frontal structure and processes in 4-D (3-D spatial and temporal). High-resolution 3-D surveys can resolve very complex dynamics. During MUSE an oceanic front was located in Monterey Bay and an AUV deployed to survey a volume around and through the front. Taking nearly 60,000 measurements from each of 6 instruments, a volume 7 km x 3 km x 70 meters was surveyed (Figure 4.4). The gray surface in Figure 4.4 is an isopycnal, showing a ridge in the density field that dropped off sharply (~15 m) toward the south, where Monterey Canyon lay. The density ridge and surface slick observed above it were aligned with the canyon shelf-break topography. The colored contours show mean temperature in the layer 10 to 20 m (11º to 12ºC; 0.2º interval). The coldest waters (dark blue contours) were above the isopycnal ridge. There was a temperature front south of the ridge and small-scale cool/warm eddy-like features south of the front (labeled C and W). The outer boundary of a concentrated phytoplankton bloom layer is shown as a green isosurface. Inside this boundary, chlorophyll fluorescence was equal to or greater than that along the outer boundary. Property distributions are consistent with the concentration of phytoplankton in the trough of an internal wave [Lennert-Coty and Franks, 1999; Pineda, 1999; Franks, 2001]. The tight physical-biological coupling was evident only with a 3-dimensional snapshot of the environment provided by the AUV, a survey adaptively planned based on real-time environmental information. Resolving the time dependence of such complex processes and thereby capturing variability in 4-D is at the forefront of technological challenges in marine ecology. The scales that we must resolve to advance adaptive research strategies and the scientific progress they enable in this dynamic environment range widely from sub-km to approx. 100 km.

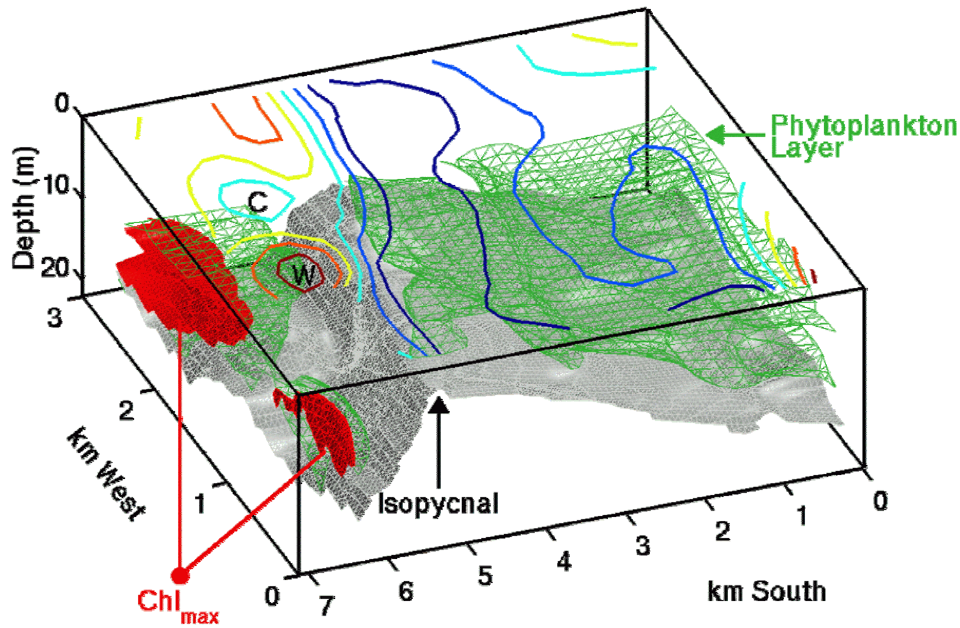


Figure 4.4: Volume view around a front / internal wave structure on the northern Monterey Bay shelf, 31 August 2000. The gray isosurface is an isopycnal. The green isosurface is a phyto-plankton- rich layer; maximum chlorophyll concentrations are shown in red. The contours are mean temperature between 10 and 20 m (see text).

4.2.2.1 Effects of wind relaxation / reversal

Wind relaxation / reversal events were associated with significant changes in the physical environment during MUSE (Figure 4.5). During conditions of predominantly upwelling-favorable winds, cold filament and eddy structures dominated the SST field (middle panel). Following weakening and reversal of upwelling favorable winds, SST rapidly increased over the region and a strong warm anomaly developed in central Monterey Bay.

