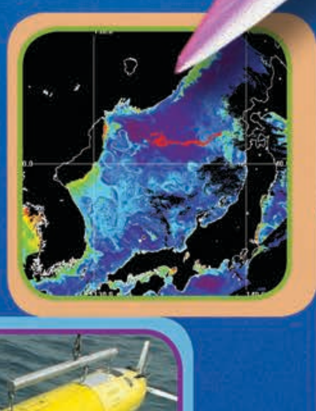
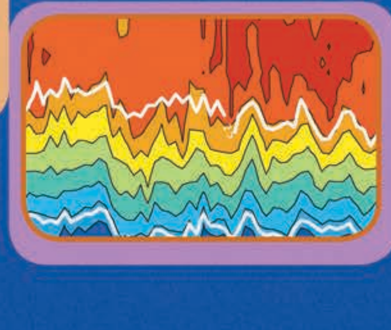
ALPS

Autonomous and Lagrangian Platforms and Sensors

A Report of the Workshop
Held March 31 - April 2, 2003
in La Jolla, California





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Organizing Committee

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Executive Summary

Background

During the last decade, oceanography has witnessed a revolution in observing capabilities as autonomous platforms, and the sensors they carry, have developed and rapidly matured. Numerous deployments of autonomous and Lagrangian platforms and sensors (ALPS) have demonstrated the power and potential of these integrated sensing systems to study ocean physics, biology, chemistry, and geology. The unique capability of ALPS to make sustained ocean observations and to execute experiments that test specific hypotheses has been noted in all of the National Science Foundation (NSF)-sponsored disciplinary and interdisciplinary reports on the future of oceanography.

What are ALPS?

The ALPS platforms are characterized as "autonomous" because they operate without tethers to ships or the seafloor. These platforms include Lagrangian surface drifters, neutrally buoyant and profiling floats, highly controllable self-propelled autonomous underwater vehicles (AUVs), and underwater gliders. The sensors integrated into ALPS are, of necessity, small, robust, and able to sample at high frequency. The present suite of sensors measures a diversity of variables, including temperature, salinity, particle concentration, current velocity, oxygen, and images of seafloor topography; new sensors continue to expand ALPS' measurement capabilities. The data collected by ALPS are typically transmitted by wireless communication to the laboratory. Many platforms have two-way communication systems that allow them to receive instructions to change sampling protocol or location during the mission, making them even more flexible sampling platforms.

Why are ALPS needed?

The fundamental observational problem in oceanography is that of sampling a global, turbulent fluid with physical, biological, and chemical processes that are active over a wide range of scales. ALPS provide a unique solution to this sampling problem in that they are scalable to the process of interest, and easily portable to relevant, possibly remote, locations. ALPS can support scientific questions related to climate change that require long-term observations on a global scale, as well as questions that require short-term observations in a local area, such as the evolution of harmful algal blooms. Adaptable networks of ALPS efficiently provide the essential spatial and temporal coverage to complement data collected with ships, fixed observatories, and satellites.

The ALPS Workshop

Because of the rapidly evolving nature of ALPS, no organized plan existed that laid out a blueprint for enabling these opportunities or the mechanisms for providing broad community access. In spring 2003, the ALPS workshop brought together 50 participants representing a wide diversity of ocean scientists and engineers to initiate a plan. Issues addressed at the ALPS workshop included current capabilities of ALPS; scientific questions that could be uniquely addressed by ALPS alone and in conjunction with other sampling modes such as ships, cabled observatories, and satellites; technological developments needed to develop even more-capable sensors and platforms; mechanisms for enabling broader community access; and needs for training and education. The complete set of white papers and presentations can be found on the ALPS web site (www.geo-prose.com/ALPS).

Recommendations

1. Although individual ALPS are relatively inexpensive, with limited lifetimes, ALPS networks and technical support must be regarded as permanent infrastructure and funded as such.
2. A group of technology innovators and scientific users should be formed to develop an implementation plan and to ensure broad community participation (some examples of implementation approaches are given in the section on *Enabling Activities*).
3. Sustained development of platforms and sensors should continue—within the context of meaningful scientific goals—to create even more-capable platforms and sensors (specific recommendations are given in the section on *Future Platforms and Sensors*).
4. Existing platforms and sensors should be combined, with relatively little additional engineering, to create new observational systems targeted at important scientific questions (examples of specific questions are given in the section on *Science Issues*).
5. A mechanism for supporting pilot projects should be established to foster the use of ALPS technologies to address important interdisciplinary problems.
6. Workshops, short courses, training programs, and fellowships are needed to address the critical shortage of trained engineers and scientists who are needed to develop and support ALPS infrastructure.

The ALPS workshop and the following report are the first steps toward enabling all oceanographers to share in the major technological advances that ALPS has made possible and to participate in the coordinated development of ALPS science and technology.

Introduction

Oceanography is a fundamentally observational science. Almost all newly discovered phenomena have been observed before they were predicted. As Henry Stommel (1989) wrote, "The chief source of ideas in oceanography comes, I think, from new observations." Every time we look at the ocean in a new way, we learn something new about how it works.

The last decade has witnessed a revolution in autonomous, ocean-observing capabilities as new platforms and sensors have developed, and rapidly matured. The new generation of oceanographic platforms has been characterized as "autonomous" because the platforms operate—tracking water masses, recording oceanographic properties, and transmitting data home via satellite telemetry—without a tether to either the seafloor or a ship. Autonomous platforms are diverse in their mechanisms and rates of motion; mission payloads, ranges, and durations; and capabilities to change sampling parameters during a mission either by receiving commands from home or by using on-board, decision-making tools. The platforms encompass Lagrangian surface drifters, neutrally buoyant and profiling floats, highly controllable self-propelled AUVs, and underwater gliders that adjust their buoyancy to glide forward through the ocean in a saw-tooth pattern. Each platform genre has its own optimum sampling domain, capability to incorporate sensors, and unique potential to contribute to sustained observation of the ocean.

Parallel to the evolution of autonomous platforms has been the revolution in new sensing systems for biological, chemical, and optical properties. The new sensors are small but robust, stingy power consumers that sample fast enough to resolve biogeochemical parameters on the same space and time scales as physical properties. Wireless communication allows all of these data to arrive at oceanographers' desktops, and be posted on the Web, within hours of collection. The combination of autonomous and Lagrangian platforms and sensors (ALPS) has ushered in a new era of sampling that is truly interdisciplinary in character and shows great promise for contributing to major advances in our understanding of ocean processes.

The terms **Lagrangian** and **Eulerian** describe different frames of reference for specifying or observing fluid properties. An Eulerian specification of a fluid property is a function of space and time. The Eulerian frame of reference is probably most familiar to people; we stand on the shore and watch the river flow by us. A Lagrangian specification is a function of an identifiable piece of fluid and time. The Lagrangian frame of reference moves with the fluid; we sit in an inner tube and float down the river.

Moorings are the most common Eulerian platforms in oceanography. Floats and drifters are the classic Lagrangian platforms. But no platforms are perfectly Eulerian or Lagrangian. Instruments on mooring lines are not perfectly fixed. Floats and drifters do not exactly follow fluid parcels. Gliders and AUVs are neither strictly Eulerian nor Lagrangian, as they move independently of the flow. Their data are usually interpreted in an Eulerian sense in that the measurements are at a sequence of locations and times.

The overarching observational problem in oceanography is that of sampling. The ocean is a global turbulent fluid, with a range of spatial scales from the size of ocean basins down to microscales at which turbulent dissipation occurs. The longest temporal scales that can be dealt with using direct observations are decadal, while the shortest of interest are no longer than seconds. The observational problem would be difficult enough if the ocean were linear, so that measurements at a single scale would be sufficient to understand that scale. However, the ocean is nonlinear, so that the evolution at any one scale is formally dependent on all other scales. The sampling problem has held the attention of oceanographers for decades. The explosion of new platforms and sensors will offer limitless new approaches to sampling design.

If sampling is the problem, the solution is to get observations on the appropriate time and space scales. Observations of the general circulation must be made on a global scale. Studies of mesoscale biophysical interactions must be done on the scales of eddies. In essence, we need observational systems that are "scalable" to the processes of interest (Perry and Rudnick, 2003).

Many phenomena in the ocean, such as storms and algal blooms, are intermittent in time and localized in space. Further, many processes are regional in nature, and the mix of relevant processes vary from place to place. For example, upwelling, river outflows, and mesoscale eddies are important components of coastal circulation, but their relative importance is different off the coast of Oregon than off the coast of New Jersey. Thus we need observational systems that are "portable" to the relevant locations and matched to the important processes.

ALPS are uniquely scalable and portable, making them perfectly suited to the major sampling problems facing oceanographers. The scalability and portability of ALPS are featured in the discussion of important science questions to follow. ALPS are being used to study general circulation and turbulent biophysical interactions. ALPS have been deployed in the path of hurricanes, and in algal blooms. The growth of ALPS is inevitable, with applications for observations and hypothesis-testing that we can anticipate now, and others we cannot yet imagine.

ALPS are notable for their inclusion in every organized vision of the future of oceanography. The most comprehensive evaluation of the current and future state of oceanography was presented in the NSF-sponsored disciplinary reports: T*he Future of Physical Oceanography* (Royer and Young, 1999), *The Future of Ocean Chemistry in the U.S.* (Mayer and Druffel, 1999), and *Ocean Ecology: Understanding and Vision for Research* (Jumars and Hays, 1999). This series of reports culminated with the publication of *Ocean Sciences at the New Millennium* (Brewer and Moore, 2001), which made clear the interdisciplinary nature of almost every important problem. To quote from the latter publication: "The profound impact of new technologies for executing novel experiments and for capturing new data from the ocean is a theme that runs throughout this report. Their success justifies a vigorous effort in technology development, implementation and support in all areas of ocean science." One of the report's recommendations was to deploy a variety of observational systems including ALPS. Similar passages can be found in any of the disciplinary reports, indicating remarkable agreement across oceanography about the importance of ALPS.

Autonomous sampling has a prominent role in ocean observing plans for the open and coastal ocean. At the CoOP Observatory Science Workshop (Janke et al, 2002), ALPS were seen as an essential part of any observing system, especially for such processes as blooms that have relatively small time and space scales. At an Ocean.US workshop held in March 2002 (Ocean.US, 2002), to develop a national plan for a sustained ocean observing system, gliders were highlighted as a mechanism for providing routine observations of the coastal ocean and as a basis for interpolating the data collected at permanent mooring sites. The community has recognized the need for ALPS in any ocean observing system.

