SENSORS: ALOHA Mooring Sensor Network and Adaptive Sampling

Project Summary

Intellectual Merit

This project will demonstrate the scientific potential of combining adaptive sampling methods with a moored deep-ocean sensor network at the Hawaii Ocean Time-series (HOT) / ALOHA Observatory (AO). We will directly address the challenge of sampling the ocean with both high temporal resolution and high vertical resolution. With the moored sensor network consisting of a profiler moving between near-surface and abyssal fixed sensors under program control, we will be able to focus the sampling and measurement capabilities on the scientific features of most interest. These include intense sub-mesoscale eddies, cold bottom water overflow events, tidal mixing, biological thin layers, and yet-unknown processes, as well as the long-term background sampling that has been the basis of HOT for the last 14 years. We will develop the optimization software tools that will maximize overall information return given the constraints of competing scientific objectives, the continually changing environment that we are observing, and the physical limitations of our observing sensors and network. The power and two-way real time communications capability provided by the recently NSF-funded cabled ALOHA Observatory is a *sine qua non* without which the sampling improvements and the sensor network, and the resulting science, would not be possible.

Broader Impacts

Subsequent deployments of similar moored sensor networks are envisioned at the Hawaii-2 Observatory in the mid-Pacific, at DEOS buoy/seafloor junction box sites around the world, and on the planned NEPTUNE cabled ocean observatory on the Juan de Fuca Plate. The project will be a contribution to the NSF Ocean Observatories Initiative and the U.S. Integrated Ocean Observing System, helping to develop new technology and methods, building toward the vision of a global system of sustained ocean observation.

The sampling and observational methods developed here will be transferable to ocean observatories elsewhere in the world. The knowledge and experience we gain can be applied to other situations, some ocean related (e.g., mission planning for undersea vehicles and floats) and some in non-ocean applications, for instance, following a pollution or biological plume using a remotely operated aircraft. The students we directly educate and train (from undergraduate to post-doc) will be better able to master the evolving trans-disciplinary nature of the science and engineering processes. Through collaboration with other programs, in Hawaii and on the east coast, we will give K-12 students and teachers real-time access to the deep-ocean in support of science and mathematics education.

Project Description

Results from Prior NSF Support

PI: **Bruce M. Howe**
Grant OCE-0116750; $1,943,183; 1 October 2001 – 31 March 2004
Development of a Power System for Cabled Ocean Observatories

This grant supports the design and prototype of a 100-kW parallel DC power system for cabled ocean observatories. The design will support regional ocean observatories such as NEPTUNE on the Juan de Fuca Plate in the northeast Pacific (www.neptune.washington.edu). NEPTUNE, with 3000 kilometers or more of fiber optic cable for power and communications, may have thirty or more nodes, each supplying up to 10 kW of power and capable of supporting complex systems of sensor networks. The power system is being designed in collaboration with JPL and the NEPTUNE Engineering Team, and is an integral part of the funded observatory test beds in Monterey Bay (www.mbari.org/mars) and the inland waters around Vancouver Island (www.venus.uvic.ca). A panel of internationally recognized experts has favorably reviewed the work. See the Web site http://neptunepower.apl.washington.edu and Schneider et al., 2002; Howe et al., 2002; Kirkham et al., 2001a,b. Four graduate students and one undergraduate student are currently involved in the project. One former undergraduate stated that her work on this project led directly to her present job. One masters student will defend his thesis based on this work in March 2003.

PI: **Roger Lukas**
Grant OCE-9811921; $971,999; 1 October 1998 – 30 September 2002
A Time Series Investigation of Climate-Related Processes in the Subtropical North Pacific Ocean

This grant supported physical observations for the Hawaii Ocean Time-series (HOT) project. We have documented seasonal and interannual variability of water masses; begun relating water mass variations to gyre fluctuations; and developed a climatology of short-term variability. We provided critical CTD/rosette sampling to the biogeochemical component of the program (Karl et al., 2001) to many ancillary investigations, and for development of new instrumentation such as Sea-Bird's new O_2 sensor. Data, documentation, and analysis results are made available via our Web site (http://www.soest.hawaii.edu/HOT_WOCE), generally within a month for CTD-based measurements. On average, 300 users each year downloaded about 500 files each month, with a maximum of 3500. The annual hits on our site increased from 3251 to 17,292 during 1997-2002. We created a CD-ROM (Lukas and Karl, 1999) that contains the HOT datasets and all documentation for the period 1988-98. A virtual HOT cruise audiovisual experience was included. We distributed this CD-ROM to colleagues worldwide, and to high schools throughout Hawaii. We have involved a large number of undergraduate and graduate students in the HOT fieldwork and in the analysis of observations. Many of the UH Research Experiences for Undergraduates participants have worked with the HOT project. Numerous graduate students from UH and other institutions have conducted thesis research and received training through graduate research assistantships under HOT primary or ancillary projects. The PI offers a graduate course every semester that involves participation in the fieldwork. More than 1500 student-ship days have been provided during the first 100 HOT cruises.

Coherent decadal time scale T-S variations in the upper pycnocline at ALOHA are apparently related to rainfall variations over the N. Pacific through subduction at the Subtropical Front (Lukas, 2001). During El Niño events, this front moves southward and active ventilation occurs at ALOHA (Lukas, 2003a). The mixed layer at ALOHA shows distinct impacts of variable freshwater fluxes, with ML salinity varying by as much as 1 psu, while ML temperature varies by only about 2°C (Lukas, 2003b). Eddies transport waters of distinctly different character to ALOHA. An extreme water mass anomaly event observed during January 2001 is attributed to a sub-mesoscale eddy carrying salty, O_2-depleted mid-thermocline waters from Baja California to Hawaii (Lukas and Santiago-Mandujano, 2001). More typically, eddies bring somewhat fresher thermocline waters to ALOHA from a genesis region about halfway between Hawaii and Mexico (Lukas et al., 2003). These eddies significantly impact biogeochemistry at ALOHA (Letelier et al., 2000). Cold, salty abyssal overflows from the Maui Deep to the Kauai Deep occur episodically, creating pronounced temperature anomalies in the lowest 300 m (Lukas et al., 2001). A time- and depth-varying eddy diffusivity model fit to observations of the thermal relaxation of the Kauai Deep yielded peak eddy diffusivities of 40–50 $cm^2\ s^{-1}$ near the sill depth for a month or more. Finnigan et al. (2002) independently confirm estimates of this enhanced near-bottom mixing at Station ALOHA.

1. Introduction and Motivation

We propose to develop and demonstrate a moored deep-ocean sensor network that maximizes the overall amount of scientific information acquired using adaptive sampling methods. The goal is to optimize overall information return given the constraints of competing scientific objectives, the changing environment on all scales we are observing, and the physical limitations of our observing sensors and network. We will integrate distributed sensor network and sampling developments with ocean science.

We need to observe temporal scales of seconds to decades while at the same time observing the entire water column from the surface to 5000 m depth with high (~10 cm) vertical resolution. Fixed sensors alone cannot do this. Even with the sensor network that we propose – a profiling sensor platform cycling between two fixed sensor suites near surface and bottom – we are limited and compromise is unavoidable. The challenge is to optimally control the profiler given the constraints to detect and target the ocean features of interest to maximize the information content of the data.

These measurements are crucial to advance oceanography. A great ongoing challenge is to understand how the ocean is stirred and mixed, and we now realize that important processes affecting the oceans are dominated by short-lived, episodic events. Many of these processes take place at scales that are difficult to observe and nearly impossible to incorporate in large-scale models; further, vastly different scales interact, such as when diapycnal mixing is enhanced by the shear of a passing eddy. New sampling and observation strategies and new technologies must be developed to adequately measure and understand these processes. Solving the problem of ocean sampling on space and time scales appropriately tuned to the processes being investigated is key to success (paraphrasing the NSF report *Ocean Sciences at the New Millennium*, 2001).

