Optimal Asset Distribution for Environmental Assessment and Forecasting Based on Observations, Adaptive Sampling, and Numerical Prediction


Contents

1 Executive Summary .......................... 1

2 Statement of Work .......................... 1

3 Technical Approach .......................... 3
   3.1 Overview .................................. 3
   3.2 Ocean Science Focus ......................... 4
      3.2.1 Scientific Background ...................... 4
      3.2.2 Scientific Objective ....................... 6
   3.3 Metric Definition ............................ 7
      3.3.1 Coverage Metric for Minimizing Synoptic Error ...................... 8
      3.3.2 Dynamics Metric for Maximizing Sampling of Important Phenomena ...................... 9
      3.3.3 Uncertainty metric ......................... 11
   3.4 Metric Optimization and Derivation of Sampling Paths ...................... 11
      3.4.1 Synoptic Error Minimization Using Coordinated Control ...................... 11
      3.4.2 Adaptive Sampling for Feature Tracking ...................... 12
      3.4.3 Predictions, Adaptive Sampling and Data assimilation with HOPS/ESSE ...................... 13
      3.4.4 Lagrangian Coherent Structures ...................... 14
      3.4.5 Optimal Procedures for Assessment of the Ocean Acoustic Environment ...................... 16
   3.5 Experimental Plan ........................... 17
1 Executive Summary

The recent proliferation of unmanned air and undersea vehicles has spawned a research issue of pressing importance, namely: How does one deploy, direct and utilize these vehicles most efficiently to sample the ocean, assimilate the data into numerical models in real or near-real time, and predict future conditions with minimal error? A corollary to this central issue would be: What constitutes the minimal necessary and sufficient suite of vehicles required to constrain the models and provide accurate ocean forecasts? Implementation of an appropriate sampling plan requires an assessment of the initial oceanographic situation, understanding the capabilities and limitations of individual vehicles, vehicle coordination and control, and numerical models equipped to assimilate and utilize data which were irregularly sampled in space and time.

The Adaptive Sampling and Prediction (ASAP) program proposed here will directly address the questions above with a focused research effort in and around the Monterey Bay, California. A combination of gliders, propeller-driven AUVs, research aircraft, and ships will be used to adaptively sample three-dimensional upwelling and relaxation processes off Point Año Nuevo at the north entrance to the bay. Quantitative metrics have been defined to guide the adaptive sampling scheme, including a coverage metric for minimizing synoptic error, a dynamic variability metric for maximizing sampling of important physical phenomena, and an uncertainty metric. A modular approach allows metric optimization via cueing on several different measures of ocean variability: a) synoptic observational error minimization using coordinated control; b) feature tracking; c) maximizing the skill of the Error Subspace Statistical Estimation (ESSE) forecast from the Harvard Ocean Model; d) optimal assessment of the ocean acoustic propagation environment; and e) efficient glider navigation using Lagrangian Coherent Structures (LCS).

The unifying scientific goal of the ASAP experiment will be to construct a volume and heat budget for the three-dimensional upwelling center off Point Año Nuevo, CA during upwelling, relaxation, and transition events. The centerpiece of the initial three-year effort will be a month-long field program in the Monterey Bay during June 2006, a month when several events and transitions can be captured. A second major experiment is planned in the Monterey Bay during June 2008. The program will be executed by a multi-disciplinary team consisting of physical oceanographers, marine acousticians, control systems engineers, and numerical modelers. The operational principals thus derived are portable and relevant to a wide variety of space and time scales. The expected project outcome is superior sampling strategies for AUVs of all types, improved data assimilation, and improved model forecast skill, resulting in the most efficient use of these vehicles in operational scenarios. DoD sectors to reap these benefits include mine intervention warfare, expeditionary warfare, undersea warfare, and marine survey.

2 Statement of Work

We will carry out a comprehensive Adaptive Sampling and Prediction (ASAP) research investigation to improve the utility of ocean sampling via autonomous vehicles by developing the most efficient possible cooperative strategies between vehicles, which will provide the data most needed for improved numerical forecasts. The research program involves theoretical and computational development and analysis together with several major experimental efforts. As seen below the theory and experimental efforts will be well integrated. The specific tasks to be carried out are as follows:

1. Leonard (Princeton University): a) Develop methodology for systematic derivation of coordinated control strategies for autonomous, adaptive vehicle fleet to maintain overall sampling coverage and minimize sampling error, to identify and track features and to contribute to the minimization of model uncertainty. Integrate this effort with others. b) Implement comprehensive adaptive sampling strategies in pilot experiment and two major field experiments. c) Analyze the performance of
the adaptive sampling vehicle network for contributions to improved understanding of the ocean and improved predictive skill.

2. **Ramp (Naval Postgraduate School):** a) Lead planning of the field experiments and ocean science focus. b) Develop means and purchase equipment to facilitate real-time transmission of data from the bottom-mounted current profilers. c) Plan and carry out all aircraft operations and surveys. d) Deploy and operate mooring to complement M1 and M2 buoys in Monterey Bay. e) Analyze experimental data from all field experiments.

3. **Davis (Scripps Institute of Oceanography):** a) Upgrade three and build one Spray glider and operate them under adaptive control during the two Monterey field trials. b) Develop a software interface to simplify around the clock control of glider fleets and demonstrate it in the two field tests. c) Work with others to develop a method to plan glider operations that maximize skill in mapping synoptic situations using a metric of the mean square mapping error from objective analysis.

4. **Fratantoni (Woods Hole Oceanographic Institution):** a) Improve glider fleet capability and endurance. b) Prepare for and carry out field operation of glider fleet. c) Participate in collaborative data analysis and synthesis.

5. **Robinson and Lermusiaux (Harvard University):** a) Perform real-time nested HOPS/ESSE (sub)-mesoscale field and uncertainty predictions and physical-acoustical data assimilation with quantitative adaptive sampling integrating 3 metrics and linking to LCS and real-time glider models. b) Develop theory and software for momentum, heat and mass budgets on multiple-scales with uncertainties, allowing for time-dependent volumes to account for evolution of plume and boundary layer effects. c) Perform science-focused sensitivity simulations under different atmospheric conditions to quantify effects of atmospheric resolution, surface and bottom BL formulations, idealized geometries on plume formation and relaxation. d) Evaluate predictive capability limits and predictability limits for upwelling and relaxation processes, improving model parameterizations based on data-model misfit and theory and software for measuring skill of upwelling plume forecast (size of plume, scales of jet and eddies at plume edges, thickness of boundary layers and surface and bottom fluxes). e) Develop new ESSE nonlinear adaptive sampling scheme for identifying future regions in most need of sampling based on a tree-structured multi-ensemble prediction, with error models for glider/AUV/ship/aircraft data (with WHOI/Scripps/MIT/NPS) and predictions of data. f) Investigate adaptive bottom and surface boundary layers with distributed GRID software, non-hydrostatic computations, theoretical upwelling and relaxation dynamics research, physical-biogeochemical balances and inter-annual variability.

6. **Marsden (California Institute of Technology):** a) Set up the LCS (Lagrangian Coherent Structure) infrastructure and perform the computations for the proposed experiments. b) Develop 3D LCS computations using Mangen (Manifold Generation) and fundamental research on the incorporation of set-oriented software. c) Study optimization using NTG (Nonlinear Trajectory Generation) for single vehicles operating in ocean currents. d) Perform fundamental research on the mechanics of networks of vehicles with applications to groups of underwater vehicles and gliders.