The ALPS Workshop

Because ALPS technologies are rapidly evolving, no plan existed for coordinated development and broad community access to these new systems. During March 31 - April 2, 2003, the ALPS Workshop brought 50 participants (Appendix 1) together in La Jolla, California, under NSF and ONR (Office of Naval Research) sponsorship, to develop a national plan describing the scientific questions that could be uniquely addressed by ALPS alone and in conjunction with other sampling modes such as ships and cabled observatories; technological developments needed to develop even more capable sensors and platforms; mechanisms for enabling broader community access; and needs for training and education.

The first day of the ALPS workshop was devoted to a series of overview talks on platforms and sensors. The talks were as follows:

- Surface Drifters – Peter Niiler
- Floats – Russ Davis
- Autonomous Underwater Vehicles – Chris Von Alt
- Gliders – Charlie Eriksen
- Optical Sensors – Mary Jane Perry
- Acoustic Sensors – Tim Stanton
- Chemical Sensors – Ken Johnson
- Molecular Sensors – Chris Scholin
- Microsystems Technology – Rosemary Smith

The discussion that follows on *Platforms and Sensors* summarizes some of the material in the talks. Complete white papers and presentations can be found on the ALPS web site (www.geo-prose.com/ALPS).

On the second day, workshop participants were divided into four parallel working groups, each consisting of physical, biological, and chemical oceanographers, and platform and sensor specialists. The four working groups had three sessions to:

1. Identify major science questions best addressed by ALPS, alone and in conjunction with other observational systems.
2. Identify needs for more capable platforms and sensors.
3. Propose models to advance technology and to enable the community's broader access to ALPS.

The parallel working groups permitted a diversity of ideas to be discussed, and made clear the areas of broad agreement.

The final day of the workshop allowed for a summary of results, and initial organization of this report. The report, a group effort of the workshop participants, tells of the successes of ALPS to date, and the possibilities for the future. ALPS must be a major component of the nation's ocean-observing strategy. The ALPS workshop and report is only the first step in making this happen.

References

Brewer, P. and T. Moore, 2001, *Ocean Sciences at the New Millennium*, UCAR/JOSS, 151 pp.

Janke, R., L. Atkinson, J. Barth, F. Chavez, K. Daly, J. Edson, P. Franks, J. O'Donnell, and O. Schofield, 2002, *Coastal Ocean Processes and Observatories: Advancing Coastal Research, Report on the CoOP Observatory Science Workshop*, May 7-9, 2002, Savannah, Georgia, Coastal Ocean Processes (CoOP) Report No. 8, November, 2002, Skidaway Institute of Oceanography Technical Report TR-02-01.

Jumars, P. and M. Hays, eds., 1999, *Report of the OEUVRE Workshop, Keystone, Colorado, March 1-6, 1998, Ocean Ecology: Understanding and Vision for Research*, UCAR/JOSS, 66 pp.

Mayer, L. and E. Druffel, eds.,1999, *Report of the FOCUS Workshop, Seabrook Island, South Carolina, January 6-9, 1998, The Future of Ocean Chemistry in the U.S.*, UCAR/JOSS, 151 pp.

Ocean.US, 2002, *Building Consensus: Toward a U.S. Plan for an Integrated and Sustained Ocean Observing System (IOOS)*, Ocean.US, Arlington, VA, 175 pp.

Perry, M.J., and D.L. Rudnick, 2003, Observing the Ocean with Autonomous and Lagrangian Platforms and Sensors: the Role of ALPS in Sustained Ocean Observing Systems, *Oceanography*, 16 (4), 31-36.

Royer, T and W. Young, eds., 1999, *Report of the APROPOS Workshop, Monterey, California, December 15-17, 1997, The Future of Physical Oceanography*, UCAR/JOSS, 178 pp.

Stommel, H., 1989, Why we are oceanographers, *Oceanography*, 2, 48-54.

EVOLUTION OF PLATFORMS AND SENSORS

Platforms

An impressive diversity of autonomous ocean sensor platforms exists (Table 1). Lagrangian drifters, perhaps the oldest technique of ocean measurement, float at the surface, although they may be drogued to follow water at shallow depths. Neutrally buoyant floats follow subsurface currents by being ballasted for a predetermined depth, or by actively adjusting buoyancy. To move horizontally through the water, underwater gliders profile vertically by adjusting buoyancy and steering. Autonomous underwater vehicles (AUVs) are highly controllable platforms that power themselves through the water. The ability of these platforms to operate independent of ships or land and for long durations promises a new age of ocean discovery.

Surface Drifters

Lagrangian techniques probably comprised the first observations of ocean flow, with scientific publication as far back as Benjamin Franklin's (1785) work using buoys and drogues. Systematic observations of drift continued with the *Challenger* Expedition in 1872 where iron "watch buoys" were tethered with cod line to sea anchors at various depths at most of the 354 stations occupied around the globe (Thompson, 1877). Over 150 years later, Langmuir (1938) used a variety of Lagrangian devices (leaves, corks, and surface floats with light bulbs for flotation and umbrellas for drogues) in the first description of the circulation cells bearing his name. With the advent of satellite communication in the early 1970s came a

Table 1.

Platform	Mode of Operation	Typical Deployment Duration	Spatial Scales	Sensor Payload
Surface Drifter	Floats on surface, sometimes drogued at depth	Weeks to years	Regional to global	Moderate, power-limited
Float	Neutrally buoyant, sometimes profiling	Weeks to years	Regional to global	Moderate, power-limited
Glider	Profiles, controls horizontal position by gliding	Weeks to months	Regional	Light, power and size-limited
Autonomous Underwater Vehicle (AUV)	Powered horizontally through water, e.g., by propeller	Hours to days	Local	Heavy

Figure 1. Preparing to deploy a Surface Velocity Programme (SVP) drifter in the Bering Sea . One of the goals of this drifter program was to demonstrate that drifters could be economically deployed by lay persons, in this case by villagers in a remote Alaskan community. SVP drifters move with the current at 10 m depth. From http://www.ims.uaf.edu:8000/NPRBdrifters. Photo by Larson King.

rapid increase of the use of drifters for transmitting data from *in situ* sensors via satellite. Many different floats (spars, boats, pill boxes, cylinders, garbage cans, inverted cones) were attached with various tethers (ropes, chains, wires, electrical cables, Kevlar®, bungee cord) to various drogues (parachutes, weather socks, window shades, butterflies, corner radar reflectors, holey socks, cruciforms). Systematic evaluations of the different designs, done in the 1980s, concluded that the key to accurate water-following was to increase the ratio of drogue to float size.

In the open ocean, the Surface Velocity Programme (SVP) drifter has a spherical plastic float, a wire tether, a holey sock drogue, and battery power sufficient for two years of operation (Figure 1). The SVP drifter can carry sensors that measure temperature and salinity, wind direction, ambient sound (for calculating wind speed and rain rate), upwelling light, and atmospheric pressure. ARGOS satellite receptions vary from 6 to 14 per day, depending on latitude and storm conditions. About 7500 SVP drifters have been deployed since 1988.

A drifter originally developed for the Coastal Ocean Dynamics Experiment in the 1980s has seen largest use in coastal and marginal sea deployments. It can be deployed from a small plane, helicopter, or boat. Location is by GPS or ARGOS. Data transmission is to ARGOS or a local paging system on land. Two types are manufactured, one with a spherical float and a radar corner reflector drogue, the other with a cruciform drogue with four small floats (Figure 2). Temperature and salinity sensors have been placed on these drifters. A power recharging option is available, making them re-deployable after recovery. About 2500 drifters of this type have been deployed in the past 10 years.

Neutrally Buoyant Floats

The initial impetus for neutrally buoyant floats was measuring subsurface currents, particularly the deep interior flows once believed to be too slow to be measured by mechanical current meters (Stommel, 1955). John Swallow (1955) devised the first successful floats by chemically

Figure 2. Coastal Ocean Dynamics Experiment (CODE) drifters follow the top meter of the surface ocean, where they respond to the instantaneous wind forcing. The small ball floats help keep the drifter upright and the currents push the "X" shape through the water. The GPS receiver and satellite transmitter antennas are sticking up from the top of the drifter. From http://www.ims.uaf.edu/NPRBdrifters/planview/code.html, courtesy of Technocean, Inc.

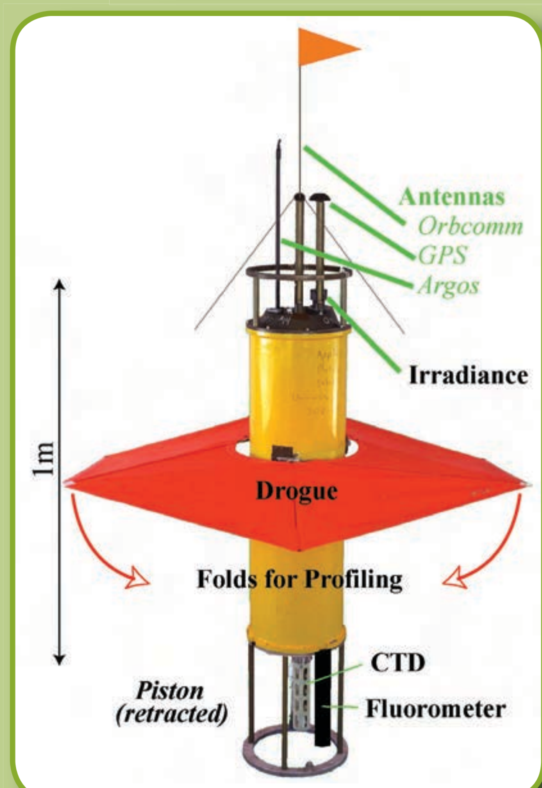


Figure 3. Top: Steve Riser holds a RAFOS float that was tracked for two years in the Kuroshio current and recovered in Hawaii after drifting for seven years. Bottom: A truly Lagrangian float that uses a combination of active buoyancy and drag to follow vertical velocity. It is used to observe vertical mixed layer velocities in convection currents and hurricanes . Bottom figure courtesy of Eric D'Asaro, University of Washington.

etching aluminum tubing, intended for scaffolding, to produce a pressure case that was light enough to be neutrally buoyant yet strong enough to withstand deep ocean pressures. Swallow floats, which produced the first observations of energetic mesoscale flows, provide an excellent example of observations that resulted in a fundamental change in our understanding of the ocean. Tracking of subsurface floats improved through use of the ocean's sound channel, and SOFAR floats became the standard during the 1970s. Development of the RAFOS (SOFAR backwards) float by Rossby et al. (1986) made basin-scale acoustic tracking tremendously more practical by replacing giant SOFAR floats with small, neutrally buoyant floats that functioned as listening stations (Figure 3, top). Autonomous profiling floats, which periodically surface for satellite locating and data relay, were developed (Davis et al., 1992) to make possible global float coverage without the need for an acoustic tracking network.