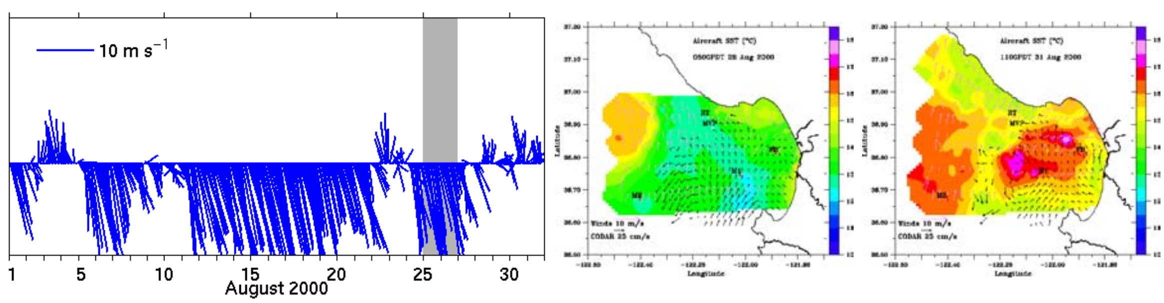


Figure 4.5: Surface winds from MBARI mooring M2 during August 2000 (left) and CODAR vectors and aircraft-measured SST on August 28 and 31 (right, S. Ramp and J. Paduan, NPS).

How do the horizontal and vertical distributions and fluxes of plankton respond to wind relaxation / reversal? What changes occur over large regions of recently upwelled water and in the nearshore zone during relaxation, e.g. does nearshore convergence develop and force downwelling of organic carbon? In this operational research scenario, real-time mooring observations provide information on wind forcing and local response, and the predictive model is critical to define the spatial and temporal attributes of sampling from gliders, drifters, and AUVs. The SST observations are insufficient for predicting water column response, whereas the model can be used to predict where the strongest lateral and vertical transports develop and hence where circulation and properties of the ocean interior will be resolved by adaptive, multi-platform deployments

4.3 Potential Partners/Capabilities

The AOSN II Project will be a multi-institutional effort, with individual collaborators supported under separate proposals. Specific participants and the resources they provide will be worked out during July-02 and the early planning meetings of Aug-02. The list of potential participants includes:

MBARI - Project coordination, definition, infrastructure, hosting (Bellingham, Chandler)

Harvard – Project Deputy (Robinson)

Harvard - Numerical Ocean Modeling / Mesoscale Circulation (Robinson)

Cal Tech - Dynamical Systems Modeling (Coulliette, Marsden)

USM - Numerical Ocean Modeling / Small Scale Dispersion (Shulman)

WHOI - Physical Observations / Glider Network, Floats, Lagrangian Drifters (Fratantoni)

UCLA / JPL - Numerical Ocean Modeling (ROMS)

NRL - Numerical Ocean Modeling (NCOM)

NRL-MRY - Atmospheric Forcing (COAMPS) / Targeted Observations (Bishop)

Princeton - Glider Dynamics and Control (Leonard, Rowley)

NPS - Surface Currents (CODAR) / Sea Surface Fields (Aircraft) (Paduan, Ramp)

Cal Poly - Bioluminescence Observations (Moline)

4.4 Target Timeline

Jul 02	Project Start
Aug 02	Team Meeting/s, Asset Decisions, System Planning
Sep 02	Detailed Science / Architecture Plan
Jan 03	External Review: System Concept
Apr 03	Field Experiment Planning Meeting
May 03	Design Modification Freeze Date
Jul/Aug 03	Field Experiment
Sep 03	Hot Wash-up Meeting
Dec 03	Data Analysis Workshop
Apr 04	Draft Papers (Journal Special Issue)
Jul 04	Final Publications

4.5 Related Projects

AOSN I, Autonomous Ocean Sampling Network I, POC: Bellingham (MBARI)

OSSE, Observation System Simulation Experiments, POC: Robinson (Harvard)

LOOPS, Littoral Ocean Observation and Prediction System (1998), POC: Bellingham (MBARI), Robinson (Harvard)

GOATS, Generic Oceanographic Array Technology (1998), POC: Henrik Schmidt (MIT)

ASCOT 01, Assessment of Skill for Coastal Ocean Transients 01, POC: Robinson (Harvard)

ASCOT 02, Assessment of Skill for Coastal Ocean Transients 02, POC: Robinson (Harvard)

4.6 Current and Proposed Efforts

SCOPE, Simulations of Coastal Ocean Physics and Ecosystems, POC: Chavez (MBARI).

MARS, Monterey Accelerated Research System, POC: McNutt (MBARI)

5 References:

Bellingham, J. G., Goudey, C. A., Consi, T. R., and Chryssostomidis, C. "A Small, Long-Range Vehicle for Deep Ocean Exploration," *ISOPE 92*, Second International Offshore and Polar Engineering Conference, Volume 2, pp 461-467. Golden, Colorado: International Society of Offshore and Polar Engineers, 1992.