7. **Schmidt (Massachusetts Institute of Technology):** a) Develop coupled physical oceanographic/ocean acoustic dynamic models for acoustic data assimilation (ADA). Integration with Harvard Ocean Prediction System (HOPS), and testing through OSSEs. b) Develop autonomous framework for adaptive acoustic sampling with AUVs, or Adaptive Rapid Environmental Assessment (AREA), including dynamic acoustic array configuration optimization. Testing with OSSEs. c) Demonstration of ADA and AAS in field experiments in Monterey Bay, in addition to providing adaptively sampled oceanographic fields to the MURI assimilation framework.

8. **Bachmayer (National Research Council, Canada - Institute for Ocean Tech.):** a) Develop methodology to use the glider as a flow sensor. b) Develop a system to monitor glider health/performance c) Contribute to an environmental detection and tracking system using multiple gliders.
3 Technical Approach

3.1 Overview

We propose a collaborative research investigation of optimal asset coordination and distribution for efficient environmental assessment and forecasting using observations, adaptive sampling and numerical prediction. A central issue is the dynamic, uncertain nature of the environment, on multiple temporal and spatial scales.

Our proposed Adaptive Sampling and Prediction (ASAP) project aims to improve the utility of ocean sampling via autonomous vehicles by developing the most efficient possible cooperative strategies between vehicles, which will provide the data most needed for improved numerical forecasts. The work will optimize the use of feedback, interconnection and adaptation of a mobile, re-configurable sensor array for advances in coordinated, autonomous, coupled observation, adaptive sampling and forecasting in the ocean. Feedback provides the means to manage uncertainty and make the system robust. Interconnection provides the means to coordinate the activities of the individual vehicles for the greater good. Adaptation refers to the ability of the individuals and the group to adapt to changing circumstances in the environment. The research will build upon previous efforts already started in Monterey Bay and elsewhere to take these ideas to the next level in a systematic and comprehensive way.

Our technical approach centers around three critical steps: (1) Define a scalar objective function to drive (and evaluate) adaptive sampling; (2) Derive a systematic approach to solve the optimization of the objective function, making the best use of available resources; (3) Define and carry-out a full-scale experiment.

We propose a modular approach to organize response to the range of inputs that can be used to drive adaptive sampling. These range from the observations themselves to inputs obtained from model predictions. The ASAP methodology will be made flexible so that adaptive sampling can be applied at multiple spatial and temporal scales and can respond to any one of these inputs independently or by integrating several inputs. This is motivated by the following: 1. Efficiency. A modular framework will allow pairs of PI’s to work together on pieces of the story rather than requiring all PI’s to simultaneously consider all problems; 2. Resilience. The modular approach can allow adaptive sampling to be run in the absence of model predictive capability by using measured fields. This will be important for rapid response when forecasts are unavailable or when new quality-controlled data are not yet available but model forecasts are; 3. Flexibility. Modular integration to develop an adaptive sampling strategy has the potential for great payoff. It will facilitate switching between sub-strategies as appropriate. This will be particularly important considering the many spatial and temporal scales of involved and the different ways tools are likely best used depending on the scales involved.

Our ultimate goal is adaptive sampling based on an automated, quantitative and seamless integration of all data and modeling inputs, in accordance with their respective uncertainties and on multiple scales. Conventional sampling is usually based on hypotheses about the processes and estimates of the scales to be observed, all of which are uncertain. From one experiment to the next, sampling patterns, platforms and sensors are in fact usually improved. Since our adaptive sampling occurs on multiple time and space scales, it includes such classic sampling evolutions. To best use past knowledge and maximize scientific progress, both experimentalists and theorists need to participate in adaptive sampling research. Experimental knowledge will be utilized to help determine adequate objective functions and constraints of platforms and sensors will be taken into account to derive systematic approaches for the optimization of these functions. Such cooperative research will improve scientific understanding and extend the predictive capabilities.
of current ocean observing and prediction systems.

To develop, evaluate, test and demonstrate approaches, we will perform idealized and realistic adaptive sampling simulation experiments based on existing data sets, and we will conduct one pilot and two full-scale at-sea experiments. Each experiment will involve dynamical process studies, predictive skill evaluations and adaptive sampling research with a significant dedicated fleet of adaptive platforms.

3.2 Ocean Science Focus

We propose to direct our Adaptive Sampling and Prediction (ASAP) study to the three-dimensional dynamics of the upwelling/relaxation processes and other coastal phenomena around the northern end of Monterey Bay. This science focus is well motivated and well suited to our research program: (1) The dynamics we propose to study are fundamental and representative of other coastal regions. Our results will shed new light on a number of open questions on these types of ocean events. (2) The science focus offers a rich set of challenges for our predictive modeling, adaptive sampling, data assimilation and dynamical system analysis capabilities, tools and methodologies. For example, in order to explore the influence of the wind stress, bottom topography and shelfbreak processes on the 3D mesoscale upwelling circulation, it will be necessary to bring to bear the new methods and capabilities that we propose to develop. (3) We will be able to build on our experience, data set and established collaborations from the 2003 Monterey Bay experiment as part of the Autonomous Ocean Sampling Network II (AOSN-II) project.

3.2.1 Scientific Background

The mesoscale circulation near Monterey Bay can be succinctly described as the interplay between the upwelling filaments rooted at headlands to the north and south of the bay with the California Current System (CCS) offshore. Two CCS features of particular relevance are the poleward-flowing California Undercurrent (CUC), and the meanders of the California Current System, especially the anticyclonic California Current meander (CCM) frequently observed just offshore of the bay itself. The circulation differs dramatically between the upwelling periods, driven by equatorward alongshore winds, and relaxation events associated with poleward or no winds. As this proposal focuses on the more northerly upwelling center located off Cape Año Nuevo, CA, the remainder of this introduction describes what is presently known about the circulation there. Unless otherwise referenced, this material is based on recent results from the MUSE 2000 and AOSN-II 2003 field programs in and around Monterey Bay.

The upwelling cycle begins with small pockets of cold, salty water appearing near Año Nuevo and Pigeon Point, which subsequently grow together and enlarge as the wind stress continues. After a period of several days, the cold water in the upwelling center may grow into a filament which sometime extends offshore and at other times spreads southward across the mouth of the bay. The circulation within the bay at this time generally takes on a cyclonic sense and is fairly well organized [3, 4]. The CCM remains well offshore of the bay and the CUC remains submerged, undetectable in the surface velocity and temperature patterns.

When winds relax, stop or reverse, a sudden transition between flow regimes occurs. The large-scale near surface flow along the coast can rapidly turn poleward [5]. This transition to poleward flow usually progresses from south to north, leading to regions of convergent alongshore flow along the way. The cold filaments may be “squirited” offshore by converging flows or disappear entirely, masked over by surface heating. The CCM translates onshore at these times,
bringing warmer, fresher offshore water with it [6]. The CUC strengthens and sometimes surfaces [1] [10] [9], and the flow within the bay itself becomes less organized.