An impressive array of floats are in use today, carrying a wide range of sensors that measure physical, biological, and chemical variables (Figure 3, bottom). Fundamental to all floats is the measurement of velocity by tracking the float's position over time. The tracking method interestingly affects the character of the velocity measurements. For example, acoustically tracked floats remain at depth, so their trajectories may be finely resolved and very nearly Lagrangian. Profiling floats must surface to be tracked, interrupting current following, so that velocity records are properly viewed as a series of displacements rather than a Lagrangian trajectory. However, profiling floats offer the opportunity to measure properties in the water column during ascents and descents. In addition to the physical variables of temperature, salinity, and pressure, measured variables have included such optical quantities as downwelling light, fluorescence, and beam attenuation. Because floats provide a very stable platform, observations of turbulent microstructure have been successful. Floats are excellent platforms for observing vertical velocity, which is notoriously difficult to measure in the ocean, either by attaching a large drogue to promote water-following, or by attaching propeller blades to measure relative vertical water motion.

Underwater Gliders

The concept of a fleet of unmanned underwater gliders patrolling the world's oceans was put forward by Henry Stommel in 1989. Stommel's vision is becoming a reality today as gliders are being developed into formidable oceanographic tools. Gliders build on the concept of profiling floats by adding wings for horizontal propulsion and the ability to steer (e.g., Figure 4). As with all autonomous profilers, gliders move vertically by controlling buoyancy. The addition of wings allows horizontal movement in a similar manner to gliders in the air. Steering is accomplished with rudders, or by internally adjusting the glider's center of mass, much as a hang glider.

Ocean-going gliders are entirely autonomous, yet their operation can be controlled via two-way telemetry. Given a set of mission parameters, gliders follow them until they are changed, reporting data as often as they surface. Following a sequence of waypoints produces a section survey. Homing on a single target while close to it results in a 'virtual mooring' mode of sampling, where a glider may maintain geographic position as well as instruments on a mooring line. Gliders can operate in either survey or mooring mode during the same mission through remote control.

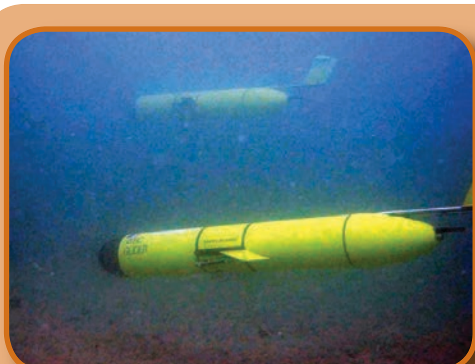


Figure 4. Two Webb Slocum gliders flying off the west coast of Florida during a red tide in January 2003. The research associated with these gliders (NSF-supported program called Operation Gulfcast) grew out of the EcoHab and ONR HyCODE programs. In the coming years, the hope is that gliders will become a routine monitoring tool for red tides in the Gulf of Mexico. See case study on p. 33 for more information. Photo courtesy of Oscar Schofield, Rutgers University.

Gliders are a technology still in development, with fully operational use in its infancy. But there have been significant successes to date. The first ten-day missions were completed in 1999. A fleet of three gliders completed a sequence of sections in Monterey Bay in 2000. In 2001, a glider made a nearly 300 km section off of San Diego. A glider successfully completed over 1000 km of repeated sections off the Washington coast in 2002 (see case study on p. 31). During the summer of 2003, fleets composed of 15 gliders operated for over a month in Monterey Bay in the most comprehensive demonstration of glider capabilities thus far.

Sensors deployed on gliders must be low power and small to minimize effects on glider hydrodynamic drag. Within these constraints, an impressive range of sensors have been deployed. Standard on gliders are sensors to measure temperature, salinity, and pressure. A depth-average velocity can be estimated using dead reckoning between profiles. Acoustic velocity sensors can be mounted on gliders, an advance currently under development. The optical quantities of fluorescence and backscatter have been measured from gliders. Oxygen sensors have been successfully deployed on gliders. The coming years will see increasing operational use of gliders, and a proliferation of attached sensors.

Autonomous Underwater Vehicles

An autonomous underwater vehicle (AUV) is driven through the water by a propulsion system and maneuverable in three dimensions (Figure 5). The origin of AUVs should probably be linked to the Whitehead Automobile "Fish" Torpedo. Robert Whitehead is credited with designing, building, and demonstrating the first Torpedo in Austria in 1866, achieving a speed of over 3 m/s over a distance of 700 m. The need to obtain oceanographic data along precise trajectories and under ice motivated Stan Murphy, Bob Francis, and later Terry Ewart to begin

Figure 5. REMUS AUVs configured with forward-looking, high-resolution sonar, a sidescan sonar, acoustic communication, and various other environmental sensors. AUVS such as these have proven especially useful in coastal surveys of bathymetry, currents, and water properties. Photo courtesy of Chris von Alt, Woods Hole Oceanographic Institution.

development of what may have been first "true" AUV in the late 1950s. The Self Propelled Underwater Research Vehicle, SPURV, became operational in the early 1960s and supported research efforts through the mid 1970s. SPURV could operate at 2.2 m/s for 5.5 hours at depths to 3 km. In the intervening decades, a number of different AUVs have been developed and operated successfully in a wide range of applications from coastal to deep ocean (Griffiths, 2002).

Because AUVs are powered, they are the most controllable of autonomous platforms. AUVs may be programmed to swim at a constant pressure or altitude, or to vary their depth and/or heading as they move through the water to complete undulating survey patterns covering both vertical and horizontal swaths. AUVs provide a highly productive means of performing seafloor surveys using acoustic or optical imaging systems. Sensor power is generally abundant on an AUV because of a relatively short deployment time on the order of hours or days. All manner of physical, optical, acoustical, and chemical sensors have been used on AUVs. With a typical vehicle speed of near 1.5 m/s, AUVs are especially effective for rapid surveys in evolving coastal regimes. For example, AUVs may be particularly useful for following plumes of a contaminant or an algal bloom near the shore.

Sensors

The natural evolution of most oceanographic sensors has been reduction in size without reduction in capability. Because most autonomous platforms described above have restricted space and limited battery capacity available for allocation to sensors, "small" is mandatory. A number of sensors that measure biological, chemical, optical, and physical properties of the water column, as well as gather information about the seafloor, have met these stringent space and power criteria and are now integrated into the full array of autonomous platforms. Temperature and salinity sensors were among the first sensors to be incorporated, followed by optical and acoustic sensors. Chemical sensing is on the brink of major advances in technology that will enable more routine incorporation into all platforms. The new integrated sensing systems, comprising sensors and platforms, are revolutionizing the way we study the ocean.

Optical Sensors

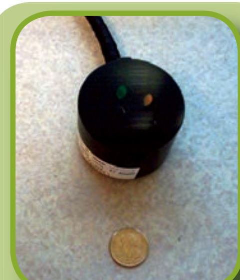
The history of optical observations and measurements of ocean color dates back at least as far as Aristotle, who speculated on the underlying reasons for the regional differences in ocean color he observed by eye. Today, the most common oceanographic applications of optics, aside from laser communications systems, are radiometric measurements in the visible wavebands and individual particle imaging. The small size and modest power consumption of radiometric sensors make them compatible with most autonomous and Lagrangian platforms, in contrast to the bulkier imaging systems that are presently incompatible with all but the largest AUVs. Flow cytometers that measure light scatter and pigment fluorescence of individual particles have been deployed on larger platforms (*Autosub*, p. 45) to quantify numbers and size distributions of phytoplankton and other particles.

Radiometric sensors include both passive and active systems; the nomenclature is based on whether the light source is independent of the sensor (i.e., the sun serves as the light source for most passive sensors) or is an integral component of the system (i.e., a LED or lamp for an active sensor). Passive sensors measure apparent optical properties such as upwelling and downwelling radiance, diffuse attenuation coefficient, solar-stimulated fluorescence, and bioluminescence. Active sensors measure inherent optical properties (absorption, scattering, and attenuation coefficients) and fluorescence. Because passive sensors depend on sunlight as the light source, they consume less power than the active sensors but cannot operate at night or below the photic zone. In contrast, active sensors can operate at night and below the photic zone (Figure 6), making it possible to detect phenomena such as diel changes in particle concentration, sinking phytoplankton aggregations, and detached nepheloid layers. Active sensors also can measure optical properties at wavelengths that have reduced penetration below the oceans surface, such as UV and infrared wavelengths. The higher power consumption associated with the operation of an internal light is a drawback of active sensors, particularly for extended deployments. Although biofouling remains a major problem for all optical sensors, experience from long-term moorings of optical sensors suggests that copper tubing and shutters can reduce biofouling. For deep-cycling gliders and profiling floats, the reduction of time spent at the surface may be the most effective strategy to retard biofouling.

Optical properties serve as proxies for important biogeochemical variables in the ocean, primarily dissolved organic materials and marine particles including phytoplankton, biogenic calcium carbonate, and suspended sediments. Radiometric optical sensing is maturing rapidly and a number of optical sensors have already been incorporated into every type of autonomous and Lagrangian platform, enabling measurement of biogeochemical entities on the same space and time scale as physical measurements. Radiometric optical sensors offer the potential for resolving responses of the carbon cycle to climatic changes in mixed layer processes, for providing a vertical dimension to surface phytoplankton and other particle fields derived from satellite ocean color imagery, and for detecting harmful algal blooms.