Bellingham, J. G., Goudey, C. A., Consi, T. R., Bales, J. W., Atwood, D. K., Leonard, J. J., and Chryssostomidis, C., "A Second Generation Survey AUV," *Proceedings AUV '94*, Boston MA, pp 148-155, 1994.

Bellingham, J. G., Willcox, J. S., "Optimizing AUV Oceanographic Surveys," *Proceedings AUV '96,* pp 391-398, 1996.

Bellingham, J.G., "New Oceanographic Uses of Autonomous Underwater Vehicles," *Marine Technology Society Journal,* Vol.31, No. 3, pp. 34-47,1997.

Chaffey, M. and E. Mellinger, 2001. Communications and power to the seafloor: MBARI's ocean observing system concept. Presented at Oceans 2001.

Curtin T., Bellingham, J. G., Catipovic, J., and Webb, D., "Autonomous Ocean Sampling Networks," *Oceanography*, 6(3), pp 86-94, 1993.

Eriksen, C. C., Osse, T. J., Light, R. D., Wen, T., Lehman, T. W., Sabin, P. L., Ballard, J. W., and Chiodi, A. M., "Seaglider: A Long Range Autonomous Underwater Vehicle for Research," *IEEE Journal of Oceanic Engineering*, 26(4), pp 424-436, 2001.

Franks, P.J.S., 2001. Spatial patterns in dense algal blooms. Limnology and Oceanography, in press.

Frye, D. E., Kemp, J., Paul, W., and Peters, D., "Mooring Developments for Autonomous Ocean Sampling Networks," *IEEE Journal of Oceanic Engineering*, 26(4), pp 477-486, 2001..

Kirkwood, W. (et al), "MBARI / MIT Ducted Propeller Control System Developed for Autonomous Underwater Vehicles," *Underwater Intervention 2001 Conference Proceedings*, Tampa Bay, Florida, January 2001.

Kreamer, W. R., "Supervisory Control of an AUV using an Acoustic Communication Link," S.M. Thesis, Department of Ocean Engineering, Massachusetts Institute of Technology, February, 2000.

Lennert-Coty, C. E. and P. S. J. Franks, 1999. Plankton patchiness in high-frequency internal waves. Marine Ecology Progress Series, 186: 59-66.

Paduan, J., Ramp, S., Bahr, F., Cook, M., Frye, D., Koski, P., Chavez,, F., Reid, F., and Bluth, R., "Atmospheric Forcing and Oceanic Response During Late Summer Upwelling and Relaxation Events in Monterey Bay," Presented at: *The Oceanography Society Biennial Scientific Meeting*, Miami, FL, April 2-5, 2001.

Pineda, J., 1999. Circulation and larval distribution in internal tidal bore warm fronts. Limnology and Oceanography 44(6):, 1400-1414.

Robinson, A.R., 1999. Forecasting and simulating coastal ocean processes and variabilities with the Harvard Ocean Prediction System, in Coastal Ocean prediction, (C.N.K. Mooers, ed.), AGU Coastal and Estuarine Studies Series, American Geophysical Union, pp. 77-100.

Robinson, A.R., and Glenn, S.M., 1999. "Adaptive Sampling for Ocean Forecasting", http://people.deas.harvard.edu/~robinson/PAPERS/Naval_Review.html

Sherman, J., Davis, R. E., Owen, W., B., and Valdes, J., "The Autonomous Underwater Glider 'Spray'," *IEEE Journal of Oceanic Engineering*, 26(4), pp 437-446, 2001.

Washburn, L. and L. Armi. 1988. "Observations of frontal instabilities on an upwelling filament", *Journal of Physical Oceanography*, **8**:1075-1092.

Willcox, J. S., Bellingham, J. G., Zhang, Y., and Baggeroer, A. B., "Oceanographic Surveys with Autonomous Underwater Vehicles: Performance Metrics and Survey Design, " *IEEE Journal of Oceanic Engineering*, 26(4), pp 711-725, 2001.

Zhang, Y., Baggeroer, A. B., and Bellingham, J. G., "Spectral Feature Classification of Oceanographic Processes Using an Autonomous Underwater Vehicle, " *IEEE Journal of Oceanic Engineering*, 26(4), pp 726-741, 2001.

Yu, X., Dickey, T., Bellingham, J., Manov, D., Streitlien, K, "The Application of Autonomous Underwater Vehicles for Interdisciplinary Measurements in Massachusetts and Cape Cod Bays." http://www.opl.ucsb.edu/opl_text/papers/paper_auv_vers10.pdf