The recent experiments described above achieved a first-order description of the flow and had some success at predicting its evolutions, but many questions regarding the underlying upwelling and relaxation dynamics remain. A brief list of such questions includes: (1) Why does the upwelling center form off Año Nuevo and Pigeon Point? (2) Why does the cold filament rooted there sometimes flow offshore and sometimes south? (3) From what depths does the upwelled water come? What are the associated vertical velocities? (4) What is the volume, heat, and nutrient content of the upwelled water? (5) What happens to the upwelling filaments during relaxations/downwelling? Is their demise dominated by across-shore advection, geostrophic turbulence or surface heating and vertical mixing?

There are several working hypotheses regarding the formation and spread of the cold, salty water at Año Nuevo, with little observational evidence to separate them. They include the following: (1) The upwelling center forms under an atmospheric expansion fan located to the south of Pigeon Point, which drives enhanced coastal upwelling there; (2) The changes in the coastline and bathymetry cause the alongshore flow to separate from the coast, contributing to increased upwelling there; (3) The volume of cold water is further enhanced by the wind stress curl; (4) The filament is forced “downstream” (southward) by a hot, dry, atmospheric jet coming out of the Santa Cruz mountains; (5) The southerly filament is actually the result of mixing under the submesoscale jet, rather than advection of water from the upwelling center; (6) The filament is forced offshore by pressure gradients arising from the spatial distribution of the wind stress curl; (7) The geostrophic adjustments and corresponding jets lead to advectons and mixing which need to be quantified.

Several phenomena can impact the wind-driven upwelling at Año Nuevo and thus affect predicted and measured upwelling budgets, in part by nonlinear interactions. Such 3D interactions are at the research frontiers in ocean physics and acoustics predictions, adaptive sampling and dynamical system analysis. They limit predictive capabilities and require research (§3.4.3). Presently, they mainly relate to the dynamical sources of the upwelled water, boundary layer interactions and effects of smaller scales. Such properties will be in the data. They need to be considered, at least in data filtering and uncertainty modeling.

Even though wind-driven coastal upwelling is dominant, internally-driven upwelling (e.g. local eddies), open-ocean driven upwelling (e.g. large-scale waves) and deep upwelling near the Monterey Bay Canyon occur [11] [6], and can impact budgets at Año Nuevo. Interactions of the internal dynamics with boundary layers also need to be accounted for in the sampling and simulations. As the three-dimensional upwelling develops, the interactions of the bottom and surface boundary layers, either directly over shallow bathymetries or through interior motions become important. For example, non-uniform wind stress (non-zero wind stress curl) and non-uniform interior flows (non-zero relative vorticity) lead to divergence/convergence in bottom and surface boundary layers which drive Ekman pumpings (downwelling/upwelling) in the interior. Turbulence and stratification modify these classic properties. For Año Nuevo, the variability of the surface fluxes (e.g. daily cycles) and bottom stresses, eddy and convective motions, and tidal forcings are of special importance. Finally, inter-annual variabilities modify the background over which upwellings form.

The adaptive sampling, filtering and modeling of the effects of submesoscale processes on the upwelling plume will be challenging. Tidal and sub-mesoscale processes occur on the shelf and in the vicinity of the Canyon. The internal wave field near the Canyon is about an order of magnitude higher than in the open-ocean, especially near the bottom [12] [13] [14] [15]. Nonlinear
effects associated with internal waves and up-canyon flows are also strongest there. Finally, strong topographic steering has been observed, leading to tidal bores and solitons. Such processes impact our physical and acoustical data. Their modeling and data assimilation for accurate predictions should be initiated.

Based on the above descriptions and on our data assimilation and physical and acoustical modeling capabilities, some interesting specific questions can be identified: (1) What are dominant interactions between the 3D mesoscale upwelling and the smaller scale processes (e.g. internal tides/waves, Canyon/shelfbreak deep upwelling)? (2) How intense is the mixing in bottom boundary layers around the Pt Año Nuevo region?, and what are its impacts on the upwelling plume budgets? (3) During 3D upwellings, how large are interactions between bottom and surface boundary layers, especially near the coast?

3.2.2 Scientific Objective

The science objective of ASAP is to understand the three-dimensional dynamics of upwelling centers in eastern boundary current regions. A critical step that will allow us to test this understanding will be constructing volume, heat and salt budgets for the upwelling center off Cape Año Nuevo, CA at the northern end of the Monterey Bay. For each event, such budgets allow the computation of the vertical velocity and vertical turbulent heat fluxes, which in turn allow greater dynamical understanding of the upwelling/relaxation process. The heat budget should allow us to distinguish between the mixing vs. advection hypotheses, and to understand what happens to the upwelled water during the wind relaxation events.

The basic approach to be used will be similar to earlier studies of two-dimensional upwelling along a relatively straight coast [2, 7] but will be executed using improved observational tools and sampling methodologies. The basic idea is to box in a portion of the coastal ocean and quantify the conservation of mass and heat within the enclosed volume. The conservation equations are

\[ \nabla \cdot u + \frac{\partial w}{\partial z} = 0 \]  
\[ \rho_0 c_p \left( \frac{\partial T}{\partial t} + \nabla \cdot (uT) + \frac{\partial}{\partial z}(wT) \right) = \frac{\partial Q}{\partial z} \]

for mass and heat, respectively, where \( T \) is temperature, \( t \) is time, \( u \) is the horizontal velocity vector, \( w \) is the vertical velocity, and \( \rho_0 c_p \) is the specific heat capacity. On the right hand side, \( Q \) represents the total vertical (radiative plus turbulent) heat fluxes. Simple point-by-point, sub-regional and plume-averaged term balances will be investigated in the primitive-equations and scale decompositions will be used to explore nonlinear transformation in the energy and vorticity equations. Assimilating the adaptively sampled data into the dynamical models will improve the accuracy of such estimates and also provide posterior error bars.

Previous studies used a moored array of current and temperature sensors to bound the alongshore and offshore sides of the control volume: This experiment will use adaptively controlled autonomous vehicles for the same purpose. Moored arrays formed a “leaky” box: there could never be enough moorings to cover sides of the box, so some representative area was assumed for each mooring. Adaptively controlled gliders, however, can use their mobility, for example, to slowly wander back and forth along a section of the boundary to form a gapless measure of the transport through each side. Gliders behaving cooperatively can also provide an improved measure of the gradient quantities required to compute all the terms in (1) and (2). Additional vehicles, both gliders and propeller-driven, can operate within the box to estimate local change,
the first term in \( \text{(2)} \). The Odyssey propeller-driven vehicles will use tomographic techniques to obtain an integrated measure of the total heat content within the upwelling filament. A low-flying aircraft will provide superior estimates of the mean and turbulent fluxes of heat and momentum, the right-hand side of \( \text{(2)} \). Therefore, this combination of assets should allow us to make direct estimates of all the terms in \( \text{(1)} \) and \( \text{(2)} \), which will help to reveal the underlying processes operating in a coastal upwelling regime.

Studying and quantifying the interactive phenomena which impact the upwelling plumes provide interesting challenges for our predictive modeling, adaptive sampling, data assimilation and dynamical system analysis and control capabilities. For example, the fleet of gliders and propeller driven vehicles provide excellent opportunities to interactively sample specific portions of the bottom layers, e.g., at the edges of the upwelling plume. In cooperation with the low-flying aircraft, similar capabilities exist for the surface boundary layer. The acquisition of such data sets allows to push the predictive limits of current dynamical models based on model-data comparisons. In particular, models need to be improved at sub-mesoscales, hence the need to acquire good sub-mesoscale data sets. For example, one can obtain mixing parameters and vertical velocities along a sloping bottom directly from data. These data-based estimates can be compared to model values and model parametrizations subsequently adjusted for better predictions and understanding, e.g., improved modeling of tidal effects.