In the next section we illustrate the need for adaptive sampling of the complex ocean environment; a sampling that carries with it the requirement for two-way real-time (2WRT) communication and power. The examples are taken from the 14-year long Hawaii Ocean Time-series (HOT) data collected at Station ALOHA 100 km north of Oahu, where we will deploy our moored sensor network in summer 2005, attaching it to the NSF-funded ALOHA Observatory (AO), a shore-cabled seafloor J-box providing 1 kW and 100 Mb/s. This power and communications capability will let us vary the vertical and temporal sampling from the default of routine top-to-bottom sampling, to zero in on episodic features of interest restricted, for example, in depth.

The Objectives and Approach section describes the components of the adaptive sampling (e.g., sensor network model, classification of oceanic signals, ocean state assessment and signal detection, and queuing – the balancing of priority versus urgency in scheduling sampling modes) and the development of the moored sensor network (e.g., integration of sensors, the profiler, and mooring system into the AO). The Work Plan describes, for instance, the profiler and mooring testing and the development of the adaptive sampling algorithms. The final section puts the effort into a broader context.

Intellectual Merit: We address the challenges of observing important ocean features by developing and demonstrating new and innovative adaptive sampling techniques and sensor networks. The science payoff will be the ability to quantify a significant, but otherwise under-observed, volume of the time-space variability of the ocean, and interactions across scales.

Broader Impacts: The sampling and observational methods developed here will be transferable to ocean observatories elsewhere in the world, building toward the vision of a global system of sustained ocean observation. The knowledge and experience we gain can be applied to other situations, some ocean related (e.g., mission planning for undersea vehicles) and some in non-ocean applications, for instance, following a pollution or biological plume using a remotely operated aircraft. The students we educate and train (from undergraduate to post-doc) will be better able to master the trans-disciplinary processes that will be important for understanding future similar problems.

1. ALOHA Science Questions – Adaptive Sampling is Essential

We seek a deeper understanding of physical variability of the water column in the North Pacific subtropical gyre, and the biogeochemical and ecosystem variations that result. Advective and diffusive processes have quite different impacts on biogeochemistry and ecosystems, and quantifying their relative importance in different situations is critical to successful modeling. For example, a Rossby wave has no net transport, while a mesoscale eddy does; impacts on nutrient distributions differ.

Eddies are both advective and diffusive, transporting waters over long distances, mixing with their surroundings along their trajectory. An extreme example is the eddy observed in the mid-pycnocline during the 122nd HOT cruise (Fig. 1).

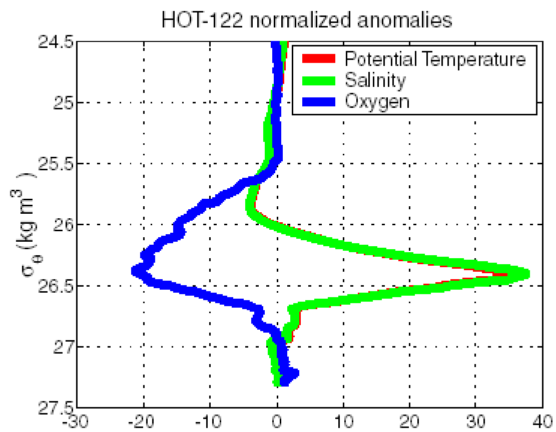

Fig. 1. Salinity and oxygen anomaly profiles in density coordinates, normalized by long-term standard deviations, associated with the "Mexican" sub-mesoscale eddy ("Meddy"). The vertical extent of the eddy is about 200 m. From Lukas and Santiago-Mandujano, 2001.

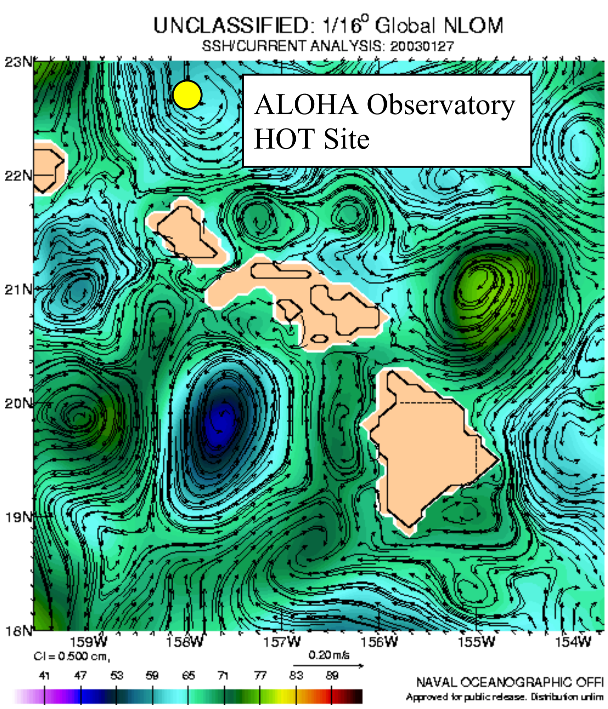

Fig. 2. Sea surface height and upper layer currents from the Navy Layered Ocean Model forced with observed winds and constrained by satellite altimetric observations.

Detected during routine ship-based conductivity-temperature-depth-oxygen ($CTDO_2$) profiling at Station ALOHA, the extremely low O_2 and high salinity were unprecedented (20 and 40 standard deviations from the mean). A spatial survey ascertained that it was indeed an eddy, but substantially smaller (~15 km radius) than the mesoscale eddies typical of the region (Fig. 2), and without any surface signature. Water mass analysis determined that the highly anomalous core waters were unambiguously from offshore of Baja California (Lukas and Santiago-Mandujano, 2001). During the first half of this journey, the eddy transport was down the local property gradients, but as it approached ALOHA the transports were opposite to the local gradients. This cannot be accounted for in a simple advective-diffusive model. Did this eddy start as a mesoscale eddy typical of those forced by coastal Kelvin waves during El Niño events (Zamudio et al., 2001)? Are such sub-mesoscale eddies as rare as suggested by their statistics at ALOHA (1 in 14 years), or have we just missed most of them because of intermittent sampling? How much do eddies like this contribute to the mixing of the ocean water masses?

Another (less) rare, but significant, event is the cold abyssal overflow from the Maui Deep to the Kauai Deep (Fig. 3). We do not know what forces these episodic overflows, but we know that there is a large enhancement of diapycnal (nearly vertical) mixing. Understanding how this enhancement is effected is crucial to modeling such overflows and their global impacts – i.e., is this "sloshing over the rim" and associated mixing ubiquitous to all deep ocean basin depressions, large and small?

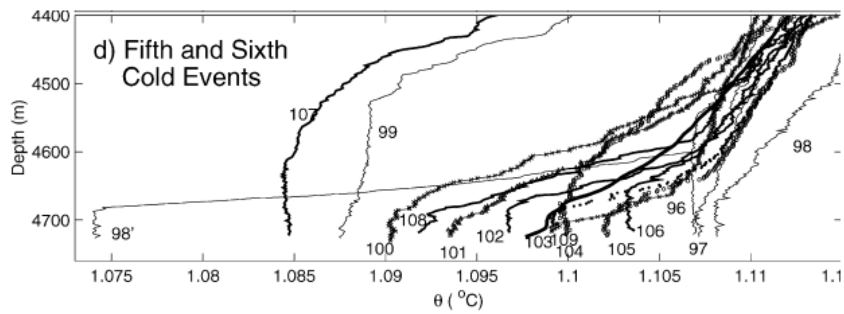

Fig. 3. The intermittent cold, deep overflow. Potential temperature profiles below 4400 m for HOT cruises 96-109 (d). Each profile is labeled by its cruise number. From Lukas et al., 2001.

