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Autonomous Ocean Sampling Network-II (AOSN-II): Integration and Demonstration of Observation and Modeling (Final Report)

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Grant Number: N00014-02-1-0856
http://aosn.mbari.org/

LONG-TERM GOALS

The long-term goals of this project are defined in its charter:
"We are designing and building an adaptive coupled observation/modeling system.

- *The system will use oceanographic models to assimilate data from a variety of platforms and sensors into synoptic views of oceanographic fields and fluxes.*
- *The system will adapt deployment of mobile assets to improve performance and optimize detection and measurement of fields and features of particular interest.*
- *The system should be sustainable in its operation, and capable of being readily relocated, in its final form.*

OBJECTIVES

The AOSN-II project explored the ability of large-scale ocean observing systems to characterize and predict ocean state. The creation of an extended coastal observatory was identified as a realizable first step. The project developed key components and assembled them into an adaptive coupled observation/modeling prediction system. Two major field programs were carried out. Technical effort addressed optimization of observation system performance, creation of data systems for supporting distributed operations managed by geographically distributed experts, and mobile autonomous platform technology.

To optimize observation system design, we developed methodologies for selecting ocean observing locations and sampling strategies for objectives such as estimation of scalar fields, currents, budgets, and fluxes. Our data system development for the AOSN-II and MB2006 field programs, created software components which made data easy to access and multidisciplinary data sets easy to search. We also created collaborative portal approaches which allowed investigators to function as an integrated team for field operations despite being located on opposite sides of the continent. Finally, insights from analysis of the field programs informed development of a new long-range autonomous underwater vehicle, the Tethys.

MBARI

June 26, 2009

Dr. Teri Paluszkiewicz
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

Re: Final Technical Report with SF298

Dear Dr. Paluszkiewicz:

I am pleased to send, on behalf of Dr. Jim Bellingham of the Monterey Bay Aquarium Research Institute, one copy of the referenced report for the project entitled "Autonomous Ocean Sampling Networks II – Integration and Demonstration of Observation and Modeling". The period of performance for this award was 1 August 2002 through 31 March 2009.

Should you require any information in addition to the enclosed, please contact the MBARI Grants Office at grants@mbari.org or telephone (831) 775 -1788.

Sincerely,

Patrice A. Carroll

Patrice A. Carroll
Senior Grants & Accounting Specialist

cc: DTIC
NRL
ONR Seattle

APPROACH

The project bought together sophisticated new robotic vehicles with advanced ocean models to improve our ability to observe and predict the ocean. The first field program (AOSN-II) to demonstrate the coupled observation/modeling system was run in Monterey Bay from mid-July to early September 2003, as illustrated in Figure 1. The second field program --- the Monterey Bay 2006 (MB2006) Experiment, built on the 2003 field program, brought a much more diverse group of investigators to Monterey Bay. The field programs and the resulting data sets provided the proving grounds both for data system and collaborative portal activity, and for research on optimal experiment design.

The AOSN-II operational system included data collection by smart and adaptive platforms and sensors (Figure 2) that relayed information to shore in near real-time (hours). On shore, the data was assimilated into numerical models. The model output helped visualize the four-dimensional fields and predict future conditions. Observations were provided by a variety of remote sensing and in situ assets. Data from these assets were communicated to shore, usually by Iridium satellite communications, where they were placed in a central repository that can be accessed via the Internet by modeling groups and other collaborators. Key to our approach was the development of adaptive sampling control strategies to command our mobile vehicles to places where their data will be most useful. Meetings of the Real-Time Operational Committee occurred every other day during the experiment, and provided a forum for reviewing progress against objectives, observational results, model output, and planning subsequent observations. Graphical observation data products and modeling results were placed on open project web sites in real time.

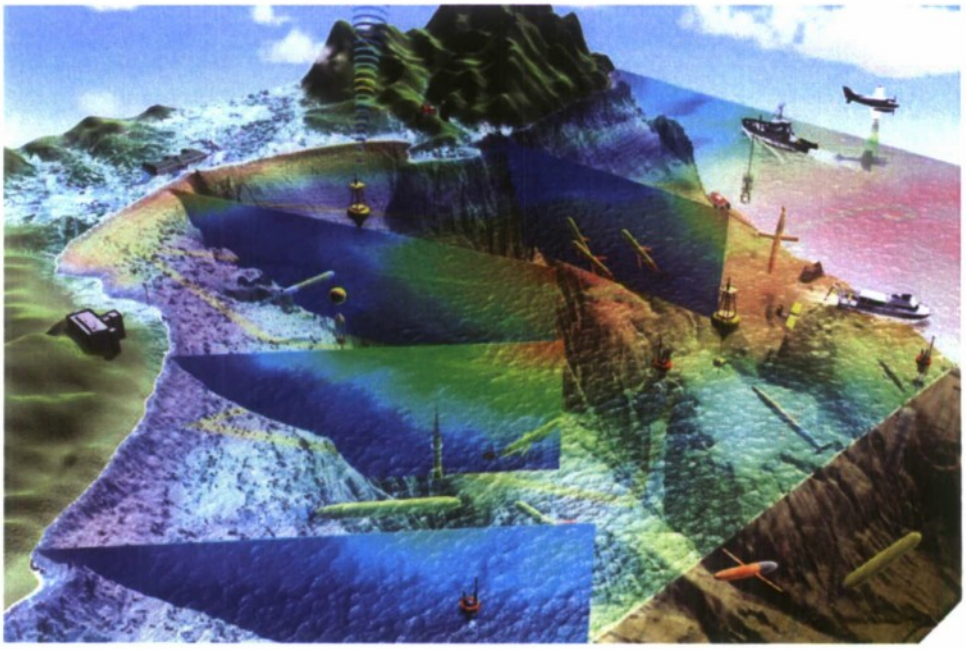


Figure 1. AOSN-II field program in Monterey Bay, CA.

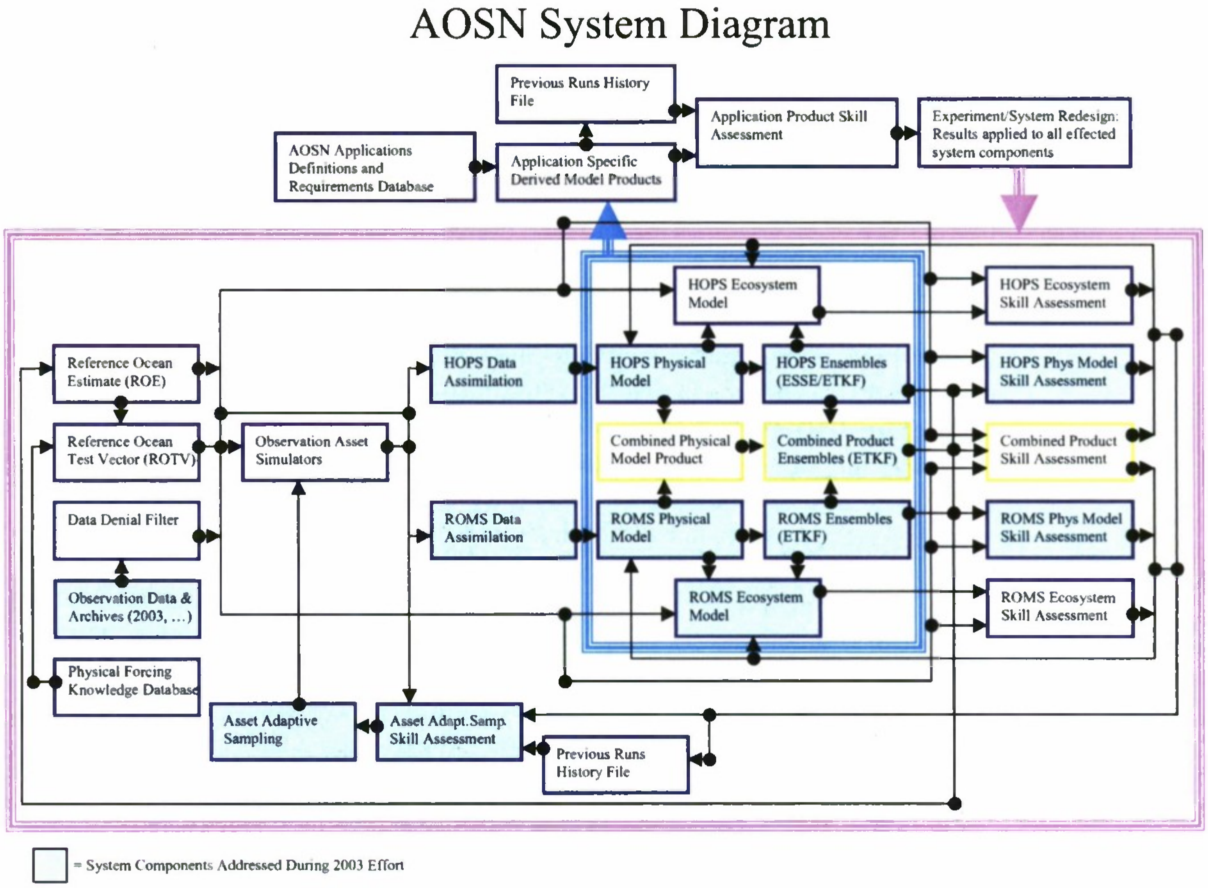


Figure 2. AOSN-II system diagram. The items in the yellow boxes were not implemented in real-time.