Representative specific questions include the following: (1) How should the submersible and aircraft sampling be adapted as the upwelling plume develops? At which time and space scales should such adaptation occur? (2) How efficient can a relatively small fleet of gliders and propeller-driven vehicles be at filtering or capturing meso-/submeso-scale interactions, sub-mesoscales and near-bottom processes?, What are adequate vehicle formations to do so? (3) What are the limits of the predictive capability of current models and can improved representation of smaller-scales processes push these limits? (4) How can dynamical system analysis (Lagrangian coherent structure and set-oriented methods, described below) and dynamical decomposition (Multi-Scale Energy and Vorticity Analysis) schemes capture, follow and quantify the evolution of 3D structures and processes such as the upwelling plume? (5) Which sampled fields most affect model performance? For example, are lots of overflights as good or better than a few glider or ship surveys?

The second field effort during 2008 will provide some opportunity to assess the interannual variability of an upwelling/downwelling system.

### 3.3 Metric Definition

The goal of adaptive sampling is to utilize available information including experimental data and knowledge, predictions and their uncertainties as well as tools that uncover dynamical system structure and exploit available resources to optimize the observational system in space (locations/paths) and time (frequencies) for the assessment and estimation of the ocean’s physics, biology and/or acoustics. We propose to consider three specific objectives for adaptive sampling:

**[Objective 1]** *Maintain overall coverage or minimize error in describing the regional situation.* The sampling array is not static and is influenced by the physical environment it is measuring. Metrics for characterizing the ability to describe a synoptic setting range from essentially geometric measures of coverage in time and space, through objective-mapping mean square error, to simple error measures developed as a part of the process of assimilating data into numerical models. The aim of this objective is to observe the whole domain of interest at minimum resolution, even if the other two objectives suggest sampling restricted areas only.
[Objective 2] Maximize sampling of important physical/biological/acoustic phenomena. Both observations and model forecasts frequently expose interesting or unusual features that require extra sampling to be well observed. Both observer experience and quantitative metrics such as measures of information-entropy and energy-vorticity will be used to develop targets for such opportunistic sampling. Regardless of how the target is developed, quantitative optimization coupled with forecasts of the velocity field will be used to minimize time-to-the-target and the energy (battery life) required.

[Objective 3] Minimize uncertainties, especially in predictions. If today we know the sensitivity of model forecasts for the day-after-tomorrow to data locations tomorrow, assets can be directed to improve the two-day forecast. We will seek to develop reliable measures of the nonlinear sensitivity of forecasts at various ranges and methods of efficiently adjusting sampling array geometry to improve predictions. The uncertainty metric aims to determine sampling plans which minimize uncertainties now (nowcasting), in the future (predictions) and also in the past (for the initial conditions).

We aim to develop the option to achieve one, two or all three of these objectives at a time, depending on the application. This could mean, for instance, optimization of a weighted sum of two or three of the metrics or alternatively strategies that switch between optimization of a single strategy.

3.3.1 Coverage Metric for Minimizing Synoptic Error

We propose a scalar, time-dependent coverage field $C : \mathbb{R}^3 \times \mathbb{R}_+ \to \mathbb{R}$ that quantifies the need for sampling as a function of space and time. For ease of presentation, we define and discuss here the coverage field specialized to a two-dimensional spatial field; however, the concepts are readily generalized to three-dimensional space. The coverage metric can be viewed as a minimally parameterized approximation of the mean square error field of objective mapping (described further below). The relatively simple expression for the coverage field will be exploited to systematize the generation of adaptive sampling strategies and to formalize what we can guarantee about performance.

Consider $n$ planar measurements which are taken at position and time $(x_k, y_k, t_k)$, $k = 1, \ldots, n$. Assume the measurement likelihood function, i.e., the conditional probability, $Pr(\text{measurement} | \text{state})$, is a Gaussian function of range with variance, $\sigma^2$, and peak probability of detection, $p$. Also, assume that the validity of the measurement decays exponentially in time according to the local time constant, $\tau(x, y)$. The natural choice is to take $\sigma(x, y)$ to be the spatial autocorrelation of the measurement field and $\tau(x, y)$ the temporal autocorrelation of the measurement field (e.g., as computed by the HOPS data-assimilating model).

The coverage field $C$ is then updated for each measurement, $k = 1, \ldots, n$,

$$C_k(x, y) = C_{k-1}(x, y) \left(1 - pe^{-\rho_k^2/2\sigma^2}\right) \cdot \left(1 - (1 - C_{k-1}(x, y))e^{-\Delta t_k/\tau(x, y)}\right)$$

where $\rho_k^2 = (x - x_k)^2 + (y - y_k)^2$, $\Delta t_k = t_k - t_{k-1}$ and $C_0 = 1$.

A low value of $C$ (on a scale from 0 to 1) at a given position $(x, y)$ and time $t$ reflects recent sampling at (or near) the location $(x, y)$ and thus little need for immediate re-sampling there. On the other hand, a value of $C$ close to 1 at a given location and time indicates the immediate need for sampling at or near this location. At a given instant of time $t$, one can make a color plot of the field $C$ over the 2D region of interest as shown if Figure [ ]. Additionally, one can define a coverage performance metric using $C$. For instance, consider a coverage threshold value
κ ∈ (0, 1) and compute the area $A_c(t)$ composed of points $(x, y)$ such that $C(x, y, t) \leq \kappa$. Let $A$ be the total area of the region of interest. Then, define the coverage ratio (or percent coverage) $R_c(t)$ as $R_c(t) = A_c(t)/A$. The mean and standard deviation of $R_c(t)$ over the course of the experiment provides a measure of coverage performance.

When appropriate, parameter $\tau = \tau(x, y)$ (or others) can be manipulated to emphasize more frequent sampling in regions of interest (e.g., for important dynamics or large predictive model uncertainty) by making $\tau$ small in those regions so that the validity of the sample decays quickly in time. Locations of little interest would be assigned relatively large values of $\tau$. Experimental insights could be used to select $\tau$ or, more systematically, fields computed as part of objective functions 2 and 3, e.g., entropy or model predictive uncertainty, could be mapped onto the parameter field $\tau$. The coverage metric is a useful guide to adaptive sampling because data-based analyses of synoptic situations are most accurate where there have recently been nearby observations. The coverage metric measures how much of the domain falls in this category. A somewhat more elaborate measure is provided by mean square error of objective mapping. If $D(x_n, x_m)$ is the covariance of the observations made at position/times identified by $x_n$, and $P(x_n, x)$ is the covariance between the observation at $x_n$ and the mapped parameter $p$ at $x$, then the minimum mean square error estimate has the error covariance $<pp^T>-P^TD^{-1}P$. The trace of this covariance, $<e^T e>=E(x_n)$, is the mean square error of the estimate summed over all the points where $p$ is to be estimated.

$E$ is a complicated function of the observation positions/times $x_n$, which are the variables available for optimizing the observational array. We will explore adapting the observational array to minimize $E$ much as the array could be optimized to maximize coverage. While optimization will likely be more difficult, an advantage of the objective mapping metric is that it can be based on measured covariances. These were estimated for various physical variables during AOSN II in Monterey Bay in 2003 and are estimated for each forecast by the HOPS data-assimilating model. Both data show the covariances to be approximately exponential with time and distance decorrelation scales of about 25 km and 5 days.