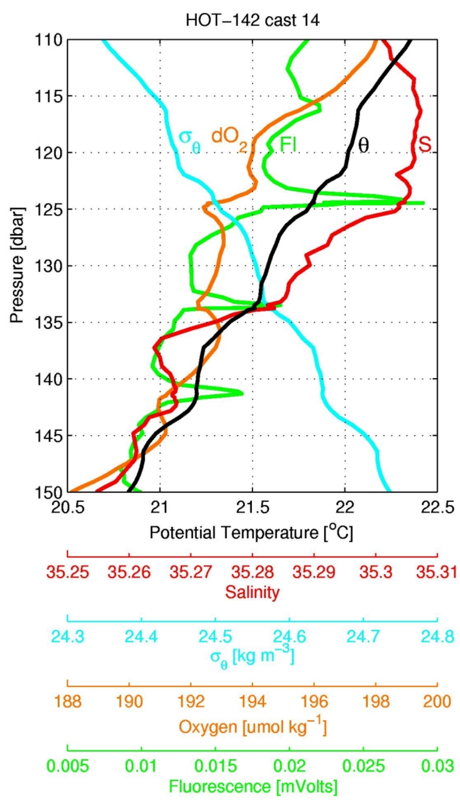

Fig. 4. Temperature, salinity, O_2 and fluorescence from a section of a HOT CTD profile.

Tidal mixing is receiving special attention in the Hawaii Ocean Mixing Experiment that is underway now. Data and models show that beams of internal tidal energy radiate from the Kauai channel, reflecting from the seafloor and affecting the water column at ALOHA (Merrifield et al., 2001) by enhancing mixing in the upper ocean (Finnigan et al., 2002). Understanding how this enhanced mixing is forced is important to improved numerical modeling, including the effects of the internal tides on upper ocean nutrients. Our analysis of internal tides over 14 years of HOT observations reveals that the part of the internal tide that is incoherent with the astronomical forcing is at least as large as the phase-locked, coherent internal tide; such non-stationarity is not well understood.

Biological "thin layers" are patches of dense phytoplankton (and sometimes zooplankton) concentration < 1 m thick (cf. Franks, 1995). In an example from CTD profiling during a recent HOT cruise, large spikes in fluorescence near 125, 134 and 141 m are associated with steps and layers in the density (Fig. 4). Perhaps turbulent overturns homogenized the density profile in places (e.g., Finnigan et al., 2002) with the result that materials originally suspended throughout the layer sank to the bottom. As

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with the Meddy, it is not clear how many cases of such thin layers were missed by ~monthly cruises. An important unknown is the degree to which such optical signals correspond to signatures of turbulent overturning.

Adaptive sampling of these and numerous other features is important for several reasons. First, they are either episodic or otherwise non-stationary. Thus, valuable and limited observational power should be focused on their observation only when there is a clear signal to study. Second, what can be learned about a feature from a particular occurrence is greatly enhanced by deliberately intensive sampling. Given the growing recognition of the importance of non-stationary dynamics, accelerating the pace of discovery and learning is an important objective. Third, many of the signals of interest occur over a limited depth range, so focusing on a subset of the water column is appropriate at times.

Adaptive sampling requires, at a minimum, 2WRT communications so that signals can be detected, and instrumentation reprogrammed. The ALOHA Observatory cabled infrastructure will be used for efficient and effective 2WRT communications with the proposed mooring. An important benefit of this approach is the continuous supply of power available for our instrumentation, allowing long-term deployments that would otherwise be impossible.

2. Objectives and Approach

The objectives of the proposed work fall into three groups: adaptive sampling, the mooring sensor network, and education and outreach. For the adaptive sampling we must:

- Model the mooring capability
- Classify oceanic signals
- Assess the ocean “state”
- Dynamically queue and execute studies/sampling strategies

For the moored sensor network, we must:

- Integrate sensors
- Modify the moored profiler
- Design and construct junction boxes
- Integrate, test, and deploy the mooring itself
- Address systems power and data budgets, command and control, and data management

Lastly, we will train students and inform the public, through education and outreach activities.

Adaptive Sampling

With 2WRT communications capability provided by the cabled moored sensor network at Station ALOHA, we can use its measuring capabilities in ways that are more efficient in terms of advancing ocean knowledge than the “standard” unvarying model of untended ocean observation. The standard ocean observing model involves programming an instrument and deploying it for a relatively long time before finding out what signals were observed, whether the sampling was adequate, and even whether the instrument worked. Adaptive sampling, on the other hand, involves more frequently reprogramming instruments and sensors taking into account the measurement history and information requirements. Adaptive sampling has been conducted using AUVs, for example during the HyCODE field study set within the LEO-15 ocean observatory offshore of New Jersey (Moline et al., 2000). To the best of our knowledge, this capability has not been applied to moored measurements.

In principle, such adaptive sampling can be done manually, but cost considerations make it impractical to conduct 24/7 operations. Human limitations make it difficult to recognize certain categories of signals, and to objectively decide sampling strategy changes. Anyone familiar with shipboard oceanographic expeditions is aware of these limitations. Thus, we intend to conduct the research required to automate signal detection and sampling strategy decision-making, using techniques that have been developed for numerous other applications, such as sonar signal detection and classification, instruction queuing in microprocessors, network optimization, and process control.

What are the limits of sampling given sensor network constraints? A heuristic model of the sampling limitations (e.g., profiler speed, sensor sampling rate, etc.) of the moored sensor network system is required to constrain possible sampling programming within feasible limits. APL engineers will generate this model. The model will require revision if sensors fail or calibrations shift or in the case that we are able to incorporate additional sensors and capabilities into the network in the future.

What do we know now about oceanic processes? The known characteristics of oceanic signals are required to enable their detection in the mooring data stream. Here, we use the term "signal" to indicate a coherent space-time variation in one or more variables that exceeds the background spectral levels (the "continuum" such as the Garrett and Munk [1975] internal gravity wave spectrum). Examples of physical signals are the mid-thermocline sub-mesoscale Meddy (Fig. 1) and the bottom cold overflow events (Fig. 3) discussed earlier. The eddy is obvious in both salinity and O_2, while the overflow signal is manifest most clearly in temperature. Biogeochemical signals such as thin layers are revealed in optical properties and in O_2 (Fig. 4).

What improvements to our understanding of oceanic signals are sought? Along with the definition of the signals of interest, we will generate the requirements for improving their quantification. For example, the probability density function of biological thin layers relative to stratification and shear are known only within wide confidence intervals (Dekshenieks et al., 2001); to narrow that range requires more cases. A target standard error offers a metric for the potential information returned from the next case observed. The salinity anomaly associated with an eddy might be well known, but the velocity signal may not be known at all. Another target for advanced understanding is the background. The GM75 spectrum is a statistical statement, and the variations of the total energy around this background are of great interest, and highly relevant to the signal detection challenge. Thus, such specifications will be rather complex, but they are needed to assist in the prioritization of sampling modes.

What mix of known signals is present? There are many techniques for signal detection, and the appropriate choice depends on the nature of the signal and the continuum. In the proposed effort, we will need to take into account vertical structure and temporal variation of signals; the profiler provides the flexibility to trade between these two dimensions. Because the energy spectrum in the ocean is red in both frequency and wavenumber domains, the techniques that work best at one end may not be as useful at the other end. **This is at the core of the research challenge**. We will first develop a "library" of signals and their characteristics in different variables, including time and space scales and typical energy levels. An example is the cold abyssal overflow event, with a typical vertical scale of 100 m, maximum signal near the bottom, a sharp gradient at the top of the layer, and magnitude of 0.01ºK or more. These have a very rapid onset, within a few days, and an exponential decay over a month or more. [Associated with these overflows is an enhancement of vertical mixing (Lukas et al., 2001), and it is desirable to better quantify this enhancement, and to understand the processes that are involved.] The bottom-mounted instrumentation will enable detection of a cold event even while the profiler is sampling a remote portion of the water column. Detecting the presence of high-salinity intrusions (studied by Kennan and Lukas, 1996) is made straightforward by their high O_2 signal in addition to their high salinity. Detecting eddies, on the other hand, is considerably less straightforward. We can insist on dynamical consistency between stratification changes and currents through the thermal wind balance. However, distinguishing between an isolated eddy and a Rossby wave is at best difficult with only information from the mooring site.