For data management, our approach has been to provide web applications that crawl, index, and serve the AOSN-II and MB2006 data collections with an intuitive and fast interface. The capabilities being developed can also be used to make other relevant data sets searchable and accessible to scientists via a common portal. Requirements on scientists generating data should be minimal: to continue their excellent data generation and data management, ensuring that their data are internally consistent. Requirements on users should also be minimal: a computer with a modern web browser and internet access.

Our theoretical research had two prongs. The first prong was to develop a method of intelligently selecting a small number of observing locations in a vast ocean field for capturing the leading spatial modes and reconstructing the field. In this method, the selection of observing locations is based on the field's empirical orthogonal functions (EOFs) extracted from historical data. Selection of each location is by a simple sorting.

We demonstrate that using observations at a small number of selected locations; one can quite accurately estimate the leading modes' amplitudes. Consequently, the full field can be reconstructed. The second prong was to design sampling strategies for estimating ocean flux using moorings or autonomous underwater vehicles (AUVs). We applied it to heat flux estimation in Monterey Bay using ocean model data.

WORK COMPLETED

During the AOSN-II field program, all assets (Figures 3 and 4) were deployed on schedule without incident, and with very few minor exceptions, operated reliably throughout the experiment. The experiment started during a wind relaxation period, continued through a significant upwelling period in mid-August (Figure 5), a wind relaxation period in late August (Figure 6), and finally ended with upwelling favorable winds and upwelling conditions. Data (e.g., AUV measurements shown in Figure 7) were captured throughout the field experiment to data servers at MBARI, Harvard, and JPL and were assimilated in real time into the Harvard Ocean Prediction System (HOPS) and Regional Ocean Modeling System (ROMS) models. The models provided forecast products for the development of adaptive sampling plans, which were then used to reprogram gliders and redeploy other assets. Data from these assets were communicated to shore, where they were placed in a central repository that could be accessed by modeling groups and other collaborators.

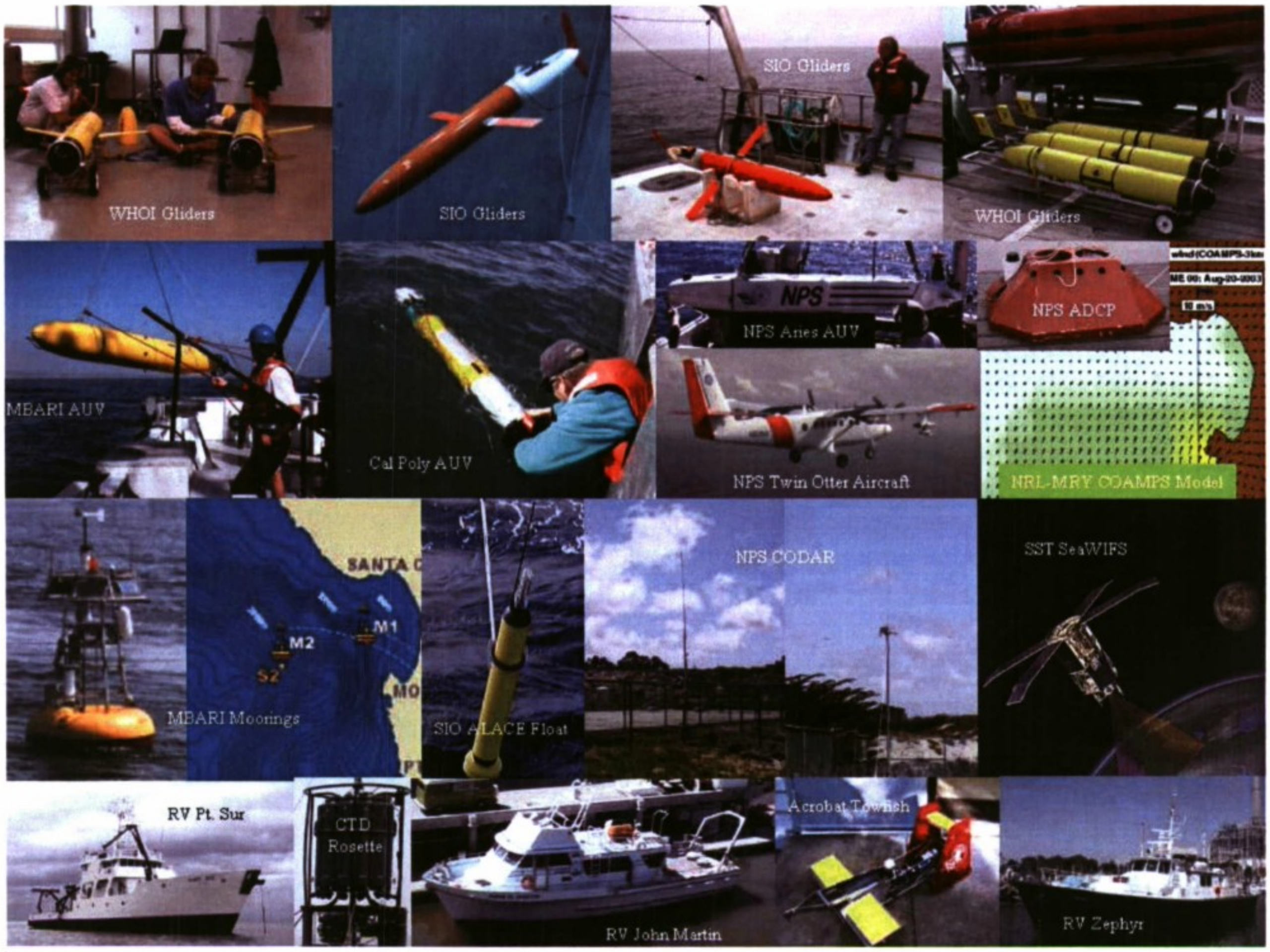


Figure 3. Observational assets used in the 2003 AOSN-II Experiment.

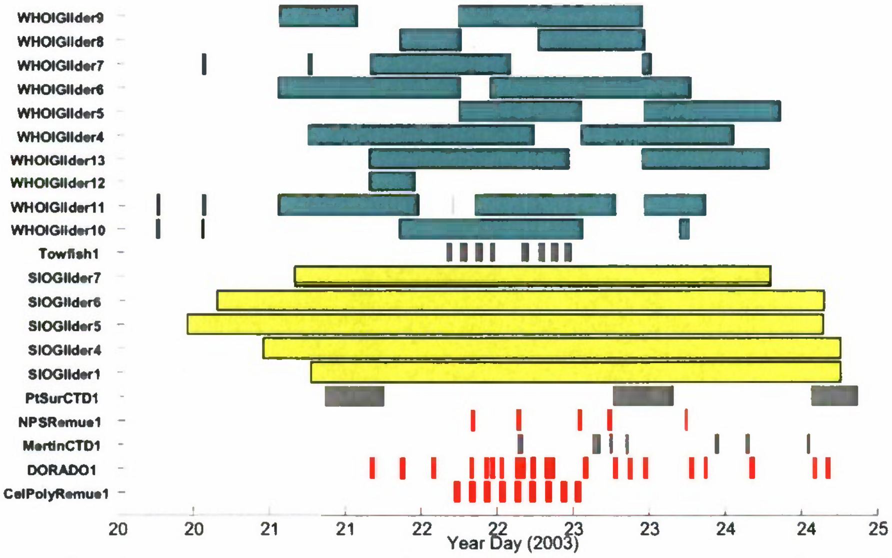


Figure 4. Combinative deployment of multiple gliders and propeller-driven AUVs.

Models provide a powerful tool for the integration of information from a variety of observational sources into a representation of the best estimate of the ocean state. The full exploitation of this capability is limited by a variety of factors. Determining these factors, quantifying their effects, and using these results to improve model performance were an important objective of the project. In addition, the modeling emphasis expanded beyond focusing on only the physics of the ocean, and began an effort to forecast biological and chemical parameters just as accurately.