Physical Sensors

Temperature probes have served well as the workhorses of physical oceanography. Their small size enables them to be integrated into the smallest platforms. In recent years salinity probes have been reduced in size, although pumping water through the sensor is often necessary to attain higher accuracies. The microstructure sensors in current use are fast-responding thermistors (Gregg, 1977) and airfoil shear probes (Osborn, 1974). Both types have been implemented successfully in propeller-driven



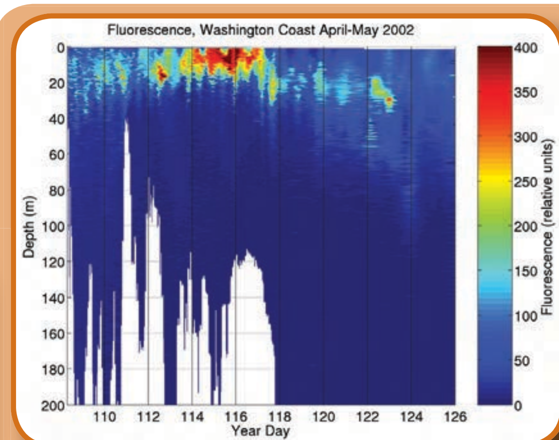


Figure 6. Chlorophyll fluorescence, a proxy for phytoplankton biomass, was measured off the Washington coast by a Seaglider instrumented with a bb2f fluorometer/scatter sensor (quarter for scale). In April 2002, Seaglider was launched at the mouth of the Straits of Juan de Fuca and recovered in deep waters off shore. Chlorophyll fluorescence is plotted as a function of time of day, rather than distance from shore, to resolve midday solar quenching of chlorophyll fluorescence near the surface. Active optical sensing allows phytoplankton biomass to be measured at night and below the euphotic zone. Autonomous platforms provide information on the vertical distribution of phytoplankton biomass—information that is missing from ocean color satellite remote sensing. By combining glider and satellite data, a more accurate assessment of total water column phytoplankton biomass and rates of carbon fixation can be determined. Data courtesy of Mary Jane Perry, University of Maine, and Charlie Eriksen, University of Washington.

platforms and the former has been incorporated into autonomous profiling floats (Sherman and Davis, 1995). The frequency response of the most popular thermistor (Thermometric FastTip FP07) is not fast enough to resolve turbulent temperature variance (TTV) dissipation rate for typical cruising speeds (~ 1-2 m/s) of propeller driven vehicles; however, a new capillary micro-conductivity sensor (Dillon et al., 2003) can resolve TTV dissipation rates at vehicle speeds as high as 4 m/s, making it suitable for propeller driven platforms. Thermocouples can also be adapted to fast moving platforms, since their frequency response exceeds 100 Hz (Nash et al., 1999). The relatively high noise level (~10^{-8} W/kg) of shear probes can be a major limitation in measuring turbulent kinetic energy (TKE) dissipation rate, especially in regions where turbulence mixing is weak (e.g., major parts of the Arctic Ocean) unless vibrations resulting from propeller motions are decoupled from probe mountings. All the turbulence sensors are suitable for the slowly moving gliders and floats because they do not generate significant noise compared to propeller-driven vehicles.

Acoustic Sensors

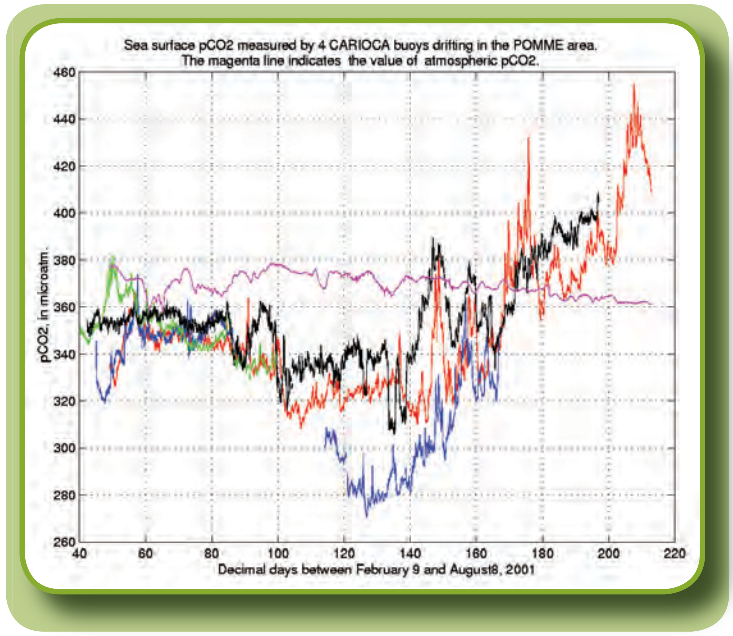
Acoustic signals can travel great distances in the ocean and are useful in a wide range of scientific applications, as well as for underwater wireless communications, including tracking of RAFOS floats (Medwin and Clay, 1998). One of the earliest recorded observations of sound transmission in the ocean was made by Leonardo da Vinci in the late 1400s. Acoustic sensing systems are characterized as passive or active, depending on whether the sensor system only listens to a signal or whether it also generates and transmits a signal. There are many natural sources of sound in the ocean, including raindrops, breaking waves, and cetacean communication; cavitation from ship propellers is also a significant source of sound. Depending upon the wavelengths used in active acoustic sensing, the targets of interest include the seafloor and suspended sediments, organisms ranging in size from small zooplankton to large fish, physical microstructure, and bubbles. Quantitative interpretation of acoustic signals is often a challenge, requiring the use of multiple frequencies to reduce ambiguity. In addition to the strength of the backscattered signal, its Doppler shift is used to measure the velocity and direction of currents.

The most common sensors are piezoelectric ceramics that are used singly to form an acoustic beam or in arrays, such as in multibeam systems. Ceramics have efficiencies of better than 50%, but the drawback is their weight, particularly at the lower frequencies and the narrow range of frequencies. Other technologies have been developed, such as broadband piezoelectric films, although many of these technologies can only be used as receivers. Active acoustic sensors have been deployed on AUVs to provide high-resolution maps of the seafloor, zooplankton, fish, and the underside of sea ice.

Chemical Sensors

Chemical sensors have not yet been routinely deployed on autonomous platforms, although there are a few notable exceptions. Commercially available electrochemical sensor systems for methane have been used on AUVs and tethered remotely operated vehicles (ROVs) to map methane generated by decomposing methane hydrates on the seafloor. Oxygen electrodes for gas exchange and biological production have been used on gliders and AUVs, and are being incorporated into profiling floats on a demonstrational basis. Manganese has been measured on *Autosub* as an indicator of redox conditions in hypoxic waters. The CARIOCA (CARbon Interface OCean Atmosphere) system of drifting buoys includes a measurement of CO_2 fugacity and has been deployed on for extended periods in the equatorial and Northeast Atlantic and Southern Ocean (Figure 7). Long-term observations of particulate organic carbon (POC) have been made on profiling floats in the North Pacific, based on optical transmission of light and a correlation between beam attenuation and POC in the open ocean. *In situ* mass spectrometers, although they presently have high power requirements (~100 W), have been deployed on

Figure 7. The goal of the CARIOCA (CARbon Interface Ocean Atmosphere) buoy is to improve quantitatively our knowledge of the spatial and temporal variability of CO_2 gas exchanged at the ocean-atmosphere interface. The quantities necessary to compute the air-sea flux are wind speed, sea surface temperature, and the gradient of partial pressure of CO_2 between the sea surface and the atmosphere. The CARIOCA buoys obtain simultaneous measurements of these parameters. A special effort has also been made to measure the quantities that control the distribution and the variability of pCO_2 at the sea surface, including: pCO_2 at a depth of 2 m; wind speed, sea surface temperature and salinity; fluorescence; and atmospheric pressure. In this figure are shown data from four CARIOCA drifters, launched during the 2001 French field program POMME in the Northeast Atlantic. The magenta line indicates the values of atmospheric pCO_2. The other curves show the time and space variability of pCO_2 in the ocean. A large inhomogeneity of the distribution of pCO_2 is observed over an area of 800 km x 1000 km, mainly during the months of April and May when biological processes are very active. Figure courtesy of Liliane Merlivat, Laboratoire d'Oceanographie Dynamique et de Climatologie, Paris, France.



AUVs for short periods of time to detect volatile gasses. Successful long-term mooring deployments of dissolved gases sensors, components of the carbon system, and nitrate analyzers demonstrate the evolution of chemical sensors toward autonomy. The rewards of extensive efforts to design robust sensors will soon yield a sufficient diversity of autonomous sensors to make *in situ* biogeochemical observations a major part of ALPS-based studies.

References

Davis, R. E., D. C. Webb, L. A. Regier, and J. Dufour, 1992, The Autonomous Lagrangian Circulation Explorer (ALACE). *J. Atmos. Oceanic Technol.*, 9, 264-285.

Dillon, T. M., J. A. Barth, A. Y. Eurofeev, G. H. May, and H. W. Wijesekera, 2003, MicroSoar: A new instrument for measuring microscale turbulence from rapidly moving submerged platforms, *J. Atmos. Ocean. Tech.*, 20, 1671-1684.

Franklin, B., 1785, Sundry marine observations. *Trans. Am. Philos. Soc.*, Ser. 1, 2, 294-329.

Gregg, M. C., 1977, Variations in the intensity of small-scale mixing in the main thermocline, *J. Phys. Oceanogr.*, 7, 436-454.

Griffiths, G., (editor), 2002, The technology and applications of underwater vehicles, Taylor and Francis, London, 342 pp.

Langmuir, I., 1938, Surface motion of water induced by wind, *Science*, 87, 119-123.

Medwin, H. and C.S. Clay, 1998, *Fundamentals of Acoustic Oceanography*, Academic Press, Boston.

Nash, J. D., D. R. Caldwell, M. J. Zelman, and J. N. Moum, 1999, A thermocouple probe for high-speed temperature measurement in the ocean, *J. Atmos. Ocean. Tech.*, 16, 1474-1482.

Osborn, T. R., 1974, Vertical profiling of velocity microstructure, *J. Phys. Oceanogr.*, 4, 109-115.

Sherman, J. T., and R. E. Davis, 1995, Observations of temperature microstructure in NATRE, *J. Phys. Oceanogr.*, 25, 1913-1929.

Stommel, H., 1955, Direct measurements of sub-surface currents, *Deep-Sea Res.*, 2, 284-285.

Stommel, H., 1989, The Slocum mission, *Oceanography*, 2, 22-25.

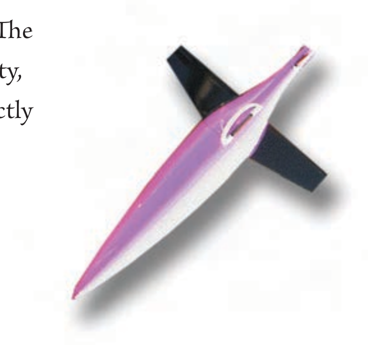
Swallow, J. C., 1955, A neutral-buoyancy float for measuring deep currents, *Deep-Sea Res.*, 3, 74-81.

Thomson, C. Wyville, 1877, *A Preliminary Account of the General Results of the Voyage of the HMS* Challenger, MacMillan, London, 424 pp.