Using only the advanced information from the moored sensor network is not optimal. Satellite observations of sea surface temperature, sea surface topography and ocean color contain valuable spatial information for the region surrounding ALOHA. However, the relationship between these ocean surface observations and deep ocean variations is not well known. The same supervised learning framework discussed above will be applied to the extended observational database. Going even further, dynamical model-based analyses of available remote and in situ observations, such as being produced under the Global Ocean Data Assimilation Experiment by various groups, provide both surface and interior estimates of the ocean state surrounding ALOHA. An example is the Navy Layered Ocean Model (Fig. 2) being run routinely at NRL. At this point, the variance and bias of such analyses is unknown, and determining these is an essential part of making optimal use of the information that they contain. Ultimately, the observations that we will make with the cabled mooring will be assimilated into such dynamical models, providing the most optimized state estimates possible. We do not propose that work here, but stand ready to collaborate with researchers at NRL and in the ECCO project to see our observations included in their analyses.

Our approach will be to employ advanced statistical learning methods to these problems. For example, Kalman filtering is often used to take into account non-stationary background conditions against which discrete events are defined. Neural networks are a form of filtering, being very efficient and well suited to nonlinear optimization problems (Haykin, 1994). Support vector machines (Cristianini and Shawe-Taylor, 2000) are a state-of-the-art learning system ideally suited for data mining, classification and pattern recognition problems. They are a method for creating functions from a set of labeled training data. The function can be a classification function where the output is binary (i.e., Is the input in a category A?) or the function can be a general regression function.

What is the best methodology to detect and verify unknown signals? Given sufficient time, unusual, but real, behavior can be discerned from most sensor degradation. The challenge is to do this as efficiently as possible, but without making the error of abandoning measurement of a novel signal. When the extreme salinity and O_2 values of the Meddy were observed during routine real-time CTD profiling at ALOHA, it was recognized immediately as an extreme event, not artifacts of system failure, because redundant sensors were used. For temperature, salinity, O_2, and optical absorption we will use the comparisons between the profiler sensors and both the abyssal and upper ocean fixed sensors to identify possible sensor problems. Simple statistical analysis of the deviations from the background will reveal the possible presence of extreme, but poorly known, signals. Once having verified sensor performance, an exploratory mode of sampling can be initiated.

How do we balance priority versus urgency? The priority that is given to a particular "study" or sampling mode must be set in consideration of competing scientific objectives. (This will ultimately require difficult work by teams of scientists hammering out the needed rankings. For the purposes of this demonstration project, however, we will do this within our research team, taking into account our broad experience in ocean research.) Over time, as more cases of a particular feature are studied, the priority for further information would be expected to be lowered, as the marginal return on effort becomes smaller. However, this relatively slowly changing priority matrix must be dynamically adjusted in consideration of the relative rarity of signals, and in consideration of the need to complete, if possible, a study that is already in progress. Since it took 12 years to first observe the Meddy, we might consider the urgency of sampling the next case even if the unweighted priority was lower than another study that was already in progress. A cost function must be developed to take this into consideration. Thus, we need to develop a weighting system that takes into account the rarity of a signal. There are also "costs" associated with switching from one mode of sampling to another. For example, switching to another mode of study may completely waste the resources used in an uncompleted study. Sensor network model constraints (e.g., a battery needs to be recharged) may prevent completion of a new study, and it would not make sense to interrupt the present study. Thus, switching between modes of sampling (for different studies) should be constrained (Hardwick and Stout, 1998).

Moored sensor network

Fig. 5 depicts the proposed configuration of sensor instrument packages, platforms, and junction boxes (J-boxes) on the mooring that make up the sensor network. Other possible future components to the mooring and the AO are also shown.

Sensors: The chosen sensors are robust, long-lived, and have a proven record of performance. With them, we expect to continue the high standards of measurement set by the HOT program. For this demonstration project, we have intentionally not called for redundancy in sensors and platforms at this time. While some investigators may take issue with this and with the specific sensors we have chosen, they will have the opportunity to use the network we create to add others in the future.

There are three locations for sensors: the moored profiler, the subsurface float, and the base or anchor of the mooring. On both the subsurface float and at the mooring anchor will be a Seabird $CTDO_2$ and a C-Star transmissometer (measuring optical attenuation). The moored profiler comes with a Falmouth Scientific CTD and acoustic current meter (ACM); we will add the Seabird dissolved oxygen sensor and the transmissometer. On the subsurface float looking up to the surface will be an RDI 300-kHz Workhorse Monitor Acoustic Doppler current profiler (ADCP). The velocity and acoustic backscatter intensity (related to biological scatterers) measurements in the mixed layer, as well as the $CTDO_2$ measurements on the subsurface float provide both the upper boundary conditions for interpreting the profiler measurements, as well as the monitoring of conditions that may affect adaptive sampling decisions, e.g., a storm or plankton bloom event, the effects of which will propagate downward with time. Similarly, the abyssal fixed sensors will be watching for relevant events while the profiler is active in the upper water

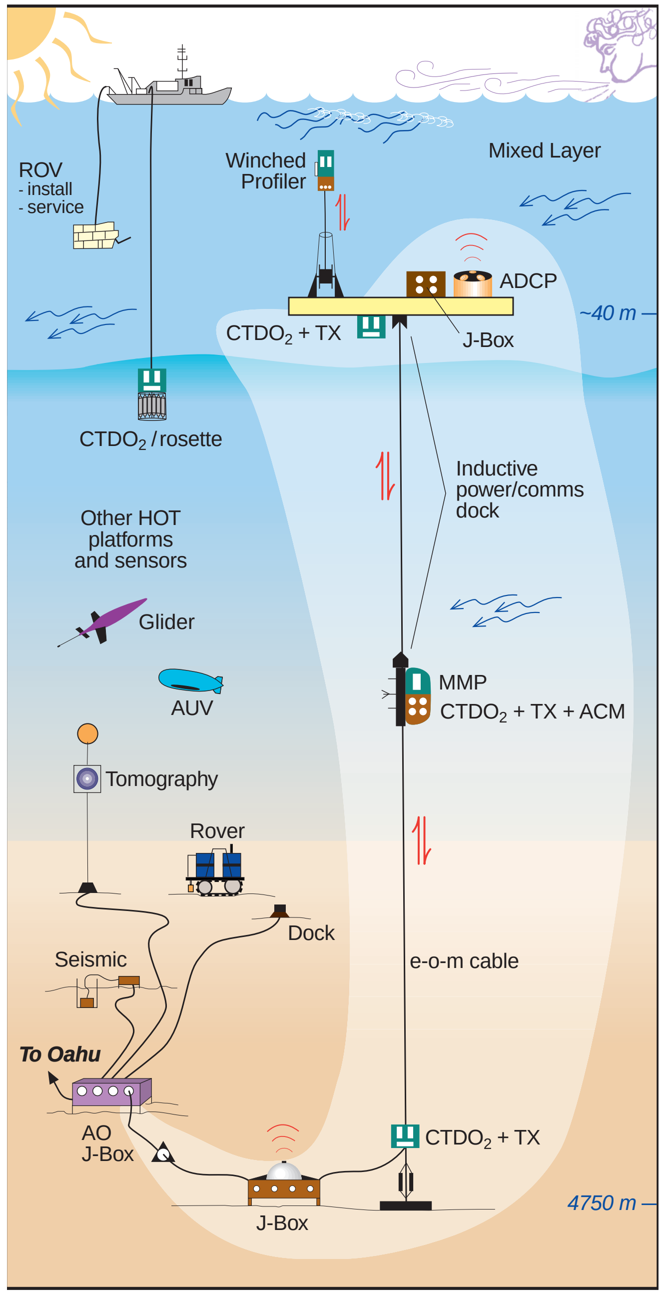

Fig. 5. The ALOHA mooring sensor network. (TX=transmissometer). The lightly shaded area indicates the proposed moored sensor network.

column. (Other than the 2-day monthly shipboard ADCP velocity measurements over a 0–250-m depth range, there have been very few velocity measurements made at Station ALOHA. Our ADCP and ACM measurements over the full water column will fill this void in the data for this unique long-term reference time series station.)