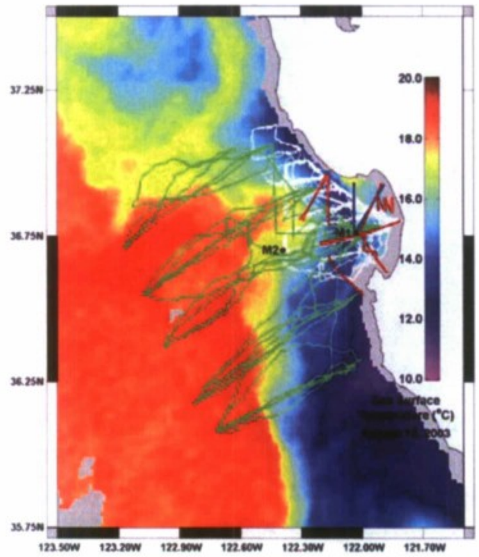


Figure 5. Autonomous vehicles' tracks are shown over the August 15, 2003 sea-surface temperature, which indicates an upwelling phase.

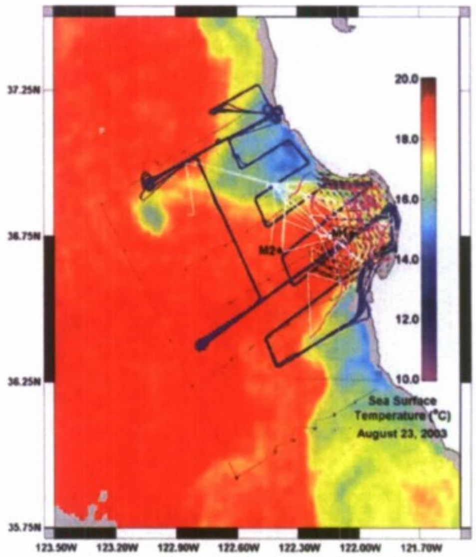


Figure 6. Aircraft, HF radar, drifters, moorings, CTD, and towfish tracks are shown over the August 23, 2003 sea surface temperature, which shows a relaxation phase.

Resulting from the 2003 field program, a series of journal papers and conference presentations have been published (see the "Publications" Section). The lists of coauthors from multiple institutions manifest the collaborative effort.

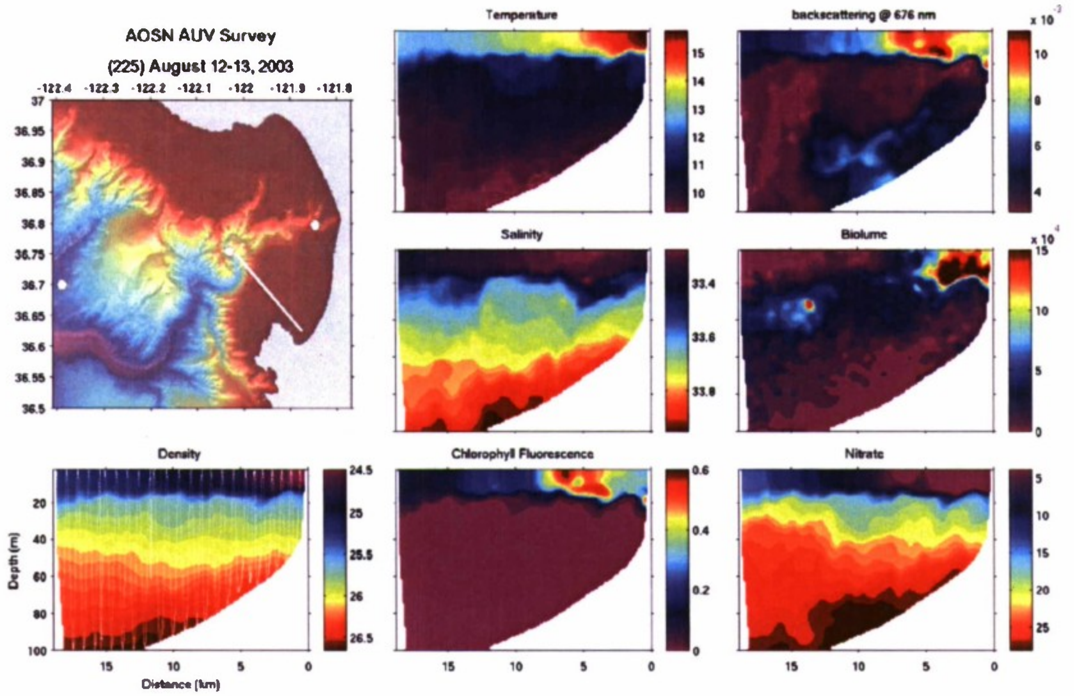


Figure 7. Dorado AUV transect measurements during the 2003 AOSN-II Experiment.

After the 2003 field program, MBARI took responsibility for developing a data system for the MB2006 Experiment (also known as the Adaptive Sampling and Prediction (ASAP) Experiment). The resulting data system leveraged and extended several aspects of MBARI's Shore Side Data System (SSDS) data catalog, resulting in a system that successfully managed several hundred thousand data files. PIs interacted with the data system, and with a wide range of derived products, via the Cooperative Ocean Observatory Portal (COOP). Further data management work has resulted in the Metadata Oriented Query Assistant (MOQuA) prototype that has been widely demonstrated and used to develop the next set of research needs for a data exploration tool. During the MB2006 Experiment, COOP was the central hub and was used frequently by PIs from the participating universities and institutions. The MOQuA prototype has also received high praise as an easy-to-use data exploration interface. The work has been published in "A Collaborative Portal for Ocean Observatory Control" in *Proceedings of Oceans '06*, "Data Exploration for Multidisciplinary Research" in *Proceedings of Oceans '07*, and "Exploring Ocean Data" in *Proceedings of Tribute to Jim Gray of the Association for Computing Machinery Special Interest Group on Management of Data.*

For intelligent selection of ocean observing locations, our paper "An Efficient Method of Selecting Ocean Observing Locations for Capturing the Leading Modes and Reconstructing the Full Field" was published in the *Journal of Geophysical Research (Oceans)* in 2008. For designing sampling strategies for estimating ocean flux, a manuscript "Error Analysis and Sampling Strategy Design for Using Fixed or Mobile

Platforms to Estimate Ocean Flux" has been submitted to the *Journal of Atmospheric and Oceanic Technology*, and is now being revised based on the reviews.

RESULTS

The 2003 AOSN-II field program was a great success. Over 21 different autonomous robotic systems, three ships, an aircraft, CODAR, drifters, floats, and numerous moored observational assets were used to produce an unprecedented data set of upwelling processes in the vicinity of Monterey Bay. Tracks of the mobile platforms are shown in Figure 8.

Besides a large number of gliders, a small number of propeller-driven AUVs were also deploymed during the experiment, and had a significant effect on the coverage rate (i.e., the cumulative speed of the deployed platforms). The coverage rate is a key parameter for quantifying survey coverage capability. Because of their much higher speed, individual AUVs were capable of doubling the coverage rate of the overall system several times during the experiment, as shown in Figure 9. Considering that AUVs also carry much more complete instrument suites than gliders, the effect of AUV deployments was indeed even higher than a simple improvement in coverage rate.

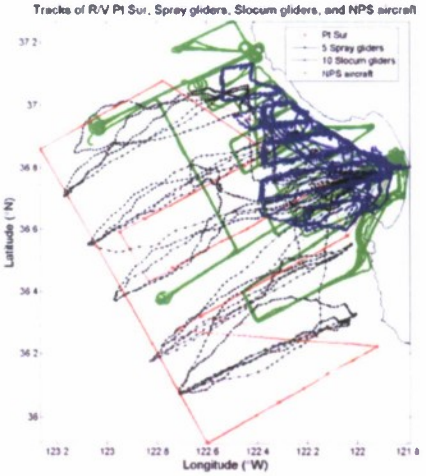


Figure 8. Tracks of gliders, surface vessel, and aircraft during the 2003 AOSN-II Experiment.

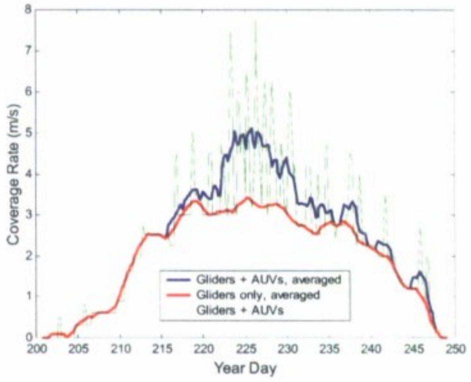


Figure 9. Coverage rate (i.e., cumulative speed) of gliders and AUVs.

Given the size of the area and the coverage rate, the suvery error (with the objective of synoptic reconstruction of the field) can be computed based on the temporal-spatial scale of the variability of the ocean field, as shown in Figure 10 and Table 1. The actual survey performance is compared with the theoretically optimum performance. The analysis reveals that the survey areas allocated to R/V Pt Sur and the Spray gliders were too large to achieve a meaningful synoptic realization of the ocean fields by the respective platforms alone, so combining different platforms is necessary.