### 3.3.2 Dynamics Metric for Maximizing Sampling of Important Phenomena

Adapting the sampling plan as a function of interesting or unusual features or dynamical hot-spots is common in oceanography. For example, one can try to follow a ring, a squirt or even a...
Figure 2: Temperature correlation vs. time (left) and vs. distance (right) from glider measurements during AOSN-II.

group of marine mammals. In our physical-acoustical ASAP, we will consider both data-based and data-model-based metrics for such hot-spots sampling. A data-based metric uses current observations to evaluate the existence of features and the need for sampling adaptation to better measure these features, while a data-model-based metric uses data and models, including data-model misfits and data assimilation, to predict hot-spots. We will also consider merging the two at different time-scales (see preliminary plans in [22]).

The data-based adaptation in our experiments will mainly correspond to unforseen but measured features. This will range from metric evaluation based on experience to feature tracking metrics using in situ measurements taken by a sub-fleet of gliders or Odysseys. For instance, in the former case, a feature is identified and the asset distribution is judged as to whether it can successfully capture the features. In the latter case, for instance, the gliders will use autonomous intelligence (e.g., cooperative gradient climbing or internal wave filtering as described in §3.4.2). For gradient climbing, the metric measures both how far the fleet is from the feature (e.g., a front) and how well the fleet is spread out to best estimate the gradient (e.g., the inter-vehicle spacing and configuration of the fleet is adaptable).

The data-model-based adaptation in our experiments will depend on dynamical predictions. The hot-spot metric will depend on: i) a definition and data-model based prediction of the dynamic variability of interest, and, ii) a measure of how efficient a sampling plan is at observing this variability.

To identify and define a hot-spot, some quantity derived from the complete dynamics, here the upwelling/relaxation at Año Nuevo, is usually selected. It often corresponds to a dynamical subspace in space or time, for example, a boundary layer process, a sub-mesoscale eddy/squirt forming at the edge of the upwelling front, or some higher frequency dynamics. Mathematically, such dynamical features, phenomena or instabilities will be defined and followed using data-model based predictions of specific velocity or tracer properties, term-balances in the dynamical equations, baroclinic and/or barotropic energy, enstrophy or vorticity properties, Lagrangian coherent structure terms, and mathematical transforms such as the Fourier or Wavelet transforms (see §3.4.3).

Once the hot-spot as been mathematically defined, the corresponding dynamics subspace $d(x, y, z, t)$, e.g., the barotropic energy conversion term, can be predicted based on data-assimilative models. In the first year of the research, the ideal sampling plan will be to sample the largest amplitudes of this dynamics $d(x, y, z, t)$. In the later years, different candidate sampling plans in time and space will be discriminated based on measures of what has been and not been sampled in $d(x, y, z, t)$, i.e., the dynamics-misfit. Since oceanic processes are correlated in time and space, a dynamics-misfit covariance matrix $D$ will be utilized and predicted. The better of the plans
will then be the one that reduces the trace of this predicted covariance the most. Note that this dynamics-misfit trace is a four-dimensional \((x,y,z,t)\) field and is analogous to the coverage field \(c(x, y, z, t)\) of §3.3.1.

### 3.3.3 Uncertainty metric

The goal is to determine the sampling plan which minimizes uncertainties in the ocean state estimate, here the upwelling/relaxation states and the corresponding budgets, based on a combination of models with data. Similar to the two other objectives, the metric depends on the predicted uncertainties of interest and on a measure of how efficient a specific sampling scheme is at reducing these uncertainties.

Uncertainties evolve because of the deterministic dynamics (advection, diffusion, pressure, etc), grow because of the non-deterministic dynamics (sub-grid-scales, model errors) and shrink because of the assimilated data and dynamical correlations. In theory, minimizing uncertainties encompasses all goals. It accounts for the hot-spot uncertainties (how good is the estimate \(d(x, y, z, t)\) in §3.3.2) and for the assimilated data and their errors (how do data reduce errors and improve \(c(x, y, z, t)\) in §3.3.1). However, in applications, uncertainty effects are only approximately represented and the main research issue is their accurate prediction.

There are several uncertainties of interest. Assuming our experiment has started, uncertainties can be minimized now (nowcast or filtering), for the future (predictions) or for the past (smoothing). For each case, one can aim to minimize uncertainties at an instant, e.g. the initial time or the final time, or over some time period, e.g. for the next two-days or over the whole experiment. In space, the focus can be on uncertainties at a point, in a sub-domain or within the whole region.

For our predictions, the main metric will be to determine the future sampling which minimizes the error standard deviation of the forecast on a series of ranges in time and space. With linear systems and minimum error variance estimation, the goal is then to find the sampling plan which minimizes the trace of the forecast error covariance matrix. For nonlinear systems, the uncertainty dynamics (pdf equation) depends on the value and pdf of the data. In the nonlinear coastal ocean, Ensemble/Monte-Carlo methods can account for these properties \[31\]. A set of candidate sampling regions/paths and the data pdf along this path are chosen. A tree of ensembles with data assimilation is then predicted (each branch corresponds to a path). The best sampling plan among the candidates is the one that minimizes uncertainties the most.

### 3.4 Metric Optimization and Derivation of Sampling Paths

We will derive adaptive sampling strategies by optimizing the metrics defined in §3.3. A central thrust is to use coordination and cooperation of the adaptable fleet to advantage. We note that the adaptable fleet is heterogeneous and includes the gliders and the Odyssey vehicles.

#### 3.4.1 Synoptic Error Minimization Using Coordinated Control

We will use the coverage field to drive the adaptive sampling, i.e., to direct vehicles to sample at locations with high values of \(C\) in order to optimize the coverage metric. We will similarly apply our tools to the very closely related observational mapping mean square error field. The goal is to derive a systematic and provable strategy that exploits coordination of the fleet.

As a preliminary step and a means to develop some intuition, simple heuristic approaches can be implemented for comparison. For fair comparison, when investigating any of these strategies, the simulated glider trajectories should be normalized by permissible horizontal speed and total
number of measurements. Coordination schemes can be classified along the following taxonomy: static vs. adaptive, independent vs. coordinated, local vs. global information, etc.

One example of a static, independent heuristic is “random bounce”. In this controller, the vehicles maintain constant headings until they reach a survey boundary (e.g. minimum/maximum isobath or other demarcation). At the perimeter, the gliders pick a new heading from a random distribution. A random bounce strategy that uses a cosine distribution to select reflection angles will achieve exponential rate of coverage of a convex polygonal survey area with uniform time constant.

An independent, adaptive strategy with global information is a “greedy” search. In this approach, each vehicle could be modelled as a self-propelled particle subject to steering control that performs gradient ascent on the coverage objective function weighted by proximity and minimal turn angle. A coordinated variant of this method would be to enable plan-sharing: i.e. each vehicle broadcasts its intended trajectory (up to a planning horizon) and conflicts are resolved on a first-come-first-serve basis.