Each connector on a junction box will have 400V and 48V and 10/100baseT Ethernet; this is the standard that is evolving for cabled ocean observatories (Maffei et al., 2001). Seabird has agreed to change the interface on their instrumentation to conform to this at no cost (see letter in Supporting Documents). The interfaces to the other sensors will be modified using "science instrument interface modules" (SIIMS) that will convert to the standard. The interface module will append metadata (e.g., serial number, calibration coefficients, etc.) to the main data stream from a sensor.

McLane Moored Profiler (MMP): Working with McLane Labs, the profiler will be modified as follows:

- The profiling speed will be made variable and increased from 0.25 m s^{-1} to 0.4 m s^{-1} so that the ~9000-m round trip top-to-bottom will take about 6 hours (at the higher speed) minimizing M_2 tidal signal aliasing. This will require 6 W rather than 2 W of electric power on average. The variable speed allows slow movement when high vertical resolution is necessary to accommodate the (relatively) slow response sensors. **The 2WRT communications and power from the mooring network is crucial**.
- Modify the profiler to mate with a dock for inductive power and communications transfer using electric car technology
- Install a J-box packaged in a small form factor with dry mate connectors on the profiler to be the interface between the MMP control system, the other sensors (e.g., the transmissometer and dissolved oxygen, as well as future ones) and the profiler docking unit
- Switch from lithium to rechargeable batteries (1 MJ NiMH)
- Extend the length and buoyancy of the MMP to accommodate the additional components

The inductive transfer technology is based on GM's Magne Charge system. It has been "ruggedized" for military use with 0.5-inch gaps for easier alignment with about 80% efficiency (K. Conroy, personal communication, 2002). The mooring network 400 V DC is chopped to obtain 130 kHz AC, which is inductively transferred to the receiver in the profiler which rectifies the signal and outputs 250-400 V DC. About 6 kW can be transferred, charging the profiler battery in a short time. The profiler can go 125 km (14 full depth roundtrips) at 0.25 m s^{-1} and 30 km (3 roundtrips) at 0.4 m s^{-1} – perfect grist for the adaptive sampling optimization procedures. The system also transfers data using the SAE J1850 standard at 10.4 kbps. The electronics in the charger and vehicle exchange some data about battery condition to control the charging, but use very little of the available bandwidth.

The fixed sensors on the subsurface float and at the base of the mooring will provide calibration checks of the profiler sensors. In the future, *in-situ* calibration of sensors can be done with a remotely operated vehicle (ROV) fitted with a similar sensor payload during service calls. The depth cycling between warm and cold water of the MMP should help reduce any bio-fouling; all sensors as appropriate will have poison packages.

John Toole at WHOI, one of the original developers of the moored profiler, is interested in these modifications and will be available for consultation (J. Toole, personal communication, 2003).

Junction Boxes: J-boxes will be placed on the subsurface float and on the seafloor immediately adjacent to the mooring. The J-boxes provide access via ROV-mateable connectors to the 400 V / 100 Mb/s mooring network backbone. On each J-box, 4 ROV-mateable connector ports (or more, as needed or anticipated) will be provided. The same ports will be used to link to the backbone system as well as for sensors; if for sensors, ports will also provide 48 V. A micro-controller will communicate with the shore power and communication control systems; the J-box itself will be an instrument in this context. For communications, a high reliability commercial Ethernet switch will be used that takes multiple input/outputs and sends the packets to the appropriate locations, whether commands to instruments or data going to the scientist and the data archive on shore. The controller and power portion of the J-box will be based on the low-voltage section of a NEPTUNE node, which UW is developing. The user 48 V and 400 V power supplies will have ground fault and overcurrent protection. Packaging will be based on the H2O and AO experience, using titanium and plastic, with connector manifolds constructed for easy ROV access and service.

Mooring cable and components: The mooring cable has 4 #18 conductors with polyethylene insulation, 4 loose fibers in a 2-mm diameter steel tube, Kevlar strength member, armor wires (above 1500-m water depth for fish bite protection) enclosed in a polyurethane jacket, and an overall diameter of 25 mm. The Kevlar strength member is the expensive part of the cable; it is necessary to keep elongation within the limits set by the optical fibers. Swivels (e-o-m) will be used at the base of the mooring and at the top beneath the subsurface float.

The 3-m diameter disc-shaped syntactic foam float will serve as the platform for the $CTDO_2$, transmissometer, J-box, and the ADCP (Fig. 5). With the available power and communications, the ADCP can be run at its maximum ping rate and a (future) winched profiler is feasible. The instrument mounts on the float will permit (in the future) addition, removal, and servicing of sensors and the other components by ROV. This type of disc buoy provides 2000 lb of buoyancy resulting in a taut mooring to minimize horizontal and vertical motion. It has been used with success for the last 17 years for ocean acoustic tomography moorings. Vertical hydrophone arrays (VLAs, 1-inch electromechanical cable) off Point Sur, California, had typical horizontal displacements at tidal frequencies of 30 m (water depth 1800 m). Just to the south of the island of Hawaii in 5000 m water depth, a similar VLA had typical horizontal displacements of 100 m. We have modeled the effects of surface gravity waves on the mooring. The vertical float velocity for float depths of 40, 100, and 200 m is estimated to be 20, 7, and 0.05 cm s^{-1} rms, respectively. The final choice of float depth will depend on many factors, including the mixed layer depth (varies seasonally between 40 m in May and 85 m in January), signals in the upper thermocline (100–200 m), wear on the MMP and cable, float attitude and impact on ADCP data, and demonstrating short-term versus long-term capability.

The AO J-box is designed for ROV underwater mateable electrical connectors. An observatory interface will connect to the AO J-box and will step the 48 V up to 400 V and convert the AO RS-422 communications protocol to/from 100 Mb/s Ethernet on fiber, necessary for the 2-km distance to the mooring. This 2-km electro-optical cable (similar e-o characteristics as the mooring cable, but only 8 mm outside diameter) will be deployed using a special ROV tool sled (already demonstrated by MBARI, JAMSTEC, and the oil industry; ROV *Jason-2* will be laying cable at H2O in summer 2004) between the AO J-box and J-box at the base of the mooring. Short cables then connect the J-box to the connector at the base of the mooring and the local instruments.

Much of the engineering, hardware, and software, will directly carry over from various related projects we are involved with: the Monterey Accelerated Research System (MARS, www.mbari.org/mars), the Victoria Experimental Undersea System (VENUS, www.venus.uvic.ca), and NEPTUNE (http://neptune.washington.edu).