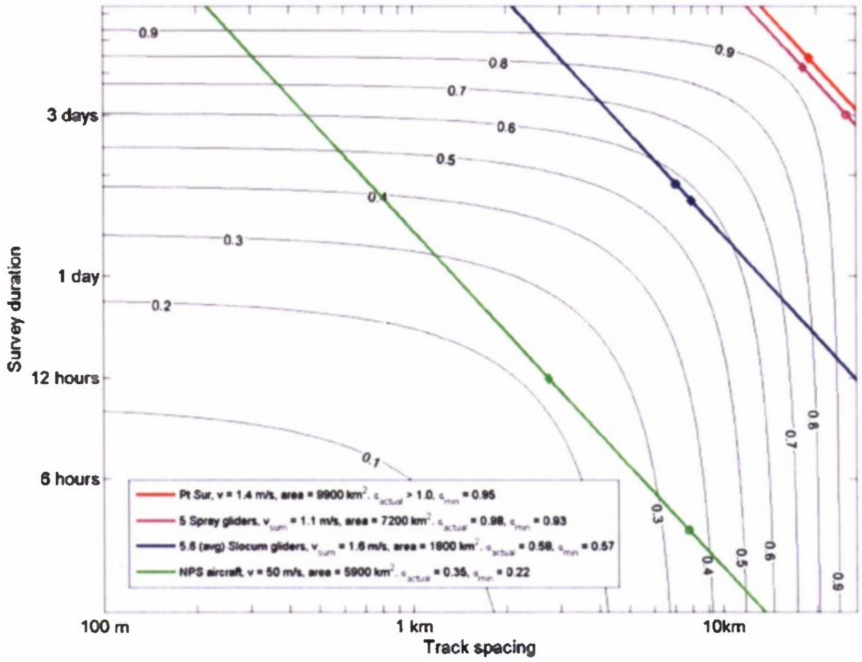


Figure 10. Grid survey errors using different platforms. On each line, the diamond denotes the optimum operation point (i.e., the minimum error), and the circle denotes the achieved error by the actual deployment in the 2003 AOSN-II Experiment.

Table 1. Grid survey errors for different platforms.

Platforms	Cumulative speed	Covered area	Actual track spacing	Actual survey duration (for covering area once)	Actual survey error	Optimum track spacing	Optimum survey duration (for covering area once)	Minimum Survey error
Pt Sur	1.4 m/s	9900 km^2	30 km	2.8 days	> 1.0	19 km	4.5 days	0.95
5 Spray gliders	1.1 m/s	7200 km^2	25 km	3.0 days	0.98	18 km	4.2 days	0.93
5.6 (avg) Slocum gliders	1.6 m/s	1800 km^2	7 km	1.9 days	0.58	7.9 km	1.7 days	0.57
NPS aircraft	50 m/s	5900 km^2	7.8 km	4 hours	0.35	2.8 km	12 hours	0.22

Field experience and analyses have generated a number of critical insights that will guide the development of future systems. Perhaps most importantly, models may provide a relief from temporal decorrelation, a principal source of error in surveys of time-varying processes. 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.

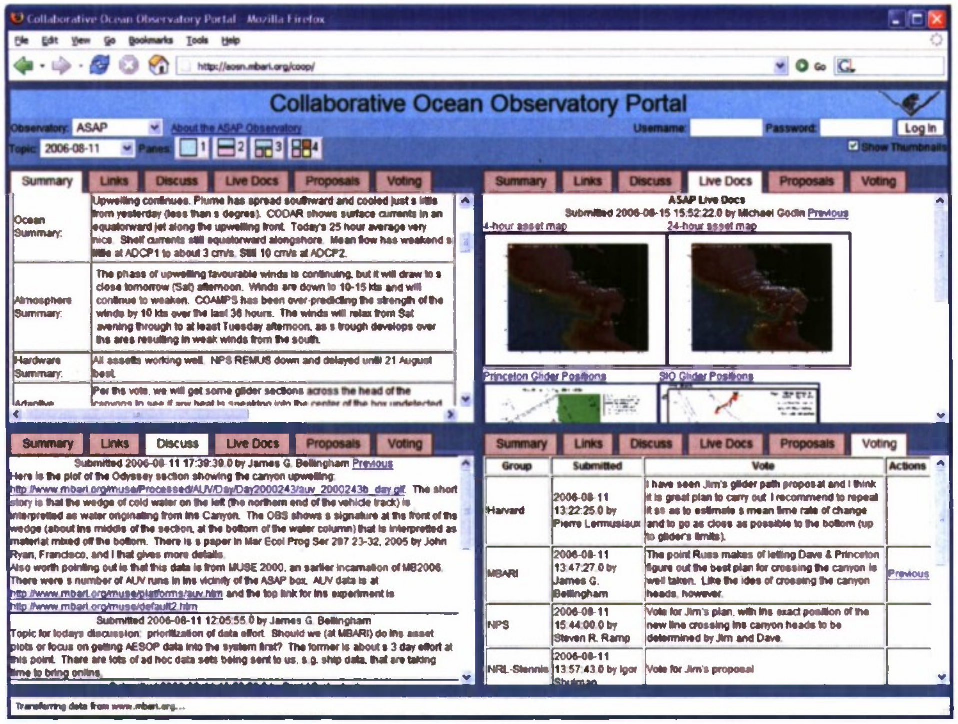
However, in analyzing model outputs and looking at model prediction skill, a variety of factors began to dominate. These quantifiable factors were found to include:

- Surface forcing for oceanographic models, e.g., net surface heat flux, are extremely difficult to obtain.
- Oceanic boundary conditions, which are also very difficult to constrain, and are usually provided by some combination of nested modeling, climatology, and/or observation.
- In situ observations, which are extremely expensive, and consequently measurements are extremely sparse even under the best of circumstances.
- The absence of proven methods for optimizing the placement of in situ observations.
- Sparse in-situ measurements and observations, which alias high frequency processes.
- Approximations to hydrodynamic equations used to make models computationally tractable, which introduce errors.
- Processes that are not modeled (e.g., tides in some models).
- The assimilation process for conditioning data for model "consumption," which often destroys information and inserts errors.

The AOSN-II data management efforts were a large improvement over those realized in earlier programs. One measure of their success is the very high rate of availability of data and model graphics via the web during the experiment. After the experiment, a revised plan was implemented, and a web-accessible data repository that continues to be online (http://aosn.mbari.org).

In preparation for the MB2006 Experiment, which involved day-to-day participation of a large group of researchers with ties to geographically diverse institutions throughout North America, we hosted several virtual experiments. In each virtual experiment, realistic, "virtual" data were generated from a model ocean, and handled in a realistic way. The virtual data was handled by the data system, plotted in common formats, and served as the basis for adaptation decisions. It quickly became apparent in these virtual experiments that tools were needed to facilitate long-distance scientific collaboration. Since the long-term, sustained co-location of researchers for situational awareness and decision-making was deemed impractical, there was a need for collaborative data distribution and situational awareness tools appropriate for the MB2006 Experiment, and eventually, for all ocean observatories.

With the virtual experiment insights and the 2003 AOSN-II experience (specifically the Real Time Operations Committee meetings); we developed the Cooperative Ocean Observatory Portal (COOP) tool. COOP supported the MB2006 Experiment, allowing investigators to interact on a continual basis to discuss and plan data collection and analysis. This effort was deemed a tremendous success, and the tool has been re-used in other oceanographic campaigns. Future versions of the COOP tool will become more and more important as future ocean observatories and observing systems (such as moored arrays and cabled observatories) begin to operate 24 hours a day, 7 days a week over many years or even decades.



Ocean Summary:	Upwelling continues. Plume has spread southward and cooled just a little from yesterday (less than a degree). CODAR shows surface currents in an equatorward jet along the upwelling front. Today's 25 hour average very nice. Shelf currents still equatorward alongshore. Mean flow has weakend a little at ADCP1 to about 3 cm/s. Still 10 cm/s at ADCP2.
Atmosphere Summary:	The phase of upwelling favourable winds is continuing, but it will draw to a close tomorrow (Sat) afternoon. Winds are down to 10-15 kts and will continue to weaken. COAMPS has been over-predicting the strength of the winds by 10 kts over the last 36 hours. The winds will relax from Sat evening through to at least Tuesday afternoon, as a trough develops over the area resulting in weak winds from the south.
Hardware Summary:	All assets working well. NPS REMUS down and delayed until 21 August best.
	Per the vote, we will get some glider sections across the head of the

ASAP Live Docs
Submitted 2006-08-15 15:52:22.0 by Michael Godin Previous

Submitted 2006-08-11 17:39:39.0 by James G. Bellingham Previous
Here is the plot of the Odyssey section showing the canyon upwelling: http://www.mbari.org/muse/Processed/AUV/Day/Day2000243/auv_2000243b_day.gif. The short story is that the wedge of cold water on the left (the northern end of the vehicle track) is interpreted as water originating from the Canyon. The OBS shows a signature at the front of the wedge (about the middle of the section, at the bottom of the water column) that is interpreted as material mixed off the bottom. There is a paper in Mar Ecol Prog Ser 287 23-32, 2005 by John Ryan, Francisco, and I that gives more details.
Also worth pointing out is that this data is from MUSE 2000, an earlier incarnation of MB2006. There were a number of AUV runs in the vicinity of the ASAP box. AUV data is at http://www.mbari.org/muse/platforms/auv.htm and the top link for the experiment is http://www.mbari.org/muse/default2.htm

Submitted 2006-08-11 12:05:55.0 by James G. Bellingham
Topic for todays discussion: prioritization of data effort. Should we (at MBARI) do the asset plots or focus on getting AESOP data into the system first? The former is about a 3 day effort at this point. There are lots of ad hoc data sets being sent to us, e.g. ship data, that are taking time to bring online.