With intuition gained and some benchmark heuristics for comparison, we will investigate optimal control of kinematic models of the gliders to derive coverage maximizing sampling algorithms. We will build on the recent work of Sepulchre, Paley and Leonard [25] on coordinated control of autonomous vehicles with the expectation that the very best, provable sampling method will make explicit use of coordination of the fleet. In [25], we use a constant-speed particle model for the group of vehicles and we prove global properties for stable coordination of the fleet into parallel and circular motions. These ”motion primitives” make for suitable building blocks for optimal strategies.

We intend to derive characteristics of an optimal technique and show convergence for simple environments. For example, on what intervals of range and time constants in the coverage metric is a self-propelled particle model appropriate? Clearly, a very large range constant diminishes the requirement to be mobile and a virtual moored glider is sufficient. Similarly, one could estimate the minimum sampling rate as a function of space and time from the temporal characteristics of a region. This could provide some insight as to the requirement for number of gliders and horizontal speed.

3.4.2 Adaptive Sampling for Feature Tracking

We will use sub-fleets of vehicles as appropriate to perform feature tracking and other tasks as a means to optimize the adaptive sampling Objective 2, i.e., to maximize sampling of important physical/biological/acoustic phenomena. We will use observations, model forecasts and LCS analysis to expose unusual features that require extra sampling and then investigate using sub-fleets to track such features.

Individual vehicles (e.g., gliders) can be redirected using their own and their neighbors’ in situ measurements. Adaptive sampling at fast scales based on the in situ data can have several scientific goals. The main one is to adapt the small-scale motions of gliders so as to best locate the features predicted at the slower scale. Others are to filter the scales which are not of interest and to estimate parameters in model parameterizations of such faster scales.

In the AOSN-II Monterey Bay 2003 experiment, we tested strategies for controlling groups of gliders as mobile, re-configurable sensor arrays using data from these gliders that was made available every two hours (the frequency of glider surfacings). The coordinating feedback control laws were derived using the virtual body and artificial potential (VBAP) framework described in [24, 23]. This framework provides a provable method for autonomous control of the translation, rotation, expansion and contraction of a vehicle group in order to perform a mission such as
gradient climbing on an environmental field.

On August 6 and 7, 2003, three gliders were controlled to move northwest through the cold plume of the upwelling in a triangle formation with 3 km inter-glider spacing. In Figure 3 the triangle at several instants of time is shown along with the estimate of temperature gradient $-\nabla T$ at 10 meters. This estimate was computed using only the glider profile data but is consistent with the satellite sea-surface temperature field. During the 2003 experiment, glider formations were successfully coordinated to deform, e.g., to change from 6 km inter-glider spacing to 3 km inter-glider spacing as a test of the capability and utility of changing the resolution of the glider fleet as mobile sensor array. Additionally, a glider was successfully controlled to track a surface drifter in real time. This latter scenario suggests promise for implementation of a Lagrangian sensor array, i.e., a fleet of gliders collecting 3D data along the path of a drifter or other path available in real time.

We will build on the successes of the 2003 and the methodology we have developed. For instance, we will investigate estimating second-derivatives in profile data (from the glider collective) to locate and track fronts, e.g., by estimating maximum changes in gradient magnitude. We note that gradient estimates can be calculated from ad hoc subgroups of the larger fleet of gliders as they follow their coverage-control-driven trajectories.

We also plan to integrate this work with the HOPS model and LCS analysis in order to best direct the gliders to features of interest (see, e.g., [22]). Reacting to model uncertainties computed at a relatively high frequency along glider paths is a one such plan.

3.4.3 Predictions, Adaptive Sampling and Data assimilation with HOPS/ESSE

Adaptive sampling theory needs to account for the nonlinear ocean dynamics [33, 31]. The optimal sensors and sampling patterns should focus on the regions of greatest dynamic variability and greatest uncertainties, compounding model, data, initial condition and forcing error sources. In Bayesian estimation, the probability density of a specific ocean state, conditioned on data and constrained by ocean dynamics, is evolved by a dynamical equation which contains all of these effects. Adaptive sampling can then be defined as optimizing certain properties (e.g. minimizing future error variances, maximizing dynamics hot-spots) of this conditional probability density. One objective here is to extend the linear time-invariant adaptive sampling problem to the linear time-variant and nonlinear cases where uncertainties depend on data

Figure 3: Glider fleet moving in a triangle formation on August 3, 2003 in Monterey Bay with temperature measurements and estimate of $-\nabla T$ at 10 meters.
values and probabilities. Ideally, operational costs and constraints (gliders) are represented. Secondary dynamical fields such as balances of terms, kinetic energy, potential energy, vorticity and enstrophy [28] should also be predicted and utilized to optimize the conditional probability density via adaptive sampling. The results of these efforts will be applied in real-time at sea using the physical-acoustical-biogeochemical Harvard Ocean Prediction System (HOPS, [35, 30, 26, 27, 29]) and Error Subspace Statistical Estimation (ESSE, [34]) forecast and assimilation scheme.

A new ESSE nonlinear adaptive sampling scheme for identifying future regions in most need of sampling based on a tree-structured multi-ensemble prediction will be developed. A set of candidate sampling regions/paths and the data uncertainties along this path are first specified. A tree of ensembles with data assimilation is then evolved forward in time. Each branch of the tree corresponds to a sampling path or a set of regions to sample. The information contained in each path is the error reduction either at the end of the forecast or integrated along the forecast duration. The best sampling plan among the candidates is the one that minimizes such uncertainty metrics the most. In collaboration with Princeton, CalTech and Scripps, the 3 adaptive sampling objectives and metrics will be combined and the corresponding sampling path optimized on several time and space scales.

From data-model misfits and interactions with the observational groups, the dynamical model parameterizations and data assimilation systems will be evaluated and improved. The focus will be on surface and bottom boundary layers, and on predicting internal tide/wave statistics. For data assimilation [32], error models for glider/AUV/ship/aircraft data will be developed with WHOI/Scripps/MIT/NPS and the data values will be predicted. The predictive capability limits and predictability limits for upwelling and relaxation processes will be estimated. The skill of upwelling plume forecast and relaxation process will be measured based on new skill metrics focusing on the properties of the plume at Pt AN (e.g. size of plume, scales of jet and eddies at plume edges, thickness of boundary layers and surface and bottom fluxes).

Based on theoretical and computational research, momentum, heat and mass budgets software will be implemented on multiple-scales with uncertainties, and allowing for time-dependent volumes to account for the evolution and relaxation of the plume and the different boundary layer effects. The evolution of the upwelling and the interesting dynamics of the relaxation process will be studied based on science-focused sensitivity simulations. These will be carried-out under different atmospheric conditions to quantify effects of atmospheric resolution, surface and bottom BL formulations and idealized geometries.

ESSE ensemble of numerical simulations with different model parameterizations will continue to be carried-out so as to improve predictions and adaptive sampling. In the optional years, a multi-agent distributed expert system for the efficient combination and improvement of oceanic models based on quantitative multi-model-data comparisons and inter-model data assimilation will be researched, implemented and tested. It will include adaptive bottom and surface boundary layers with distributed GRID software and non-hydrostatic computations. The upwelling and relaxation dynamics will be researched theoretically, physical-biogeochemical balances will be identified and the inter-annual variability will be assessed.