Power and data budgets: The table summarizes the power and data budgets. The estimated power for the proposed instrumentation and infrastructure is about 23 W, dominated by the MMP and J-boxes. The high ADCP sample rate will allow us to temporally resolve the energy containing part of the gravity wave spectrum, as orbital velocities can be significant in the upper ocean, especially for the longer wavelengths. The scenario for future expansion shown in Fig. 5 brings the power budget to 53 W, well within the 100 W available on a single connector from the AO. To meet high instantaneous power demands (such as the MMP battery charging) and associated I^2R losses in the long runs of small diameter cable, energy is buffered in 1 MJ "smart" ultra-capacitor banks (http://www.powercache.com). The ultra-capacitors will connect to a J-box at 400 V just like a feeder from another power source (using auctioneering diodes); they will be located at the base of the mooring and on the subsurface float.

	Power W	Data rate b/s
ADCP (2 pings/s)	2	5,000
$CTDO_2$, optics (2 ea)	1	1,000
MMP Profiler and dock	10	2,000
J-box (2 ea)	10	100
Future sensors (Fig. 5)	10	3,000,000
Future winched profiler	20	200
Totals	53	3,008,300

Data rates are modest and will not stress the system (~10 Mb/s); broadband acoustic devices completely dominate this crude estimate of future requirements. There is adequate margin for additional sensors and network components.

Command and control: At the most basic level, the observatory control system on shore will monitor voltages, currents, ground faults, etc., throughout the sensor network so that it can take corrective action if necessary, such as opening a breaker on a particular J-box connector. Given power and communications "contracts" with the different users (which may change dynamically given adaptive sampling), it will determine if there are conflicts and be the ultimate arbiter; this will be especially important in coordinating the operation of the MMP and the ultra-capacitor energy storage (and a possible winched profiler in the future), given the finite amount of power available.

Instrument command and control capabilities are essential for realizing the observational power of the proposed sensor network and the adaptive sampling. Real-time sensor status will be essential for monitoring the MMP performance, and the ability to change the profiler programming will be used to diagnose, possibly even overcome, profiler system crises (e.g., fouling of the mooring line). Sensor/system failure detection will trigger alerts with AO/mooring managers and PIs.

Information management: A comprehensive Data Archive and Management System is beyond the scope of this project; this will have to wait until subsequent science proposals are funded. The HOT renewal proposal (under review, and building on existing capability) will support the following. For routine automated quality control, scientific analysis, and education/outreach functions, a real-time data management system will be built. Raw data (Level 1) will be held online in an accessible format for as long as possible, and then ported to optical media. Calibration and quality control will be conducted in two modes. Level 2 data will be available with the minimum delay associated with the modes of sampling and automated processing. Level 3 data will be delayed-mode, involving retrospective calibration and quality control procedures that will use all other information that is available within a reasonable time frame (e.g., laboratory calibrations, other *in situ* measurements). All levels of data will be archived, and Level 2 and 3 data will be accessible online along with all metadata. Designated federal oceanographic data archives will be able to access the data and products on schedules that are convenient for their staff.

To support scientific analysis and curiosity-driven browsing, we will set up a live action server based on readily available public domain software. An example is the service provided by the NOAA PMEL/TAO program, where equatorial data (e.g., El Niño) are viewed easily. This will enable direct Internet access to the information contained in the datasets through online plotting, as well as the ability to subset and download data. This would be supported by the HOT renewal proposal.

Education and Outreach

AO data will be made available in near real time via the Internet using the (proposed) Live Access Server that provides visualization tools. In addition to the undergraduate and graduate students that presently participate in HOT, we will expand the involvement of students both in the classroom and at sea by participating in new educational and outreach initiatives, including the HOT Scientist-Educator Associations (SEA) program and the Bluewater Marine Laboratory (BML) program. Both SEA and BML target Hawaii middle and high school students, and both programs address the country's dire need to provide challenging science, technology, engineering and mathematics education to our students. SEA will provide teacher training by establishing functional linkages between individual HOT program scientists (including advanced graduate students) and professional educators in Hawaii's Department of Education (H-DOE) where there is a great need for improved science education. SEA will involve qualified K-12 teachers spending time in the field with NSF-funded scientists, in turn passing the excitement of marine science along to their students. The BML program began in Hawaii in 1971 as a novel marine education program providing a hands-on, field-oriented experience that targeted high school students. The "teachers" were senior students who had already "graduated" from BML – fully trained and mentored by UH ocean scientists. Despite the remarkable success and the popularity of the program, it was terminated in 1984. A proposal now pending at NSF (Ed Laws, PI) plans to restart the BML program as a new partnership between UH and H-DOE. We will collaborate with Prof. Michael De Luca (Rutgers University), PI of the Mid-Atlantic Center for Ocean Science Education Excellence. This Center is a regional consortium of marine science partners with existing real-time (coastal) ocean observatory and marine educational expertise. We will bring additional (deep ocean) observatory perspectives to the educational activities, which include visualization and K-12 classroom use of observatory data, teacher training and outcome evaluation. We will contribute to developing a national educational strategy for ocean observatories, building on and extending models such as the C.O.O.L. Classroom based on Leo-15. This collaboration will benefit both the SEA and BML activities described above. An ocean engineering summer intern will participate in the project at UW, a graduate student at UMaine, and a post-doc at UH.

3. Work Plan

Sensor network development and testing – Year 1

The modifications and new designs associated with the MMP, and the design of the J-boxes, will occupy much of the first year. The MMP must be adapted for our use and involves the interfacing with a commercial entity/product. The J-box development is associated with the NEPTUNE power system development and should thereby benefit. Prior to prototyping, the Preliminary Design Review (February 2004) will be held to assure ourselves and others that we are on the right track. To insure good coordination, representatives from the AO, HOT, and NEPTUNE development programs will be invited to attend. We will coordinate this effort closely with HOT scientists in particular as well as the community in general, in order for the science and engineering results and lessons learned to be optimized and applicable to cabled observatories in general. After the PDR, in the second half of the first year, we will build the first prototypes, integrate the sensors, and perform "dry" testing.

Sensor network testing, integration, and field work – Years 2 and 3

The second year is devoted to completing the engineering work. In the first 3 months (last quarter CY2004), in-house "wet" testing of the MMP and J-boxes will be done in the School of Oceanography test tank. A short (~10 m) test mooring system with all sensors will be connected together and tested with a realistic (accelerated) sampling schedule so that the MMP is moving, data is flowing, and so on. The system will be allowed to run for weeks with changes made and tests repeated, as long as necessary to assure ourselves all is operating as required. A 100-m long prototype mooring will then be constructed and deployed using the APL R/V *Miller* in Saanich Inlet on the VENUS node in 120-m water depth. This will be done in coordination with other VENUS work so as to minimize costs (see letter from V. Tunnecliffe in Supporting Documents). When satisfied with its performance, the Critical Design Review will be held (March 2005).

Then the full-scale system for AO will be built and tested on land. During this period, a safety review of the deep-water deployment plans will be conducted. These essential steps towards deployment will be documented on the project Web site, allowing the scientific community and others to participate, either actively or vicariously in the process. In summer 2005 the mooring will be deployed at the ALOHA Observatory. A special purpose winch will be used for the deployment of the mooring cable. The mooring will be deployed float first; the anchor will be lowered on a release as the mooring is towed and flown into the chosen location. (This is very similar to the precision placement of FLIP on Jasper Seamount, and of 5 vertical hydrophone array moorings spaced 600 m apart off Point Sur, for which the lead PI was responsible). In coordination with the installation of the AO and other activities, ROV *Jason-2* will be used to deploy and connect the bottom cable to the AO interface and the J-box at the base of the mooring. We expect to spend several days to one week inspecting and verifying the moored network model. We will plan to make available near real-time video of the shipboard and underwater activities through the project Web server. While not as visually exciting as a Space Shuttle launch, there will be educational value in this pioneering process of extending the Internet to the seafloor at 5000 m and then back up to the surface. The mooring will be recovered after 1 year in summer 2006.