Group	Submitted	Vote	Actions
Harvard	2006-08-11 13:22:25.0 by Pierre Lermusiaux	I have seen Jim's glider path proposal and I think it is great plan to carry out. I recommend to repeat it so as to estimate a mean time rate of change and to go as close as possible to the bottom (up to glider's limits).	
MBARI	2006-08-11 13:47:27.0 by James G. Bellingham	The point Russ makes of letting Dave & Princeton figure out the best plan for crossing the canyon is well taken. Like the idea of crossing the canyon heads, however.	Previous
NPS	2006-08-11 15:44:00.0 by Steven R. Ramp	Vote for Jim's plan, with the exact position of the new line crossing the canyon heads to be determined by Jim and Dave.	
NRL-Stennis	2006-08-11 13:57:43.0 by Igor	Vote for Jim's proposal	

Figure 11. Collaborative Ocean Observatory Portal (COOP).

In designing COOP, researchers defined desirable functionality and experimented with prototype versions of COOP. A survey of MB2006 Principal Investigators identified a hierarchy of needs, revolving around four central requirements: access to observational data and model outputs, data-sharing tools, on-line meeting spaces, and tools to facilitate decision making processes. As implemented for the MB2006 team, the COOP tool set consists of several components, starting with a publicly viewable, web-based tool for reviewing the day's progress and proposed actions. Registered scientists are able to discuss the day's progress (and attach illustrative data), propose actions (and back up those proposed actions with supporting data), and discuss and vote upon proposed actions. The tool provides links to other system components, such as a database of data collections in both original and common formats, interactive data access and manipulation tools, and pages of automatically generated graphical summaries of observational results and model forecasts. A screenshot of COOP is shown in Figure 11.

The Metadata Oriented Query Assistant (MOQuA) was originally developed as a tool to enable exploration of the extensive AOSN-II Experiment data, and continues to evolve today into a tool that can be used to query and retrieve real-time data. With MOQuA, answers to questions such as "what data is available around Año Nuevo in August," or "which datasets contain both temperature and optical attenuation" can be quickly answered. MOQuA can handle real-time data streams, and to interactively deliver data from selected regions of time and space, allowing one to perform both custom and pre-defined queries across data sets. A screenshot of MOQuA is shown in Figure 12.

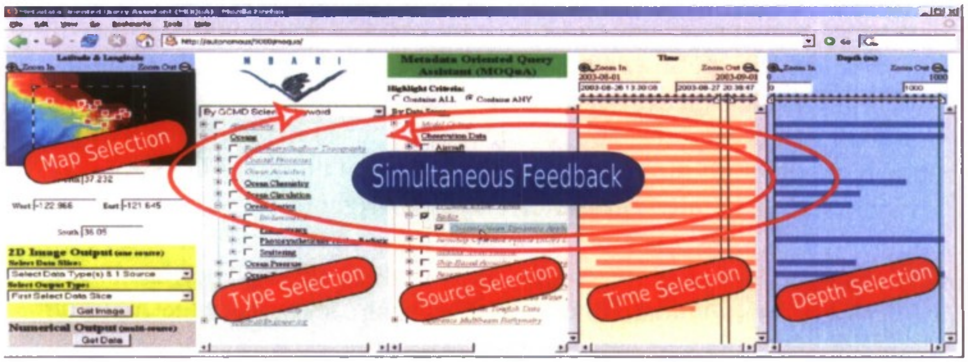


Figure 12. Metadata Oriented Query Assistant (MOQuA).

Estimation of synoptic ocean fields using a limited number of observing locations is a pervasive problem in oceanography. We need to pick the locations that are "representative" of the field, so that we can use observations at those locations to capture the variability of the field and reconstruct the field. In analyzing the AOSN-II sea surface temperature (SST) measured by the satellite and aircraft, we found that a high fraction (56%) of variability in the inner Monterey Bay can be represented by just the first leading mode, and that the upwelling index can be deduced from in situ observations with high confidence.

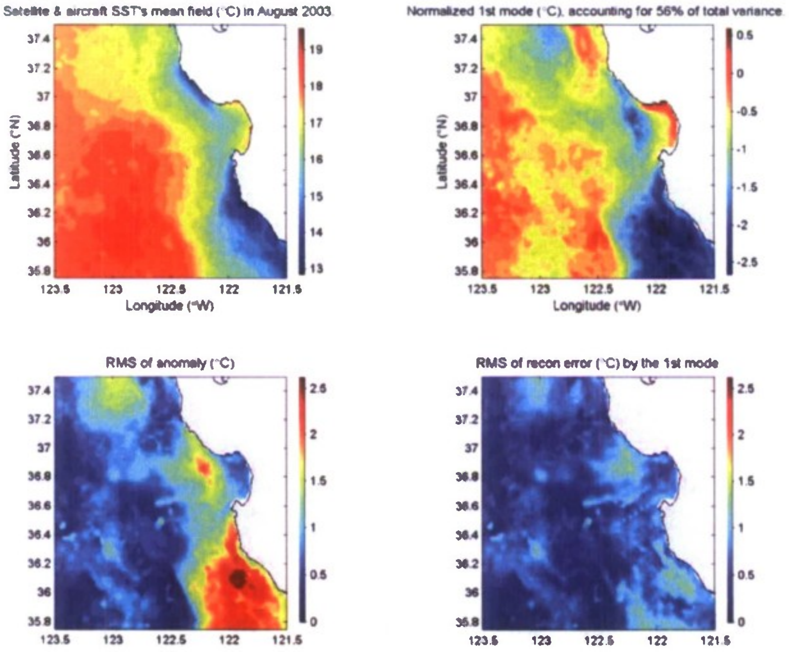


Figure 13. EOF analysis of SST in Monterey Bay in August 2003. Upper-left: mean SST field. Upper-right: the first mode of the SST anomaly fields. Lower-left: RMS of the SST anomaly fields. Lower-right: RMS of the reconstruction error using the first mode alone.

The surprising result is that although the coastal ocean has high spatial and temporal variabilities, at least at some times, its large-scale variability is comparatively simple. In the upper-left panel of Figure 13, we show the mean SST in Monterey Bay in August 2003. In the lower left, the root-mean-square (RMS) of the anomaly field is shown. The anomaly field is the residual field after the mean field is subtracted. In the upper right, we show the first EOF, which captures 56% of the total variance in the anomaly field. Comparison with the RMS of the anomaly field shows that the first EOF strongly captures the upwelling signature near shore. The lower-right panel shows the RMS of the difference of the true anomaly field and the reconstructed anomaly field, where the reconstructed anomaly field is produced by simply multiplying the coefficient of the first EOF (which varies in time) with the first EOF. This figure shows that the first EOF captures the major upwelling signature.