3.4.4 Lagrangian Coherent Structures

In recent years, the Dynamical Systems community has shown strong theoretical and experimental evidence that invariant manifolds, finite-time invariant manifolds and the more recent Lagrangian Coherent Structures (LCS) reveal interesting dynamical features in fluid systems. These systems include large-scale ocean flows, coastal processes, bays and estuaries. Examples
of such edifices are fronts, time-dependent curves or surfaces representing barriers to fluid particles, vortical structures, plumes and alleyways governing transport of tracers. The usefulness of LCS for understanding and visualizing complicated flows has been well-demonstrated in for example, mixing in turbulent flows and the determination of optimal pollution release [21].

Time-independent flows are often studied in terms of their stable and unstable manifolds, however, these manifolds are often not well defined for general time-dependent flows. Finite-time invariant manifolds and Lagrangian Coherent Structures may be regarded as a generalization of the concept of stable and unstable manifolds to velocity fields that have general (turbulent) time-dependence and are known only over a finite interval of time. However, the existence of finite-time invariant manifolds and their numerical computation is subject to hypotheses that are rarely met in noisy experimental data sets, such as CODAR measurements or a high-resolution model of Monterey Bay. For the AOSN-II experiment and this proposed work, we use the most recent concept of LCS. As shown in [19], these are robust to noise and deterministic perturbations. In the time-dependent context, one does not literally search for these invariant manifolds or streamlines directly, but rather for distinguished material lines or surfaces that are attracting or repelling. It is known (see the cited works of Haller and references therein) that a good way to reveal these manifolds is to look at a ridge of a scalar function called the DLE (direct Liapunov exponent) that is constructed from the maximum eigenvalue of the Cauchy-Green tensor. Notice that plotting the level sets of the DLE and looking at the LCS in a flow reveal the Lagrangian features of the flow directly. Many authors established relationships between Eulerian (frozen-time) and Lagrangian behaviors. Here, we use the finite-time Cauchy-Green strain tensor that encapsulates information about the time-dependence.

LCS were computed during the AOSN-II experiment with an efficient software package called MANGEN and developed by Coulliette and Lekien at Caltech, under the mentorship of J. Marsden. In fact, once everything was set up properly, MANGEN was used to compute LCS in real-time for Monterey Bay.

For the proposed experiments, LCS will be computed in real-time on velocity data from the HOPS model. Both nowcasts and one-day forecasts of LCS will be available, as was done for AOSN-II (see http://mangen.caltech.edu). This and other LCS information may be useful for tracking and studying the upwelling plume, and for glider planning and exploration of this and other interesting flow structures (optimization of Objective 2). We will explore using MANGEN output to help bias coverage-based optimization as discussed in §3.3.1 and §3.4. Further, we will explore how the work in [16, 25] on groups of vehicles with gyroscopic controls and in [23] with potential-based controls (from AOSN-II), can be merged with the LCS computations for optimal coordinated control. We will also investigate using NTG (Nonlinear Trajectory Generation) software, designed for real time trajectory optimization for dynamical systems, to compute energy and time optimal glider trajectories.

To achieve these objectives, it will be necessary to further develop LCS capabilities to handle 3-D flows and data sets. Some of the theory for this is already underway [18], and we expect a future generation of MANGEN to explore this avenue. In addition, there is another exciting possibility emerging, namely set oriented methods, which have already proved to be a useful complement to MANGEN in transport calculations in other problems [17]. The plan is to implement these techniques in the context of the present proposal for purposes of 3-D visualization of LCS structures. Preliminary results emerging from the work of a collaborator, Katherin Padberg, have already shown that complex structures can be successfully extracted from 3-D flows. This technique makes use of some clever computational methods for direct expansion rates done by means of the Dellnitz framework of set oriented methods.
3.4.5 Optimal Procedures for Assessment of the Ocean Acoustic Environment

We will develop optimal procedures for assessment of the ocean acoustic environment through adaptive sampling and assimilation into ocean forecasting frameworks of acoustic and non-acoustic data. The uncertainty of the acoustic predictability is one of the major obstacles to adapting new model-based sonar processing frameworks to the coastal environment. The coastal environment is characterized by variability on small spatial scales and short temporal scales, which obstruct the formation of a robust and reliable tactical picture. Thus, a Rapid Environmental Assessment (REA) capability has long been recognized as a tactical need, but its implementation is being constrained by limited \textit{in situ} measurement resources adequate for capturing the acoustic uncertainty.

Recent years have seen major steps forward in the development of ocean forecasting frameworks based on modeling and data assimilation. Equivalent to weather forecasting this concept has been demonstrated to remedy the under-sampling provided by the measurement resources, and producing 4-D field estimates, and the associated error fields. However, even though highly applicable to a wide range of applications such as coastal environmental management, the uncertainty of the forecasts is totally inadequate for direct use in acoustic environment prediction frameworks. This is due to the high sensitivity and nonlinear relation between the ocean variability and the acoustic environment statistics and the constraints of the limited observation resources. New adaptive sampling concepts based on previous forecasts are being developed which in principle could be used to subsequently deploy the limited tactical resources in a manner which is optimal to the acoustic forecasting. Thus, the ocean forecasting can be used for identifying features such as fronts which are particularly critical to the predictability of the acoustic environment, and which should therefore be targeted by the REA resources.

Adaptive Rapid Environmental Assessment (AREA) is a new probabilistic approach to the adaptive sampling problem of littoral REA, currently being investigated by MTI under the ONR ‘Capturing Uncertainty’ DRI. AREA is envisioned as a real-time tactical tool for determining the optimal deployment of the REA resources for capturing the acoustic uncertainty of significance to specific sonar systems.

A specific aspect of AREA which we propose to investigate as part of the proposed ASAP project is the assimilation into the forecasting of acoustic data. Acoustics are clearly the most direct way of assessing the acoustic environment, but their use has traditionally being prohibitive because of the need for deployment of extensive Ocean Acoustic Tomography (OAT) networks. Thus, we propose to develop further the concept of Acoustic Data Assimilation (ADA) allowing the assimilation into the forecasting framework of any type of available acoustic data, including active sonar data, acoustic communication data, etc., with consistent handling of model and data uncertainty. The ADA framework will be based on the preliminary analysis and concept development at MIT, HU, and NPS through various NOPP, ONR and NSF sponsored programs.

A potentially rich source of acoustic information will be provided by the acoustic navigation, communication and sensing systems of the rapidly emerging off-board autonomous sensor networks now being transitioned into operational systems by the Navy, the off-shore industry, and for coastal observatories. In the proposed field effort in Monterey Bay, we will investigate the feasibility of collecting and assimilating such ‘moving baseline’ tomographic data into the forecasting framework. Specifically we will investigate how the usefulness of such acoustic data can be improved by adaptive behavior of the autonomous platforms. MIT currently possesses two Odyssey III AUV’s with acoustic transmission and receiving capabilities, ideal for this work, and compatible with the AUV resources of MBARI, which will be collaborating on the experimental
Figure 4: Sea surface temperature from August 17, 2000 as observed from the TWIN OTTER aircraft at an altitude of 133 m. The wind vectors are shown in magenta, CODAR surface current vectors in black. The plot serves as a locator map for the observational plan.