Adaptive sampling and data analysis

Physical and optical oceanographic signal definition supporting the development of mooring sampling strategies will be undertaken with existing observations (including the extensive HOT database) prior to deployment. A high priority for data analysis both before and after deployment is to develop the software for mooring data quality control. This requires our prior experience with HOT observations in terms of distinguishing signals from background noise, as well as anticipating modes of possible sensor failure. Research to apply adaptive sampling methodologies, including learning machines, will begin as soon as a post-doctoral fellow with appropriate background is located. Prof. Will Gersch, UH Information and Computer Sciences, has considerable experience with the theory and applications of statistical modeling of time-series as well as support vector machines; his help will be invaluable to recruit highly qualified postdoctoral candidates to work with Lukas on adaptive sampling. Software to automate sampling changes will be developed later in the second year, and will be tested after sufficient experience with the mooring has been acquired to trust the moored network model and the queuing model.

In addition to direct comparisons of moored sensors with similar sensors used during HOT cruises, the optical data will be regularly compared with biogeochemical variables (e.g., particulate and dissolved organic carbon, chlorophyll, nutrients, as measured from discrete water samples obtained during CTD casts). This will allow us to evaluate how accurately we can invert optical measurements to obtain biogeochemical parameters at the ALOHA site and provide a context to interpret the observed particulate and dissolved matter dynamics.

4. The Broader Context

In the environmental observing systems of the future fixed and mobile systems that can provide sustained time-series observations will be essential for research on phenomena ranging from earthquakes and ocean circulation patterns to changes in ecosystem and mineral resources. “Long-term nano- to global observations require sensing devices and systems that are persistent, robust, non-polluting, self-calibrating, and capable of distinguishing the desired signal from the background noise. Research on distributed, self-configuring environmental sensor networks … are … critical for advancing the development of observing systems" (Pfirman and the AC-ERE, 2003).

These statements lead naturally into the NSF Sensors and Sensor Networks program solicitation. With the proposed work, we will be "advancing fundamental knowledge about sensor networking systems in a distributed environment, the integration of sensors into engineered systems, and the interpretation and use of sensor data in decision-making processes" (NSF 03-512).

Ocean Observatories

How does our proposed work fit into oceanography programs in general and the ALOHA Observatory and HOT programs specifically? The recent NSF-sponsored report, *Ocean Sciences at the New Millennium* (Ocean Sciences Decadal Committee, 2001) and the NRC report, *Illuminating the Hidden Planet* (NRC, 2000), emphasize the need for long duration Eulerian observations and make a compelling scientific case for seafloor-based observatories. The challenge for acquiring sustained *in situ* observations is supplying the required power and two-way communications. For these and other reasons, NSF has undertaken the transformational Ocean Observatories Initiative (OOI; http://www.geo-prose.com/projects/ooi.html) with three elements: 1) a regional cabled plate-scale observatory, consisting of interconnected sites on the seafloor that span geological and oceanographic features and processes, 2) several tens of deep-sea observatories based around a system of buoys and seafloor nodes, and 3) an expanded network of coastal observatories (Clark, 2001). The Dynamics of Earth and Oceans Systems committee is advising NSF on the implementation of the OOI (DEOS, http://www.coreocean.org/deos).

Fixed, cabled observatories are acknowledged to be an essential complement to more traditional observing schemes. Examples include H2O (Petitt et al., 2002), LEO-15 (Schofield et al., 2002), the funded AO, and the planned NEPTUNE system (NEPTUNE Phase 1 Partners, 2000). See Edson et al., 2002, for a special issue of *IEEE Journal of Oceanic Engineering* on this topic. We must prepare the components of the sensor network so they are ready when the observatory infrastructure (e.g., the AO, "DEOS" buoys, and cabled systems VENUS, MARS, and NEPTUNE) is installed in 2004 and after.

HOT and the ALOHA Observatory

The HOT Station ALOHA (A Long-term Oligotrophic Habitat Assessment) has been supported by NSF under the JGOFS and WOCE programs, with approximately monthly ship-based sampling since October 1988 (Karl and Lukas, 1996; http://www.soest.hawaii.edu/HOT_WOCE). Significant responses of the water column physics, chemistry, and biology to episodic and climate variations have been observed and studied (Karl et al., 2001). HOT observations have provided fundamental insights into the functioning of the North Pacific subtropical gyre and its ecosystem, challenging some of the most closely held assumptions in ocean biogeochemistry.

These insights have led to new objectives for HOT including: 1) ***enhancing critical time series measurements with high frequency and spatial sampling***; 2) improving our understanding of critical physical and biogeochemical processes for improved predictive modeling capabilities; 3) identifying the most important variables (and their time and space scales) for sustained observations to quantify carbon cycling; 4) ***testing advanced sensors for measuring these variables and integrating them into observational systems***; and 5) testing advanced ocean analysis and prediction capabilities. ***HOT will evolve from the on-going intensive shipboard observational strategy to one that relies on continuous time series with less frequent shipboard work. The measurements will be made from moorings to provide critical time series, and using AUVs, gliders, tomography, and other platforms and techniques to provide essential spatial context. The availability of power and communications is crucial for this transformation.***

The goal of the NSF-funded ALOHA Observatory project is to establish cabled observatory infrastructure for the next generation of the HOT (http://kela.soest.hawaii.edu/ALOHA). The AO seafloor J-box will be deployed in late 2004; it will provide power to scientific equipment and 2WRT communication between sensors and scientists for at least the next ten years (1 kW and 100 Mb/s). Continuous measurements will then enable scientists and students to detect trends and episodic events that are not well observed by standard ship-based methods. AO is designed for maximum flexibility, with the ability to support a wide range of experiments, from simple listening devices to vertical arrays with ports for removable sensor systems. With the proposed mooring, observing systems from the deep ocean floor to the ocean surface will benefit from AO.

The AO will be an important part of NSF's contribution to the Integrated Ocean Observing System, providing sustained *in situ* observations of key ocean variables beyond temperature and salinity, and resolving shorter time and space scales than can be achieved by satellites and the Argo float array. It provides the co-located multivariate reference time series observations required by interdisciplinary scientific objectives (Send et al., 2001). In addition, AO will provide a high quality testbed for development of novel sensor technologies to observe key ocean variables, as proposed here.

The ALOHA Observatory with the sensor network development proposed here will help the HOT program attain the long-term goal of reducing cruise time by increasing the use of real-time onsite systems. The latter will enable modes of adaptive sampling that will allow investigators to view their subject in new and different ways. Further additions and extensions undoubtedly will include a winched profiler mounted on the subsurface float to sample the depth range 0–200 m, many more optical sensors, direct chemical and biological sampling, small-scale turbulence and mixing studies from the bottom boundary layer to the air-sea interface, and drifters, gliders, AUVs, and tomography to extend the HOT footprint, for instance. Our goal is to make it as easy as possible for new investigators to use the mooring sensor network and to be able to painlessly add their particular sensors (facilitated ultimately by ROV servicing capability of all components) and obtain the data and related information products in a seamless way. Then, with experience, we will be better able to judge long-term service issues and costs: how should we balance frequency of ship visits with calibration needs and sensor/platform reliability? As systems like this are envisioned in one form or another at many sites around the world, this will serve as a useful first case and a resource for the community.

References

Clark, H.L., 2001: New sea floor observatory networks in support of ocean science research, *Proceedings of the Oceans 2001 MTS/IEEE Conf., Honolulu, Hawaii, November 5–8*.

Cristianini, N. and J. Shawe-Taylor, 2000: An Introduction to Support Vector Machines and Other Kernel-Based Learning Methods. Cambridge University Press, Cambridge, UK, 189 pp.