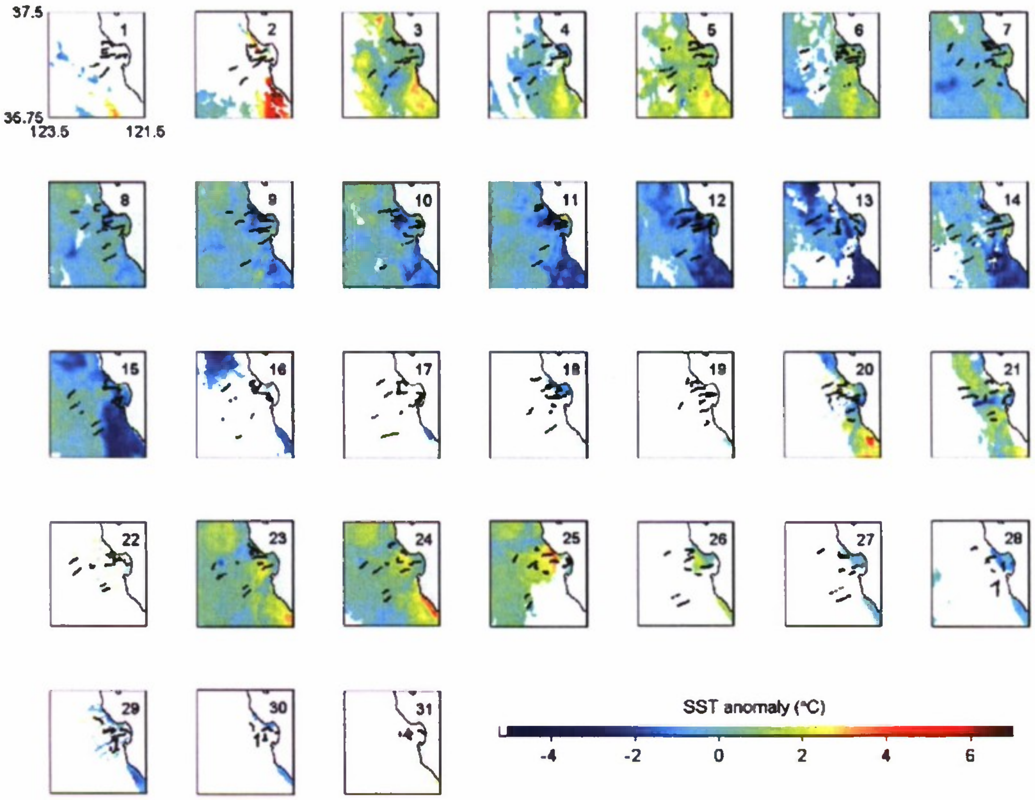


Figure 14. Tracks of Dorado, Spray, and Slocum AUVs in the upper 5 meters superimposed on satellite SST in August 2003 during the AOSN-II field program.

To accomplish the reconstruction in Figure 13, the observation system must be capable of determining the EOF coefficients. For this AOSN-II data set, we do not have the luxury of optimally placing observations, so we have to make do with assets which were in place, which were quite numerous. From in situ temperature measurements made by Dorado, Spray, and Slocum AUVs, we extract measurements in the upper 5 meters and consider them surface temperature. We call them the AUVs SST. They constitute an SST data set independent of the satellite & aircraft SST data set. Figure 14 shows the AUVs' tracks in the upper 5 meters.

One metric to evaluate the AUVs' survey performance is how much of the upwelling mode they captured (the upwelling mode is based on satellite & aircraft SST). Using the AUVs SST data only, we estimate the upwelling mode's amplitude, as shown by the red curve in the lower panel in Figure 15. It tracks the blue curve (upwelling mode's amplitude estimated by satellite & aircraft SST) closely up to August 24: correlation coefficient = 86%. It also correlates quite well with the upwelling index up to August 24: correlation coefficient = 76%. Towards the end of August, however, the AUVs swarmed into the mouth of the Bay, distancing from the upwelling centers. This leads to less accurate estimates of the upwelling mode's amplitude. Consequently, the correlation of the estimated amplitude with the upwelling index decreases. This analysis provides important insights and lessons for AUV sampling strategy design.

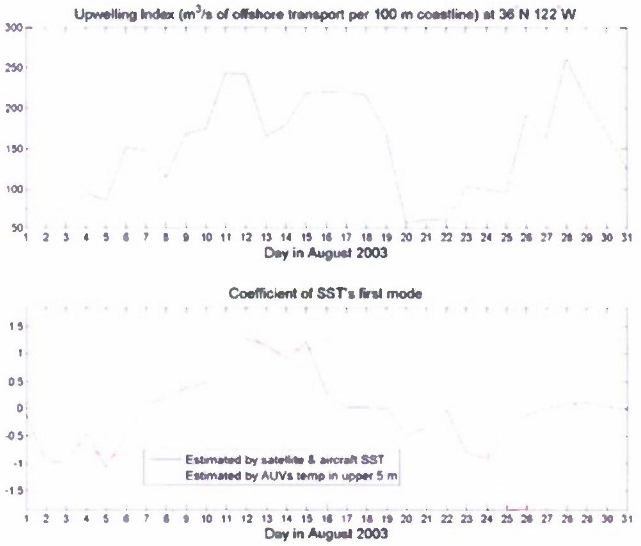
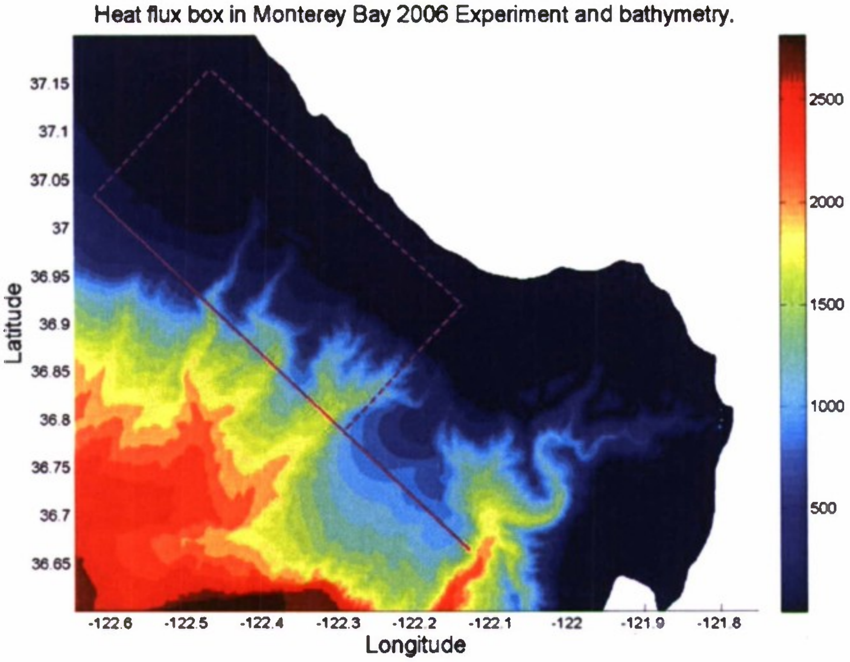


Figure 15. Upwelling index (upper panel) and coefficient of the first EOF as estimated by satellite and aircraft SST (lower panel, blue) and by AUVs (lower panel, red).

Measuring flux of water mass, heat, chemicals, and biological organisms is very important for studying ocean circulation, marine ecology, and global climate. Temporal and spatial variabilities of the ocean introduce a challenge since fixed platforms sample sparsely in space, while mobile platforms might not be fast enough to synoptically capture ocean fields. We have developed a method of analyzing the flux estimation error and designing the sampling strategy for fixed or mobile platforms. We show that moorings and AUVs possess respective advantages under different scenarios of temporal and spatial variabilities. We also find that a larger number of slower AUVs can achieve a more accurate flux estimate than a smaller number of faster AUVs under the same cumulative speed, but the performance margin shrinks with the increase of the cumulative speed. Using the error analysis results, one can wisely choose the type of platforms and optimize the sampling strategy under resource constraints.

The science goal of the MB2006 Experiment was to study heat transfer in a control volume around an upwelling center at Point Año Nuevo. The control volume was a box about 40 km long and 20 km wide, with a variable depth down to several hundred meters, as shown in Figure 16. For flux estimation, we conduct simulated AUV/mooring surveys using the ROMS data for Monterey Bay in August 2003 for the AOSN-II Experiment. Note that our objective is to use the model data for demonstrating the flux estimation error analysis, instead of validating the model.



Heat flux box in Monterey Bay 2006 Experiment and bathymetry.

Figure 16. The heat budget control volume for the Monterey Bay 2006 Experiment. Heat flux out of the southwest side (solid line, with an extension) is estimated by moorings or yo-yoing AUVs.

We investigate heat flux through a section on the southwest side of the control volume (with an extension of 20 km) from sea surface to 100-m depth, as marked by the solid line in Figure 16. The temporal and spatial e-folding scales of the flux variable (i.e., the product of temperature and current's normal velocity) turn out to be 17 hours and 16.6 km, respectively. Using the analytical method we developed, the predicted relative errors of flux estimation by AUVs or moorings are shown in Figure 17.

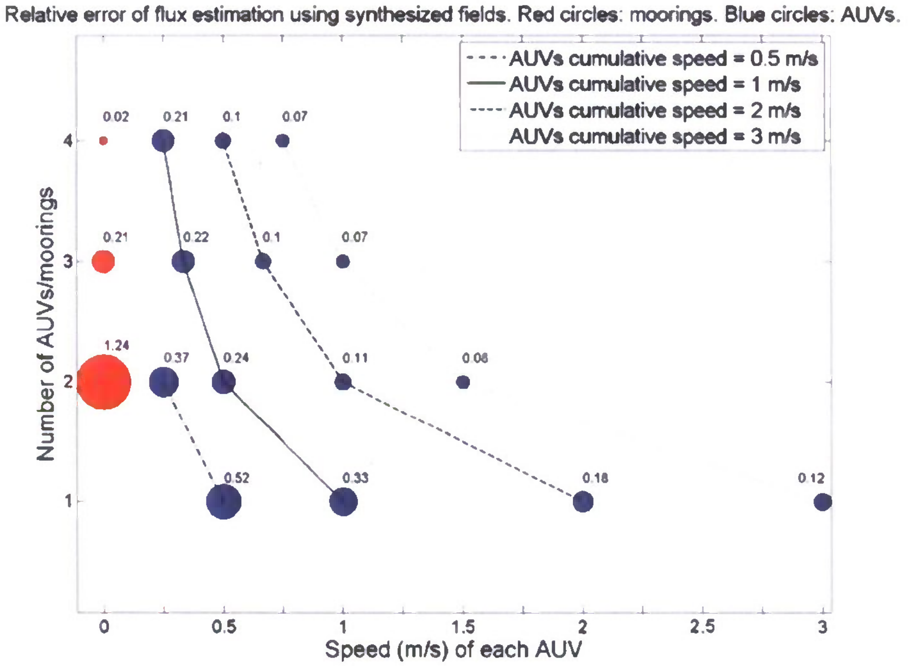


Figure 17. Relative mean-square error (by analysis) of flux estimation at different combinations of number of moorings/AUVs and AUV speed.