3.5 Experimental Plan

Three field efforts will be conducted as part of the proposed ASAP project: A pilot study in summer 2005 and the first main effort in June 2006 and the second main experiment in June 2008. The time leading up to the experiments will be used to purchase and test equipment and further refine the vehicle control theory. The year following the main field program will be dedicated to analysis. The 2005 pilot study will be one week in duration and will be used to test equipment, vehicle control, and experimental concepts. Since climatology is not critical for the pilot study, the month of August has been chosen to allow for historically good weather. The information flow between the field team and the numerical modelers will also be fine-tuned during the pilot study. The main effort will be held during June 2006, the month when maximum coastal upwelling historically occurs. The project will be one month in duration to allow the capture of several upwelling and relaxation events. Importantly, previous observations have eluded earlier attempts with fixed assets, which invariably miss important aspects of the dynamics. The ASAP experiment will circumvent these difficulties by using mobile sampling strategies that minimize the sampling/prediction errors and capture the essential elements of the circulation, regardless of where it may form. The operational plan is described below for the main field effort, with the pilot study a much reduced version of the same concept.

The observational region will extend from the center of the Monterey Bay to just north of the upwelling center surrounding Pigeon Point and Cape Ano Nuevo (Figure 4). (1) Prior to the start of the vehicle deployments, the boundary of the box will be surveyed by ship for purposes of model initialization. This can be done using vehicles in the future, but for now, it is best done by ship as it is not critical to the technology to be demonstrated. The shipboard CTD data also provides an accurate estimate of the prevailing T/S relationships which are useful in glider sensor calibration. A mid-sized UNOLS research vessel such as the POINT SUR will be used for this purpose. Six days of POINT SUR time are requested in summer FY06 for this experiment. (2) As a next step the shallow (WHOI) and deep (SIO) underwater gliders will be deployed using a smaller research vessel such as the SHANA RAE out of Santa Cruz. The vehicles will operate in an adaptive sampling mode in order to optimize the three sampling metrics defined in §3.3 (maximize coverage, maximize sampling of significant dynamics and minimize model uncertainty). The three boundaries (Figure 4) will be observed
during the course of the experiment according to the need to minimize sampling error and model uncertainty. As appropriate, given the ocean events, some gliders will form cooperative subgroups in order to track the development and movement of features such as cold filaments. These vehicles will not only observe the location of the filaments, they also will track the local change in the heat content within the upwelling filaments. (3) The southern boundary will also be patrolled occasionally by a DORADO propeller driven vehicle, owned and operated by cooperating investigators at MBARI [J. Bellingham and F. Chavez]. This line goes through surface buoys M1 and M2, also maintained operationally by MBARI. These buoys have a very complete suite of sensors including current, temperature, and salinity in the upper ocean and wind, temperature, and solar insolation in the atmosphere. (4) Inside the box, two Odyssey vehicles will cooperate to map both the interior and high-gradient regions of the upwelling center using both direct observations (CTD, ADCP) and acoustic tomography techniques (Figure 4 dotted magenta line). These vehicles are best deployed by the MBARI vessel ZEPHYR, purpose-built for handling these vehicles. (5) A low-flying (33 m) aircraft will map the region to observe the air and sea surface temperatures, dew point, wind stress, and turbulent fluxes of heat and momentum from the atmosphere to the ocean. This will be done using the TWIN OTTER aircraft owned and operated by the Naval Postgraduate School. Two kinds of flights will be conducted. Large-scale surveys require about 5 hours per flight and will be done approximately weekly during the main field effort. The purpose of these flights is provide the synoptic context for the upwelling center and update the SST for the numerical models. The smaller-scale flights will focus on the upwelling center, the region inside the box (Figure 4). These flights will be adaptive based on atmospheric forecasts, and will be clustered around the times of rapid change from the upwelling to downwelling states and vice-versa. About four short flights of 2.5 hours each are envisioned per transition. These may take place at the rate of 2-3 per day when they are most needed. (6) An additional mooring will be deployed along the northern glider line as a calibration check and to make a minimal suite of meteorological observations in that region. This mooring will be complimentary to buoys M1 and M2 on the southern line but will be smaller and less comprehensive. The data will be transmitted to shore in real time via an acoustic modem/wireless internet network. (7) All observations will be delivered to the modeling and adaptive sampling team in real or near-real time. Various modular adaptive control schemes will be applied to the vehicle movements based on both observational data and model output as available, as described in that section of this proposal.

Supplementary observations include the shore-based CODAR HF radar current mapping network, which it is anticipated will cover the entire area by 2006. These instruments provide hourly current vector maps in approximately 1 km range cells. The observations compliment the in situ observations by providing complete maps of the surface currents, which allow direct computation of the along- and across-shore correlation scales for data assimilation purposes. Similar calculations can be performed on the aircraft SST to find the correlations scales for temperature. These two data sets provide a very complete picture of how features are moving around within the observation region.

Glider Objectives in the Experiments Buoyancy-driven autonomous underwater gliders provide a flexible, economical and reasonably covert way to maintain observations in an ocean region. They have operational lifetimes of many weeks to many months that are achieved by moving forward slowly at O(25 km/day). Because they surface every few hours for satellite locating and communication, gliders can easily be controlled, either singly or in groups, on the time scale of hours. Therefore, for the purpose of the proposed experiments, direct inter-vehicle
communication does not provide significant advantages over the indirect communication and navigation scheme as it was used for AOSN II.

The challenges of low-level glider control are less sophisticated than the scientific and adaptation objectives, but are essential to sustaining effective use of gliders on a 24-hour per day basis. In the 2003 AOSN II experiment, several control errors led to groundings and gliders that were unnecessarily blown off their target tracks by currents. The press of data quality control and operational monitoring of vehicle performance required more than two fulltime people to operate a fleet of 12-15 gliders. Minimal requirements are software support to effectively and accurately control vehicles in response to predicted currents, desired sampling paths and any vehicle anomalies (for example, a failed altimeter or poor communication). An effective control aide would also alert operators to malfunctioning altimeters, impending dangers of grounding, unexpectedly strong currents or any other operating anomalies. Developing such an operating aid will be a collective goal of ASAP.

Because developing and demonstrating adaptive sampling capabilities will be a goal of ASAP we cannot specify the observational array. We can, however, outline the archetypical sampling strategies from which our adaptive arrays will be constructed. To maximize the ability to observe budgets for the Año Nuevo upwelling center we could establish a well-measured perimeter from gliders that patrol relatively short segments (20-30 km) of the perimeter. With net speeds of O(25 km/day), this would give adequate sampling of interfering noise such as that from internal tides and high spatial resolution. At another extreme, much less dense sampling spreading well beyond the upwelling control box would improve the ability of models to predict the timing and structure of ocean responses to varying winds. An even more adaptive sampling strategy might be called "feature sampling." Here an unusually significant feature might be detected in model forecasts or by observations and defined to be important target for local high-resolution adaptive sampling. The allocation of gliders to combinations of these prototypical arrays in response to observations, model predictions, and the sensitivity of prediction skill to observation placement will be the goal of adaptive sampling.

The primary glider observations will be frequent sampling of temperature and salinity profiles and vertically integrated velocity obtained from measured velocity through the water and navigation (e. set and drift). The WHOI ‘Slocum’ gliders will also report profiles of chlorophyll-a fluorescence and optical backscatter at two wavelengths. The SIO ‘Spray’ gliders will also measure velocity shear using a 600-kHz Acoustic Doppler Current Profiler. Combining these shear measurements with set and drift will provide absolute velocity profiling that will be of particular importance in defining Ekman transports and the depth to which momentum is mixed in the surface and bottom boundary layers.

References