SCIENCE ISSUES

A major goal of the ALPS workshop was to identify science issues best addressed by ALPS alone or in combination with other platforms. Workshop participants spanned the range of oceanographic disciplines, engaging in discussions of a wide variety of important ocean science research problems. For some scientific problems, ALPS have already provided the means to make significant progress. For other, particularly multidisciplinary problems, ALPS have only begun to yield important results, with the promise of more to come. The distinguishing characteristics of ALPS—their scalability, portability, adaptability, and efficiency—will lead directly to new and better science.

Several scientific themes emerged from the workshop: The Ocean's Role in Climate, Biogeochemical Cycles, Coastal Ocean Fluxes and Exchanges, Marine Food Webs, and High-Latitude Science Issues. This section summarizes some of the workshop discussions of these themes. Specific case studies within each theme highlight the exciting science that has already been, and will be, accomplished using ALPS, as well as lessons learned and future technology development needs.



OCEAN'S ROLE IN CLIMATE

Introduction

Peter Niiler, Scripps Institution of Oceanography

The principal scientific questions are how well can we describe or model the ocean circulation today and how well can these descriptions or models predict the evolution of future climates.

The oceans have a profound effect on the atmosphere, and thus Earth's habitability, because they are the principal reservoirs of heat, moisture, and accessible carbon. If the temperature of the lower layers of the atmosphere over the oceans is different from that of the sea surface, there is a vigorous exchange of heat and moisture between the two, with the temperature of the atmosphere adjusting to that of the sea surface because of its low heat capacity.

Sea surface temperature (SST) depends upon the thermal energy and freshwater reservoirs of the ocean thermocline and its circulation patterns. This is most vividly demonstrated by the observation that, in the present climate state, the warm surface layers of the subtropical oceans are separated from the cold deeper layers by a main thermocline. Such a vertical distribution of temperature cannot be maintained in a conducting water column over many centuries unless a volume flux of cold water is supplied to the lower layers and a net heating or a volume flux of warm water is supplied to the surface layers. Because there is a net transfer of heat from the atmosphere to the oceans in the tropics and subtropics, there must be an equivalent transfer of heat back to the atmosphere in the sub-polar and polar regions. Thermal energy absorbed in the ocean in low latitudes is transported poleward by ocean circulation where it is given back to the atmosphere (e.g., Roemmich, 1980). The transfer rate back to the atmosphere and the production of cold water that fills the space below the thermocline depends upon the depth of winter mixing, which is also controlled by the freshwater transport cycle (Aagard and Carmack, 1989). To understand the ocean's heat and freshwater distributions in and above the thermocline, and hence Earth's climate, we need to understand the general circulation, or property transports, of the oceans.

The principal scientific questions are how well can we describe or model the ocean circulation today and how well can these descriptions or models predict the evolution of future climates.

Climate-scale changes in oceanic and atmospheric temperature can occur when net surface heat, freshwater, and CO_2 flux distributions between the ocean and atmosphere are disturbed or when ocean circulation changes. Spatial scales can be several tens of kilometers, such as those that characterize present bottom and deep water formation regions (Steffan and D'Asaro, 2002) , or many thousands of kilometers, such as those that characterize the global El Niño-Southern Oscillation (ENSO) phenomena (Horel and Wallace, 1981). Observations of ocean property distributions are most variable at the lowest resolved frequencies, so we do not know if useful large-time-scale bounds can be established for ocean-climate phenomena. Gathering the data necessary to refine our understanding of the ocean's role in climate is a daunting task because of the wide range of spatial and temporal scales that need to be measured.

It is important to the assessment of the health, and even survival, of today's civilizations that predictions of the effects of climate change are made with realistic ocean circulation models. Associated with, for example, the predicted global warming due to the increase of CO_2 and other greenhouse gases in the present atmosphere, is an increased melting of glacial and continental ice sheets and a rise in sea level. How this freshwater flux from the ocean boundaries is incorporated into the oceans, how quickly sea level will rise follow melting, and how effectively the melt water affects the deep ocean convection are questions that can be answered only by ocean models that have correct circulation physics. An assessment of the limits of El Niño or North Pacific Oscillation prediction can only be done in context of ocean circulation models that embody accurate simulations of both temporal mean and variable circulation as well as realistic initial conditions of the ocean state. The reality of ocean circulation models must be determined with spatially and temporally extensive data sets of the state of the circulation and property distributions of the global oceans.

An important contribution that ALPS can make to climate change science is to provide sustained and systematic measurements of the circulation and property distributions of the oceans. ALPS are well-suited to cover the required 200 km and larger spatial scales and 7 days and longer time scales. The location history of Lagrangian sensors can be used to compute ocean horizontal velocity and sensors can be added to also determine vertical velocity (Lavender et al, 2002).

ALPS can continuously observe the circulation and property distributions of the remote oceans as a function of depth during all weather conditions. This is important for the observation of deep and intermediate water mass for-

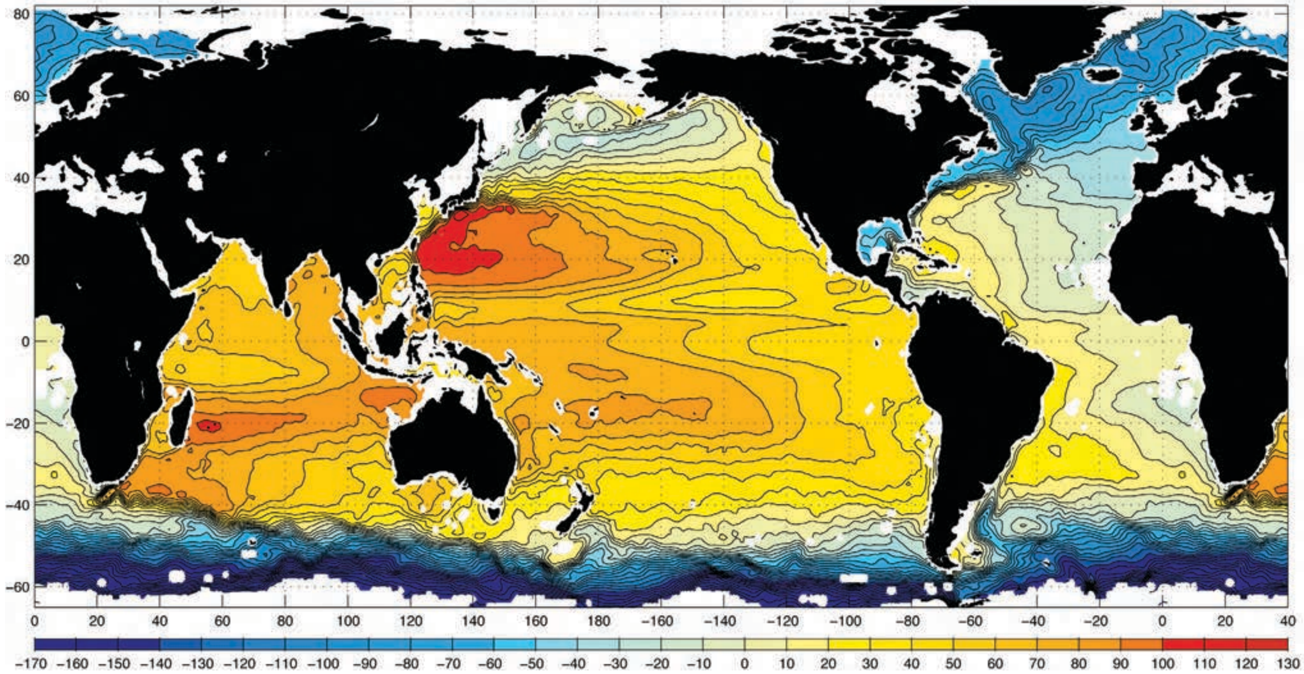


Figure 8. Time mean, for 1992-2002, of global sea level from surface drifter geostrophic velocity, corrected using geostrophic velocity anomalies from satellite altimeters. This combination of ALPS and satellite measurements is an excellent example of modern climate observation.

mation that occurs during times of high wind and strong heat fluxes from the oceans to the atmosphere. For example, vertical profiles of temperature and salinity during winter in the Labrador and Irminger Seas (Lavender et al, 2002) and the Southern Ocean were obtained using arrays of PALACE floats in the late 1990s.

ALPS can be used to determine the spatial scales and along-current extent of circulation patterns that do not appear in traditional ship-borne data. For example, the extent and strength of the boundary current on the western flank of the Riekyes Ridge (Lavender et al, 2000), the multiple eastern boundary currents in the Norwegian Sea (Orvik and Niiler, 2000), and the longitudinal extent of Aghulas Extension (Pazan and Niiler, 2003) and the Azores Current (Niiler et al, 2003b) were not accurately known until drifters had been deployed in these regions in a systematic basis for five or more years. The currents along steep topographic features of the North Atlantic have strong barotropic signatures that do not appear in hydrographic data. The longitudinal extents of zonal current systems have not been investigated from ships because mesoscale activity precludes a coherent interpretation or because these current systems are too remote to be followed by ship.

ALPS global observations can be used in conjunction with satellite sensing of the ocean surface to enhance the capability of both systems (Niiler et al., 2003a). In principle, two altimeters flying in parallel orbits can resolve 150-km horizontal spatial structure of sea level. ALPS observations can be used to determine the vertical structure, and to test various models of converting altimeter observations to surface currents. Today, SST observations provided by drifters (and profiling floats in the very near future) are used to in conjunction with satellite retrievals of SST to map the SST patterns of the global ocean. Ocean surface circulation maps are made in limited regions using both satellite and ALPS data sets (Bonjean and Lagerloef, 2003). These combined circulation maps can be made global if regional methodologies are pieced together in more systematic ways than are now done.

References

Aagard, K. and E.C. Carmack, 1989, The role of sea ice and other fresh water in the Arctic circulation. *J. Geophys. Res.*, 94, 14,485-14,498.

Bonjean, F., and G.S.E. Lagerloef, 2003, Diagnostic model and analysis of the surface currents in the tropical Pacific Ocean., *J. Phys. Oceanogr.*, in press.

Horel, J.D. and J.M. Wallace, 1981, Planetary-scale atmospheric phenomena associated with the Southern Oscillation, *Month. Weather Rev.*, 109, 813-829.

Lavender, K.L., R.E. Davis and W.B. Owens, 2000, Mid-depth recirculation observed in the interior Labrador and Irminger seas by direct velocity measurements, *Nature*, 47, 66-69.

Lavender, K.L., R.E. Davis, and W.B. Owens, 2002, Observations of open-ocean deep convection in the Labrador Sea from subsurface floats, *J. Phys. Oceanogr.*, 32, 511-526.