We run simulated AUV surveys on a yo-yo track. In Figure 18, we plot heat flux densities estimated by one 2 m/s AUV, two 1 m/s AUVs, and three equispaced moorings. At this cumulative speed, AUVs' flux estimation accuracies are higher than that of three moorings. Under the same cumulative speed, two 1 m/s AUVs provide a more accurate estimate than one 2 m/s AUV.

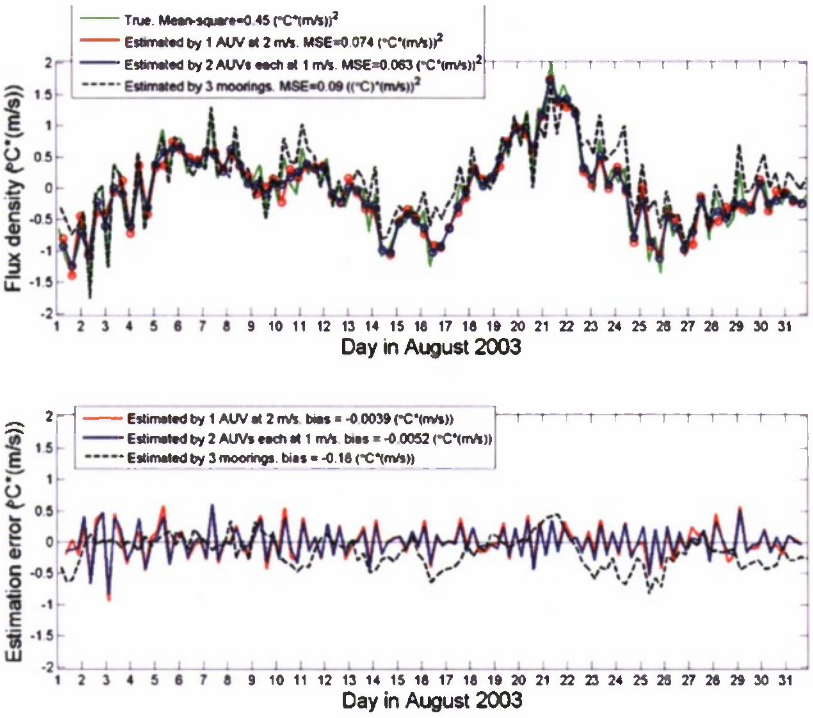


Figure 18. True heat flux density compared with estimates by one or two AUVs with cumulative speed 2 m/s, and by three moorings.

The relative estimation errors are shown in Figure 19. Most of the relative errors agree reasonably well with the analytical prediction in Figure 17. For two moorings, severe spatial aliasing causes a big estimation error (relative error > 1 in both results), but the error using ROMS data is much higher than the predicted error. Two factors contribute to this relatively large discrepancy. (1) At higher aliasing, the actual flux estimate is more sensitive to modeling mismatch. (2) When using a small number of moorings, the flux estimate may carry a relatively large bias which is not included in the analytical prediction.

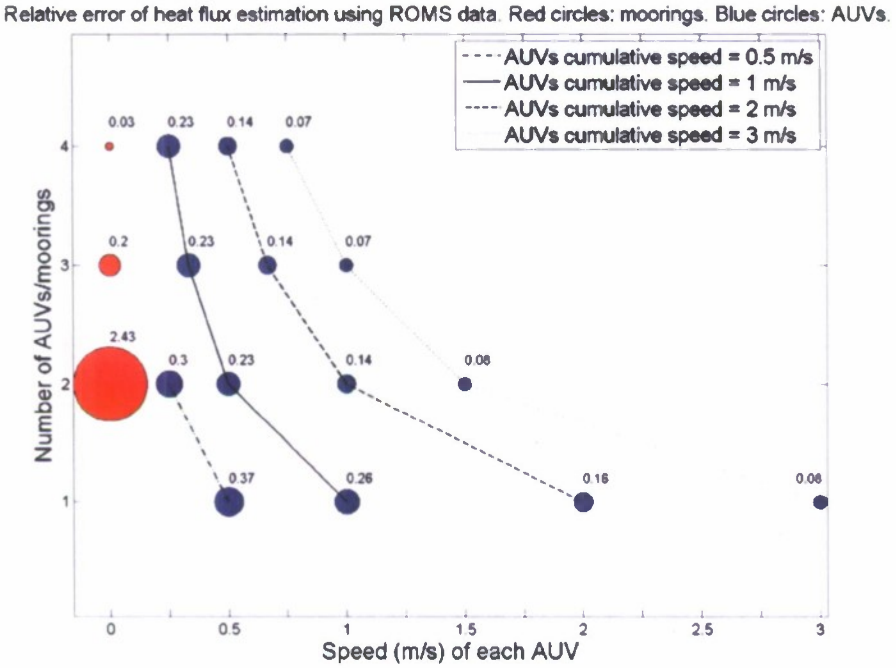


Figure 19. Relative mean-square error of flux estimation at different combinations of number of moorings/AUVs and AUV speed, using ROMS data.

In addition to theoretical studies, we also started processing AUV-borne acoustic Doppler current profiler (ADCP) data from the MB2006 Experiment in the following two steps: i. Use the calibration tracks to make corrections to the raw ADCP data. ii. Remove the vehicle's own velocity to extract the earth-referenced current velocity. The result for the AUV mission on Day 234 is shown in Figure 20. Current velocities measured by Dorado AUV compare well with those measured by two bottom-mounted ADCPs (installed by the Naval Postgraduate School) near the AUV path, as shown in Figure 21.

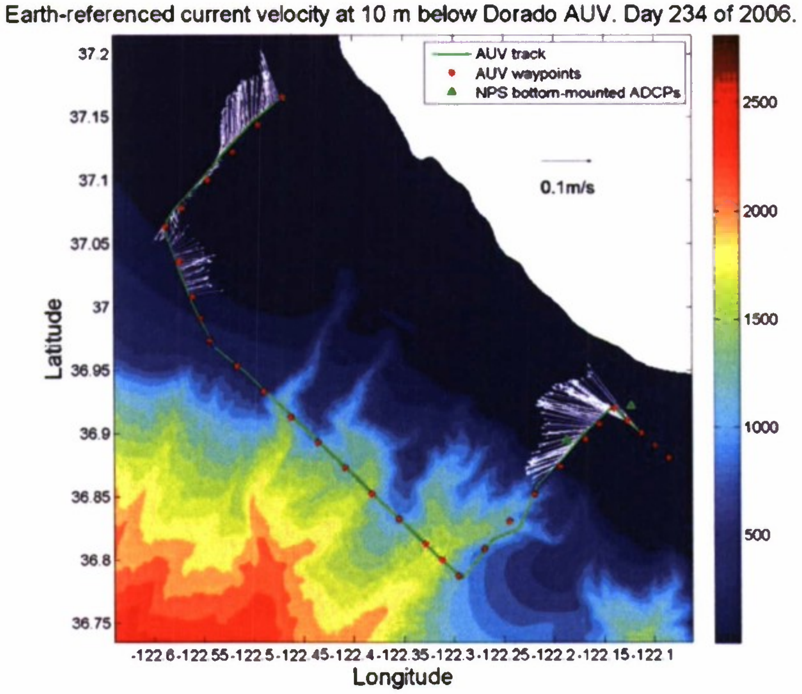


Figure 20. Earth-referenced current velocity measured by MBARI Dorado AUV during the MB2006 Experiment.