Dekshenieks, M.M., P.L. Donaghay, J.M. Sullivan, J.E.B. Rines, T.R. Osborn, M.S. Twardowski. 2001: Temporal and Spatial Occurrence of Thin Phytoplankton Layers in Relation to Physical Processes. *Mar. Ecol. Prog. Ser*., 223, 61-71.

Edson, J. B., A. D. Chave, M. D. Dhanak, and F. D. Duennebier, 2002: Guest editorial on cabled Ocean observatories, *IEEE J. Ocean. Eng.*, 27, 145.

Finnigan, T.D., D.S. Luther and R. Lukas, 2002: Observations of enhanced diapycnal mixing near the Hawaiian Ridge. *J. Phys. Oceanogr*., 32, 2988-3002.

Franks, P.J.S. 1995: Thin layers of phytoplankton: a model of formation by near-inertial wave shear. *Deep-Sea Res. I*, 42, 75-91.

Garrett, C.J.R., and W.H. Munk, 1975: Space-time scales of internal waves: a progress report, *J. Geophys. Res*., 80, 291-297.

Hardwick, J.P., and Q.F. Stout, 1998: Flexible algorithms for creating and analyzing adaptive sampling procedures, in *New Developments and Applications in Experimental Design*, N. Flournoy, W.F. Rosenberger, and W.K.Wong, eds., Institute of Math. Stat. Lecture Notes – Monograph Series Vol. 34, 91–105.

Haykin, S., 1994: *Neural Networks, A Comprehensive Foundation*. Macmillan College Publishing Co., 696 pp.

Howe, B.M., H. Kirkham, and V. Vorpérian, 2002: Power system considerations for undersea observatories, *IEEE J. Ocean. Engr.*, **27**, 267-274.

Karl, D.M., and R. Lukas, 1996: The Hawaii Ocean Time-series (HOT) Program: Background, rationale and field implementation. *Deep-Sea Res. II*, 43, 129-156.

Karl, D.M., J.E. Dore, R. Lukas, A.F. Michaels, N.R. Bates and A. Knap, 2001: Building the long-term picture: The U.S. JGOFS time-series programs. *Oceanography*, 14, 6-17.

Kennan, S.C. and R. Lukas, 1996: Saline intrusions in the intermediate waters north of Oahu, Hawaii. *Deep-Sea Res. II*, 43, 215-241.

Kirkham, H., B.M. Howe, V. Vorpérian, and P. Bowerman, 2001: The design of the NEPTUNE power system, *Proceedings of the Oceans 2001 MTS/IEEE Conf., Honolulu, Hawaii, November 5–8*.

Kirkham, H., V. Vorpérian, and B.M. Howe, Parallel power for undersea application: The basic considerations, *SubOptic 2001, The Fourth International Convention on Undersea Communications, Kyoto, Japan, May 20–24*.

Letelier, R.M, D.M. Karl, M.R. Abbott, P. Flament, M. Freilich, R. Lukas and T. Strub, 2000: Role of late winter mesoscale events in the biogeochemical variability of the upper water column of the North Pacific Subtropical Gyre. *J. Geophys. Res*., 105, 28,723-28,740.

Lukas, R., 2001: Freshening of the upper thermocline in the North Pacific Subtropical Gyre associated with decadal changes of rainfall. *Geophys. Res. Lett*., 28, 3485-3488.

Lukas, R., 2003a: Variability of the T-S relationship observed in the Hawaii Ocean Time-series. (manuscript in preparation)

Lukas, R., 2003b: Mixed layer variability in the Hawaii Ocean Time-series. (manuscript in preparation for submission to *Deep-Sea Res*.)

Lukas, R. and D. Karl, 1999: *Hawaii Ocean Time-series (HOT): A Decade of Interdisciplinary Oceanography*. School of Ocean and Earth Science and Technology, U. Hawaii, Rept. SOEST-99-05, CD-ROM.

Lukas, R. and F. Santiago-Mandujano, 2001: Extreme water mass anomaly observed in the Hawaii Ocean Time-series. *Geophys. Res. Lett*., 28, 2931-2934.

Lukas, R., F. Santiago-Mandujano, F. Bingham and A. Mantyla, 2001: Cold bottom water events observed in the Hawaii Ocean time-series: Implications for vertical mixing. *Deep-Sea Res. I*, 48, 995-1021.

Lukas, R., F. Santiago-Mandujano, and L. Zamudio, 2003: Eddy transport of anomalous waters in the Hawaii Ocean Time-series. (manuscript in preparation for submission to *J. Geophys. Res*.)

Maffei, A.R., G. Massion, J. Bailey, A. Bradley, H. Frazier, A.D. Chave, S. N. White, S. Lerner; D. Yoerger; and R. Buddenberg, 2001: NEPTUNE Gigabit Ethernet Submarine Cable System, *Proceedings of the Oceans 2001 MTS/IEEE Conf., Honolulu, Hawaii, November 5–8*.

Merrifield, M.A., P.E. Holloway, and T.M.S. Johnston, 2001: The generation of internal tides at the Hawaiian Ridge. *Geophys. Res. Lett.*, 28, 559-562.

Moline, M.A., W.P. Bissett, S. Glenn, D. Haidvogel, and O. Schofield, 2000: An operational multi-scale real-time long-term ecosystem observatory (LEO-15) for the coastal ocean. *Ocean Optics XV*, Monte Carlo, Monaco, 7 pp.

National Research Council (NRC), 2000: *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science*, National Academy Press, Washington, D.C.

NEPTUNE Phase 1 Partners (University of Washington, Woods Hole Oceanographic Institution, Jet Propulsion Laboratory, Pacific Marine Environmental Laboratory), 2000: *Real-time, Long-term Ocean and Earth Studies at the Scale of a Tectonic Plate: NEPTUNE Feasibility Study* (prepared for the National Oceanographic Partnership Program), University of Washington, Seattle. See also http://www.neptune.washington.edu.

Ocean Sciences Decadal Committee, P. Brewer and T. Moore, co-chairs, 2001: *Ocean Sciences at the New Millenium*, University Corporation for Atmospheric Research.

Petitt, R., D.W. Harris, B. Wooding, J. Bailey, J. Jolly, E. Hobart, A.D. Chave, F.D. Duennebier, R. Butler, A. Bowen, and D. Yoerger, The Hawaii-2 observatory, *IEEE J. Ocean. Eng.*, **27**, 245-253, 2002.

Pfirman, S., and the AC-ERE, 2003: *Complex Environmental Systems: Synthesis for Earth, Life, and Society in the 21st Century*, National Science Foundation, Washington, D.C.

Schneider, K., C-C. Liu, T.M. McGinnis, B.M. Howe, and H. Kirkham, 2002: Real-Time Control and Protection of the NEPTUNE Power System, *Proceedings of the Oceans 2002 MTS/IEEE Conf.*, *Biloxi, MS*.

Schofield, O., T. Bergmann, P. Bissett, J. F. Grassle, D. B. Haidvogel, J. Kohut, M. Moline, and S. M. Glenn, 2002: The long-term ecosystem observatory: an integrated coastal observing system, *IEEE J. Ocean. Eng.*, 27, 146-154.

Send, U., R. Weller, S. Cunningham, C. Eriksen, T. Dickey, M. Kawabe, R. Lukas, M. McCartney, and S. Osterhuis, 2001: Oceanographic time series observatories. in *Observing the Ocean for Climate in the 21st Century*, C.J. Koblinsky and N.R. Smith, eds., Australian Bureau of Meteorology, 376-390.

Zamudio, L., A.P. Leonardi, S.D. Meyers, and J.J. O'Brien, 2001: ENSO and eddies on the southwest coast of Mexico. Geophys. *Res. Lett*. 28, 13-16.