Niiler, P. P., N. A. Maximenko, G. G. Panteleev, T. Yamagata, and D. B. Olson, 2003a, Near-surface Dynamical Structure of the Kuroshio Extension, *J. Geophys. Res.*, 108, 3193.

Niiler, P. P., N. A. Maximenko, and J. C. McWilliams, 2003b, Dynamically balanced absolute sea level of the global ocean, *Geophys. Res. Lett.*, in press.

Orvik, K. A. and P. Niiler, 2002, Major pathways of the Atlantic water in the northern North Atlantic and Nordic Seas toward Arctic, *Gophys. Res. Lett.*, 29, 1896.

Pazan, S. and P. Niiler, 2003, A New Global Drifter Data Set, *EOS*, Transactions of the American Geophysical Union, in press.

Roemmich, D., 1980, Estimation of meridional heat flux in the North Atlantic by inverse methods, *J. Phys. Oceanogr.*, 10, 1972-1983.

Steffan, L.E. and E.A. D'Asaro, 2002, Deep convection in the Labrador Sea as observed by Lagrangian floats, *J. Phys. Oceanogr.*, 32, 475-492.

Assessing Large-Scale Ocean State with the Argo Float Array

Dean Roemmich, Scripps Institution of Oceanography

One of the most compelling scientific problems in oceanography today is the role of the ocean in the coupled climate system, including its variability. The basic elements of climate are heat and freshwater. An improved understanding of climate requires knowledge of how heat and freshwater are stored, exchanged, and transported through the ocean/atmosphere/land system.

Argo profiling floats are a major contributor to the improved understanding of the ocean's role in climate by making repeated measurements of heat and freshwater storage and transport in the upper ocean on large spatial scales (1000 km to global) and on seasonal and longer time scales. Argo floats cycle every 10 days, dropping to a parking depth of 1-2 km where an estimate of the mid-depth reference velocity is obtained from the trajectory. Floats then collect a high-quality conductivity-temperature-depth (CTD) profile to the sea surface. The CTD data, trajectory, and engineering parameters are immediately transmitted via satellite to Argo data centers for public availability via the GTS and Internet. By integrating these data, we can directly measure the storage of heat and freshwater in the oceans. In addition, these Argo profiles are key data to be assimilated into global computer models of ocean state.

Argo implementation was initiated with regional arrays in the northern and tropical oceans—areas of highest priority to the float-providing nations (Figure 9). As these

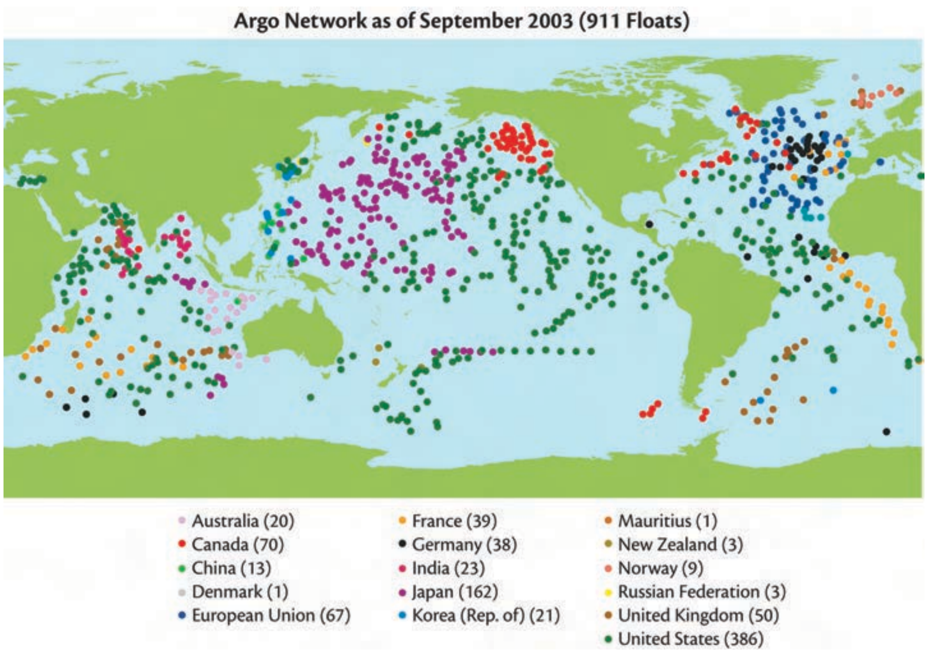


Figure 9. Left: Positions of active Argo floats as of September 2003 (http://argo.jcommops.org). Argo is an international program that calls for the deployment of 3,000 free-drifting profiling floats, distributed over the global oceans, that will measure the temperature and salinity in the upper 2,000 m of the ocean providing 100,000 temperature/salinity profiles and reference velocity measurements per year. This will allow continuous monitoring of the climate state of the ocean. There are sufficient commitments of floats from the partner nations to complete the phased deployment of Argo in 2006.

arrays grow to effective float densities, they have now begun to expand into the remote areas of the southern hemisphere oceans. As of September 2003 there were 911 profiling floats active in all of the oceans, deployed by partner nations. A complete global Argo array of 3000 floats is planned for 2006, and will be distributed approximately every 3° of latitude and longitude. This spacing will provide an array whose density increases with latitude to overcome the increased noise-to-signal ratio at high latitude due to mesoscale variability.

Argo is in its early stages of implementation, but many scientific investigations are already underway. These include:

- Ocean heat balance. The Argo data set is being analyzed by itself and with other *in situ* and satellite data in local, regional, and global heat budgets.
- Combination of Argo data with satellite altimetry. A high fraction of the variability in altimetric height is due to steric change, and this synergistic aspect is used for improved estimation of subsurface variability.
- Salinity variability and the hydrological cycle. Salinity variability in the surface layer is the result of local evaporation minus precipitation modified by horizontal advection and mixed-layer entrainment.
- Detection of mid-depth T/S variability. Subducted water masses carry the signature of past hydrological cycle variability. T/S anomalies in thermocline layers have been seen in Argo data from the tropical Pacific and the southern Indian Ocean.
- Ocean circulation. The first basin-scale maps of mid-depth circulation were made during the World Ocean Circulation Experiment (WOCE). These are being improved in resolution and accuracy, and further information on variability of mid-depth circulation is being analyzed.
- Water mass formation. The broad-scale float array is an effective means of studying the distribution, evolution, and characteristics of mode waters and other upper ocean water masses (e.g., Figure 10).

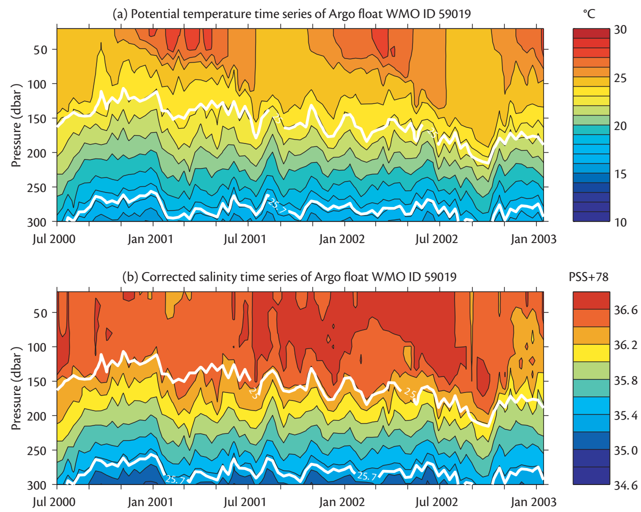


Figure 10. Temperature and salinity time series from an Argo float near the formation region of South Pacific Eastern Subtropical Mode Water. Heat storage in the ocean is dominated by the annual cycle. Interannual changes are evident in the salinity record. As Argo time series lengthen in coming years, these direct observations of changes in ocean climate promise a new understanding of the underlying processes. Modified from A.P.S.Wong and G.C. Johnson, 2003, *Jour. Phys. Oceanog.*,33(7), p. 1501, Copyright July 2003, American Meteorological Society (AMS).

- Mixed layer thickness/ upper ocean stratification. Anomalously shallow winter mixed layers were recently observed in Argo profiles in the subpolar North Pacific, with possible biological consequences in the coming year.

Argo technology development is ongoing, with the focus on improving profiling floats for the Argo mission. Work is underway to improve communications systems for shorter float surface times and greater message length, to increase the robustness and reliability of floats for longer lifetime, to improve the accuracy and stability of salinity sensors, and to increase the efficiency and depth capability of pumping systems. Outside of Argo, there is additional development work on new sensors with profiling float applications. New sensors may be integrated into Argo once they are demonstrated to be compatible with and complementary to the basic mission. Depending on sampling requirements and sensor characteristics, new programs might either share platforms with Argo or deploy additional floats in embedded or ancillary arrays.

A Census of Coherent Eddies in the Northern North Atlantic Ocean

Tom Rossby, University of Rhode Island

Accurate models of the ocean's role in stabilizing climate on the one hand, and its potential to change state and induce major transitions in climate on the other, depend upon understanding the underlying mechanisms that shape the general circulation of the ocean. Because of the extraordinary range of scales that contribute to the general circulation of the ocean, a proper understanding of the ocean as a dynamical system cannot be achieved by considering only those scales associated with the time-averaged mean flow. We need to characterize and understand the role of the energetic mesoscale eddy field, which is not only time-dependent, but also can have quite different spatial and temporal properties in different regions. Here we draw attention to a particular class of eddy motion, the ubiquitous, energetic coherent eddies that seem to occupy a substantial, but as yet not fully charted, fraction of the total ocean volume.

As part of the Atlantic Climate Change experiment (ACCE—a component of U.S. WOCE), a large number of acoustically tracked RAFOS floats were deployed in the late 1990s to map out the mean circulation and eddy activity on an isopycnal surface in the thermocline in the Atlantic Ocean north of about 40°N. Bower et al. (2002) reported on the mean circulation and the role of fracture zones in steering flows across the Mid-Atlantic Ridge. Here we give another example of how the data from continuously tracked RAFOS floats can be used.