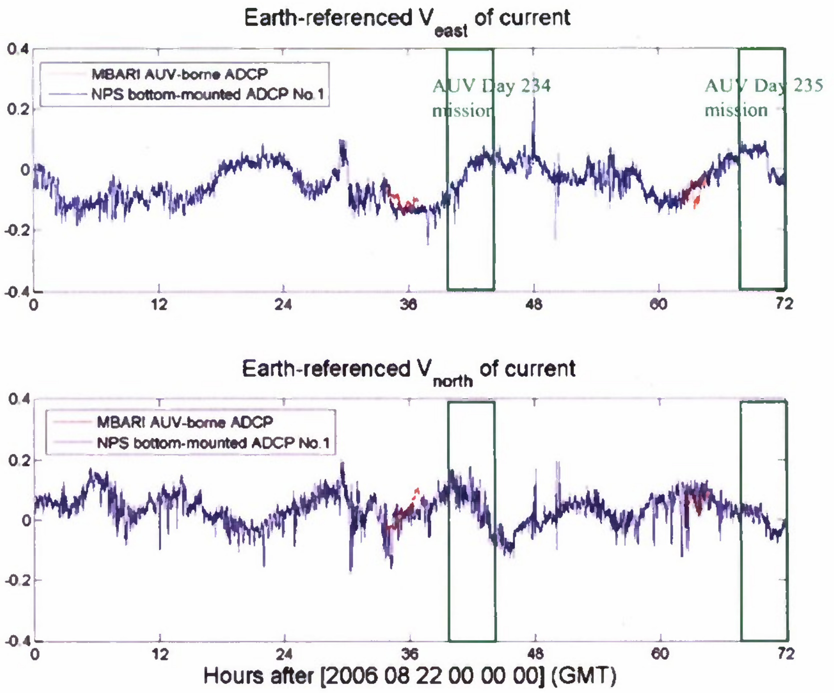


Figure 21. Comparison of Earth-referenced current velocities measured by Dorado AUV and bottom-mounted ADCPs.

Ocean observation calls for long-duration AUV surveys. We have built a prototype long-range AUV named Tethys, as shown in Figure 22. Various tests are in advanced stages. In-water tests are expected in summer/fall 2009.

Figure 22. Long-Range AUV Tethys.

IMPACT/APPLICATIONS

The AOSN-II project served as a technology demonstrator to prove concepts and methods for ocean observing systems. The system has the potential to provide 3-5 day forecasts of important oceanographic physical, chemical, and biological events using continuously deployed autonomous assets coupled with models. Use of adaptive coupled observation/modeling oceanographic prediction systems may someday be as commonplace as the use of atmospheric models and will perhaps have even greater impact on science due to their ability to reveal events difficult to observe in any other way. The AOSN-II project and experiments represented the first attempt to fully integrate major components of an adaptive coupled observation/modeling prediction system into an engineered system. The use of multiple vehicles allowed synoptic surveys that would otherwise be prohibitively expensive. The development of survey error analysis and sampling strategy design methods enables us to not only quantify survey performance, but also to maximize the joint effectiveness of mobile and fixed platforms.

Several large ONR programs are building on progress achieved in the AOSN-II program. The data systems and collaborative portals have had particular impact, as they offer the prospect of making long-distance collaboration much more effective. They are under evaluation for adoption by other ONR programs, for example the Impacts of Typhoons (ITOP) effort.

RELATED PROJECTS

The AOSN-II program was the lead element of an ONR effort collaboratively linked with the following ONR funded efforts:

1. "Adaptive Sampling and Prediction (ASAP)"
2. "Layered Organization of the Coastal Ocean (LOCO)"
3. "Persistent Littoral Undersea Surveillance Network (PLUSnet)"
4. "Implementing FORMS (Feature oriented regional modeling system) for the Monterey Bay forecasting system using HOPS and ROMS", Avijit Gangopadhyay, N0001410206
5. "Development of a Monterey Bay Forecasting System Using The Regional Ocean Modeling System (ROMS)", Yi Chao, N000140310208
6. "Adaptive sampling during AOSNII", PI: S. J. Majumdar, N000140310559
7. "Deep Autonomous Gliders for the "Autonomous Ocean Sampling Network II' Experiment", Russ E. Davis, Jeffrey T. Sherman, N000140311049
8. "Coastal Bioluminescence: Measurement and Prediction", J.F. Case, N000149710424, Grant Supplement, Mod. 13
9. "Aerial Surveys of the Atmosphere and Ocean off Central California", S. R. Ramp, J. D. Paudan, W. Nuss, and C. A. Collins, N0001403WR20002, N0001403WR20006
10. "Hyperspectral Radiometer for Airborne Deployment" S. Ramp, N0001403WR20209
11. "High-Resolution Measurement of Coastal Bioluminescence: II. Improving short-term predictability across seasons", Steven Haddock, N000140010842
12. "QUANTIFICATION OF LITTORAL BIOLUMINESCENCE STRUCTURE AND INDUCED WATER LEAVING RADIANCE", Mark Moline, N000140310341
13. "Use of a Circulation Model to Enhance Predictability of Bioluminescence in the Coastal Ocean", Igor Shulman, Naval Research Laboratory, Grant Number: N0001403WX20882 and –20819, Leslie Rosenfeld and Jeffrey Paduan, NPS, Grant Number: N0001403WR20009, Dennis McGillicuddy, N000140210853
14. "Participation in AOSN II", A. Healey, N0001403WR20063
15. "Autonomous Ocean Sampling Network II (AOSN II): System Engineering and Project Coordination", J. G. Bellingham and P. Chandler, N000140210856
16. "Underwater Glider Networks and Adaptive Ocean Sampling", Naomi Leonard, Clarence Rowley, and Jerrold Marsden, N000140210826
17. "Underwater Glider Dynamics and Control", Leonard (PI), N000140210861
18. "Autonomous Ocean Sampling Network II: Assessing the Large Scale Hydrography of the Central California Coast", Margaret A. McManus and Francisco Chavez, N000140310267
19. "An Autonomous Glider Network for the Monterey Bay Predictive Skill Experiment / AOSN-II", David M. Fratantoni, N000140210846
20. "Instrumentation in support of autonomous glider operations", David M. Fratantoni, N000140310736
21. "Glider communication and sensor enhancements in support of AOSN", David M. Fratantoni, N000140210846

22. “Development of a Regional Coastal and Open Ocean Forecast System:
23. Harvard Ocean Prediction System (HOPS)” (Included under this are "Quantitative Interdisciplinary Adaptive Sampling OSSEs for Monterey Bay and the California Current System - AOSN-II" and "Adaptive Sampling OSSEs for Monterey Bay and the California Current System - AOSN-II"). A.R. Robinson, N000149710239
24. “Monterey Bay Sampling”, Craig Bishop, N0001403WX20009
25. “Developing of a Monterey Bay Forecasting System Using the Regional Ocean Modeling System (ROMS)”, James C. McWilliams, N000140210236, Fei Chai, N000140310208

As the repository of data associated with several ONR field programs, we also supported a variety of requests for data and modeling results from other ONR efforts.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
26-06-2009

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
01-08-2002 to 31-03-2009

4. TITLE AND SUBTITLE
Autonomous Ocean Sampling Networks II - Integration and Demonstration of Observing and Modeling

5a. CONTRACT NUMBER
N/A

5b. GRANT NUMBER
N00014-02-1-0856

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
James G. Bellingham, Yanwu Zhang, and Michael A. Godin.

5d. PROJECT NUMBER
N/A

5e. TASK NUMBER
N/A

5f. WORK UNIT NUMBER
N/A

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Monterey Bay Aquarium Research Institute
7700 Sandholdt Road
Moss Landing CA 95039

8. PERFORMING ORGANIZATION REPORT NUMBER
704270-Final

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
1107 NE 45th Street, Suite 350
Seattle WA 98105-4631

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
N00014-02-1-0856-Final

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unrestricted

13. SUPPLEMENTARY NOTES
None

14. ABSTRACT

The AOSN-II project bought together sophisticated new robotic vehicles with advanced ocean models to improve our ability to observe and predict the ocean. The first field program (AOSN-II) demonstrated the coupled observation/modeling system in Monterey Bay from mid July to early September 2003. This field effort demonstrated the power of autonomous platforms to provide a pervasive and persistent pretense in the coast ocean, sustaining an average of 11 autonomous platforms at sea for a month. Data was communicated to shore and assimilated into two real-time ocean prediction systems. The second field program, MB2006, built on the 2003 field program, bringing a larger and more diverse group of investigators to Monterey Bay. Our data system development for the AOSN-II and MB2006 field programs, created software components that made data easy to access and multidisciplinary data sets easy to search. We also created collaborative portal approaches which allowed investigators to function as an integrated team for field operations despite being located on opposite sides of the continent. To optimize observation system design, we developed methodologies for selecting ocean observing locations and sampling strategies for objectives such as

15. SUBJECT TERMS
Autonomous, observation, model, adaptive, control, sustainable, forecast, prediction, data management, synoptic, physical, chemical, biological, upwelling, undercurrent, AUV, gliders, Monterey Bay, dynamics.

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Susan Lantis
Unclassified	Unclassified	Unclassified	None	25	19b. TELEPHONE NUMBER *(Include area code)* 831-775-1788