The frequent location of each float, at least once daily, enabled us to study their motion in considerable detail (visit www.po.gso.uri.edu/rafos for further details about the RAFOS system and technology). We were struck by the numerous examples of floats executing looping motions in their trajectories. Such motions have been observed and studied before and have always been attributed to the orbital motion or rotation of coherent vortices. But the large number of long trajectories (up to two years) over a wide area allowed us to take a census of coherent eddies (Slater et al., 2003). Here we considered a float to be in a coherent eddy if it made at least two consecutive loops in the same direction (a "looper"). Figure 11 gives a complete inventory of all observations of anticyclonic (red) and cyclonic (blue) motion. We found that 16% (25 float-years) of all float data were in loopers. One hundred and eight loopers were identified in 96 different eddies with almost perfect equipartition in cyclonic and anticyclonic eddies (49 and 51%). This ratio apparently varies from region to region such that the European Basin featured a larger percentage of anticyclonic eddies, perhaps due to the shedding of meddy-like features along the eastern boundary. Some eddies remained stationary for very long periods of time (> 1 year), but most of the eddies that could be followed for a period of time moved in the direction of the general circulation as observed by the non-looping floats. Several floats were trapped in eddies just upstream (west) of the Charlie Gibbs (52°N) and Faraday (50°N) Fracture Zones, which also seem to be preferred routes for flow crossing the Mid-Atlantic Ridge (Bower et al., 2002).

An analysis of SOFAR float trajectories from the Sargasso Sea (Rossby et al., 1983) also revealed a number of instances where floats were caught in coherent eddies and exhibited similar orbital motions, both cyclonic and anticyclonic, with rough equipartition. Looping motions were observed in both the main thermocline and at depth, but the fraction of time floats were looping was much less (about one half) than the 16% observed in ACCE. Thus,

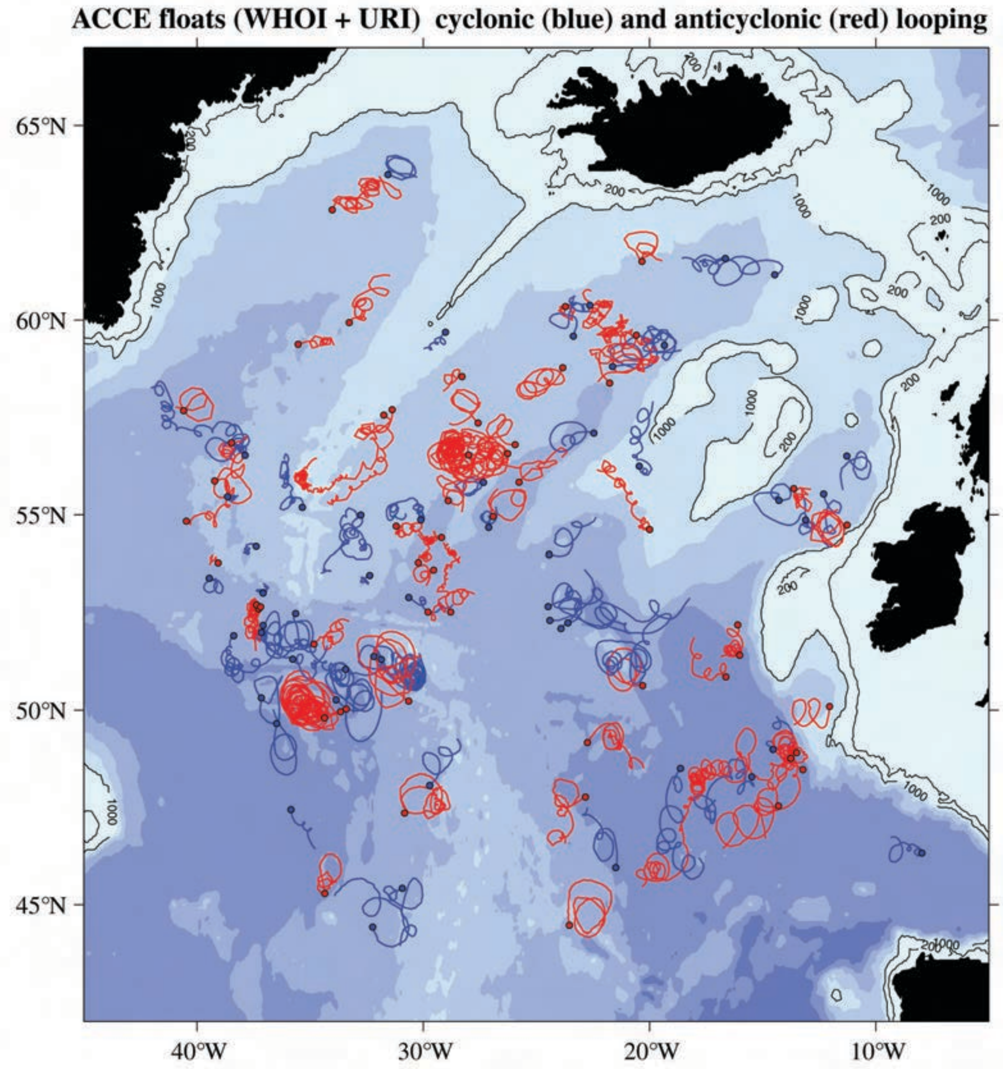


Figure 11. By acoustically tracking RAFOS floats in the northern North Atlantic, coherent eddies, defined as where the floats make at least two loops in the same direction, were shown to account for a fraction of the total eddy motion in the ocean. Studies of coherent eddies contribute to our understanding of mixing and transport processes in the oceans, accurate knowledge of which is essential to studies of the oceans' role in global climate change.

acoustically tracked floats have taught us that coherent eddies (or lenses, since these are embedded in the stratified water column) occur in different oceans, geographies, dynamical regimes. Some eddies clearly last for months to years. Some are shed by boundary currents or meandering fronts, while others appear to be formed spontaneously in the open ocean. The high-resolution trajectories obtained with acoustic tracking of isopycnal floats are particularly well suited to studies of such eddy features.

References

Bower, A. S., B. Le Cann, T. Rossby, W. Zenk, J. Gould, K. Speer, P.L. Richardson, M.D. Prater, and H.M. Zhang, 2002, Directly measured mid-depth circulation in the northeastern North Atlantic Ocean, *Nature*, 419, 603-607.

Rossby, H.T., S.C. Riser and A.J. Mariano, 1983, The Western North Atlantic—A Lagrangian Viewpoint, In, *Eddies in Marine Science*, A. R. Robinson, Ed. Springer-Verlag, Berlin.

Slater, D.R., P.L. Richardson, A.S. Bower, and H.T. Rossby, 2003, Discrete eddies in the northern North Atlantic as observed by looping RAFOS floats, *Deep-Sea Res.*, in revision.

Introduction

Ken Johnson, Monterey Bay Aquarium Research Institute

It is essential to understand the response of ocean biology and chemistry to...natural climate oscillations if we are to predict the response of the ocean carbon cycle to long-term changes in climate.

Primary production of particulate carbon in the ocean plays a fundamental role in the global carbon cycle. Each year, phytoplankton in the ocean fix 35 to 65 Gt of inorganic carbon into organic molecules, which is about one half of the planetary primary production (Field et al., 1998; Behrenfeld et al., 2001). Simulations with numerical models suggest that atmospheric carbon dioxide would increase about 400 ppm above pre-industrial values of 280 ppm without this biological uptake of carbon dioxide in the ocean. However, our understanding of the environmental factors that regulate primary production in the global ocean are very poorly constrained. There are never enough shipboard measurements in any one year to determine primary production of the global ocean or a single ocean basin. Remote sensing of ocean color measures only variability in phytoplankton concentration near the sea surface and it does not measure primary production directly. Nor does remote sensing detect changes in the deep chlorophyll maximum, which is present throughout much of the oligotrophic ocean. As a result, interannual variations in carbon cycling that are driven by processes such as El Niño are not well understood. It is essential to understand the response of ocean biology and chemistry to such natural climate oscillations if we are to predict the response of the ocean carbon cycle to long-term changes in climate.

Today, nearly 1000 vertical profiling floats that are equipped with temperature, salinity, and pressure sensors are operating throughout the ocean in the Argo array (see case study on page 18). These floats are designed to make approximately 150 vertical profiles to 1000 or 2000 m depth at 10-day intervals over a time period of four to five years. The Argo system provides a global assessment of heat storage in the ocean, a key component of Earth's climate system. Presentations at the ALPS workshop made it clear that there has been a very significant advance in the development of robust biogeochemical sensor systems capable of operating on profiling floats. It is now feasible to consider the development of a basin-scale, biogeochemical observing system that is based on vertical profiling floats similar to those used in the Argo array.

Biogeochemical sensors on a network of floats could be used to detect large-scale changes in the abundance of nutrients that control marine primary production. The changes in the concentration of chemicals such as oxygen, which are produced when carbon dioxide is fixed into organic matter, could be used to calculate the net amount of primary production. Observations of particle abundance in the upper ocean would enable an estimate of the fraction of primary production that was transported into the deep sea. For the first time, ocean scientists could directly observe basin- to global-scale changes in the carbon cycle and factors that regulate it. Operated over multiple years, this system would provide essential data on the response of ocean ecosystems and the ocean carbon cycle to short-term changes in climate. Such data would provide much of the understanding needed to predict variations in the carbon cycle that might result from global warming.

Robust biogeochemical sensors that have the potential to operate over extended time periods have been developed for dissolved oxygen, Particulate Organic Carbon (POC), nitrate, and chlorophyll fluorescence. The scientific potential of these sensors has been demonstrated by equipping profiling floats with optical sensors for light transmission, fluorescence, and backscattering (Bishop et al., 2002). These floats have detected a remarkable shift in POC standing stock (Figure 12), which appeared to be associated with an Asian storm that deposited iron-rich dust on the surface of the North Pacific. Phytoplankton in this region are iron deficient and the dust-derived iron stimulated a large-scale plankton bloom.

Experiments to assess the feasibility of monitoring dissolved oxygen with sensors on vertical profiling floats are well underway. Preliminary results, shown in a poster presented at the ALPS meeting, demonstrate remarkable stability of the deep-water oxygen concentrations reported with a float-mounted oxygen electrode up to the present. An optical sensor system capable of measuring dissolved nitrate in seawater over long time periods on deep-sea moorings, CTD profilers, and undulating towed vehicles such as SeaSoar has been developed (Johnson and Coletti, 2002). While this system has not been tested on floats, there is no inherent reason why it would not work.

A global or basin-scale array of vertical profiling floats equipped to measure oxygen, nitrate, POC (via light transmission), and fluorescence could be used to address a range of questions that are related to regulation of primary productivity by nutrient availability, annual and interannual variation in ocean net primary production, and export of carbon to the deep sea. Measurements of the oxygen and carbon isotopic composition of air show that the net ocean uptake of carbon dioxide may vary interannually from 1 to 3 Pg C/y (Battle et al., 2000). This variation is comparable to the uptake of fossil fuel carbon dioxide by the ocean (~2 Pg C/y). The atmospheric observations provide little mechanistic understanding of why these changes in ocean CO_2 uptake occur. We do not know whether such changes are controlled by variability in ocean biology or ocean physics. There is abundant evidence, however, that large-scale changes in ocean biology do occur and these changes are linked to fluctuations in atmospheric carbon dioxide (Chavez et al., 2003). It is critical that we understand when and how such changes in ocean primary production occur so that better predictive models of the ocean-atmosphere partitioning of carbon dioxide can be developed.

Such an array of biogeochemical floats would be particularly interesting in the Southern Ocean. The Southern Ocean has a disproportionately large influence on climate variations because of the ventilation of deep, carbon dioxide-rich waters in that region and low, but variable primary production. Observations in the Southern Ocean are rare because few ships operate there due to its remote location, and extreme weather makes it difficult to deploy moored buoys. A network of profiling floats would provide ocean scientists with an unparalleled opportunity to monitor biogeochemical changes in this region over many years.

Planning is currently underway to implement the ocean component of the U.S. Carbon Cycle science plan (Doney et al., in preparation). The research that could be addressed with an array of biogeochemical floats is broadly consistent with the CCSP and with the specifics of the ocean component. There are five overarching scientific goals in the CCSP (Sarmiento and Wofsy, 1999), three of which have significant ocean components:

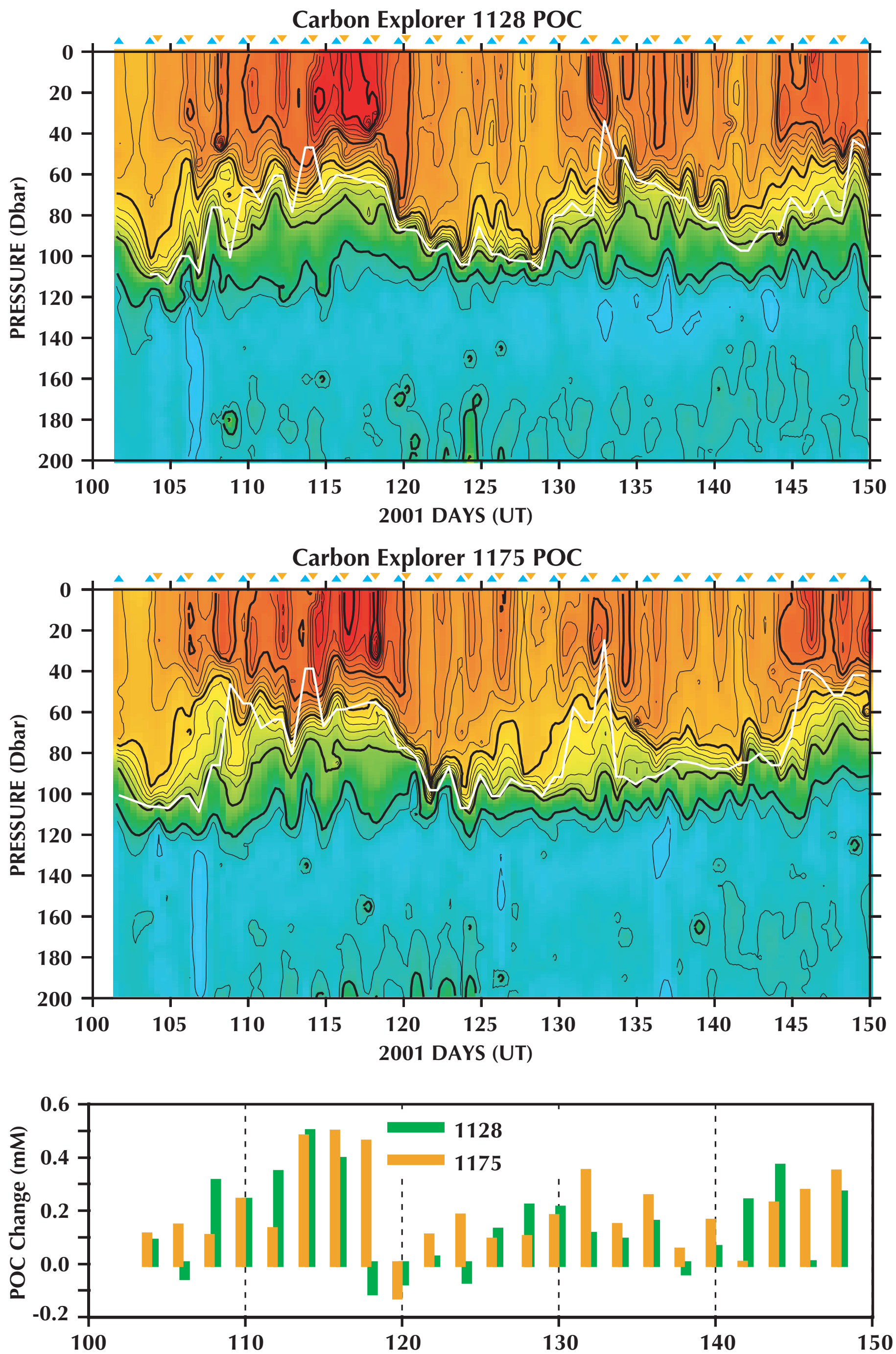


Figure 12. Vertical profiling floats equipped with optical sensors for light transmission, fluorescence, and backscattering have been used to detect Particulate Organic Carbon (POC) in the North Pacific (50°N, 145°W). Top and middle panels show time series of POC variability from two floats during the first 50 days of deployment. The lock-step nature of both records indicates that observed POC variability is a response to large-scale forcing. The bottom panel shows enhanced net growth of POC on days 114 through 118, approximately two weeks after Gobi Desert dust passed over the area. The iron in the dust apparently stimulated a large-scale plankton bloom. Reprinted with permission from Bishop, J.K.B., R.E. Davis, and J.T. Serman, 2002, Robotic observations of dust storm enhancement of carbon biomass in the North Pacific, *Science*, 298, 817-821. Copyright 2002 American Association for the Advancement of Science.

- Understanding the Northern Hemisphere land sink
- Understanding the ocean carbon sink
- Improving projections of future atmospheric CO_2.

The draft Ocean Implementation Plan (Doney et al., in preparation) calls for a phased, basin-by-basin approach. "In phase 1 (beginning in 2003 ramping up to the full program in 2005-2009) emphasis will be placed on the North Atlantic and Pacific in conjunction with the North American Carbon Program. Southern Ocean synthesis and pilot studies are also proposed for phase 1 followed by a full Southern Ocean field effort in phase 2 (2010-2014)." Emphasis is placed in phase 1 on "accelerating technology development and field testing for new biogeochemical techniques, ..., and autonomous sensors and platforms that have the opportunity to revolutionize how ocean carbon cycle research is conducted and will provide the capability to measure important properties over large sections of the ocean on an almost continual basis." The system discussed here would provide an essential step towards implementation of this plan.

To assess the feasibility of an observing system based on biogeochemical sensors deployed on an array of profiling floats, several additional steps need to be undertaken. First, a preliminary design study for a fully instrumented biogeochemical float needs to be undertaken. Such a study must identify the key sensors, power budget, float profiling cycle, and required endurance. A modeling study that constrains the density of floats and the precision of measurements needed to observe new primary production and nutrient stocks over an ocean basin is also necessary. A modeling study could also assess the feasibility of using periodic hydrographic surveys of deep-sea chemical properties, which are proposed in the CCSP Ocean Implementation Plan to assess sensor drift in a float array and, potentially, to serve as a calibration point. Finally, studies must be implemented to demonstrate the stability of key sensor systems, such as for nitrate. The feasibility of developing additional sensors for pH should also be assessed. Observations of pH change in the ocean on seasonal time scales would provide an additional constraint on rates of new primary production as the uptake of carbonic acid is a primary control on ocean pH.

References

Battle, M., M.L. Bender, P.P. Tans, J.W.C. White, J.T. Ellis, T. Conway and R.J. Francey, 2000, Global carbon sinks and their variability inferred from atmospheric O_2 and ^{13}C, *Science*, 287, 2467-2470.

Behrenfeld, M., et al., 2001, Biospheric primary production during an ENSO transition, *Science*, 291, 2594-2597.

Bishop, J.K.B., R.E. Davis and J.T. Sherman, 2002, Robotic observations of dust storm enhancement of carbon biomass in the North Pacific, *Science*, 298, 817-821.

Chavez, F. P., J. Ryan, S.E. Lluch-Cota, and M. Ñiquen C., 2003, From anchovies to sardines and back: multidecadal change in the Pacific Ocean. *Science,* 299, 217-221.

Doney, S.C. (chair), In preparation, *An Ocean Implementation Plan for the U.S. Carbon Cycle Science Program* (CCSP-Oceans).

Emerson, S., Mecking S., and Abell J, 2001, The biological pump in the subtropical North Pacific Ocean: Nutrient sources, Redfield ratios, and recent changes, *Global Biogeochemical Cycles,* 15, 535-554.

Field, C.B., M.J. Behrenfeld, J.T. Randerson and P. Falkowski, 1998, Primary production of the biosphere: integrating terrestrial and oceanic components, *Science*, 281, 237-240.

Johnson, K.S. and L.J. Coletti, 2002, *In situ* ultraviolet spectrophotometry for high resolution and long term monitoring of nitrate, bromide and bisulfide in the ocean, *Deep-Sea Research I*, 49, 1291-1305.

Sarmiento, J.L. and S.C. Wofsy (co-chairs), 1999, *A U.S. Carbon Cycle Science Plan*, Report of the Carbon and Climate Working Group, prepared for the agencies of the U.S. Global Change Research Program, 69 pp.

Resolving Spring Bloom Dynamics in the Sea of Japan

Greg Mitchell, Scripps Institution of Oceanography

Following deep convective mixing in winter, many high-latitude regions experience thermal stratification during late winter and early spring resulting in significant spring phytoplankton blooms associated with the shoaling of the mixed layer. Globally, spring blooms are of considerable importance in mediating the flow of atmospheric carbon dioxide into the oceans. Marine plants such as phytoplankton consume carbon dioxide, thus increasing the rate at which atmospheric carbon dioxide enters the ocean surface.

The Japan Basin in the Sea of Japan annually experiences deep convective mixing as a consequence of Siberian low pressure systems that bring high wind and very cold air masses to the region. Thus, this is an ideal region to study the onset of spring blooms caused by thermal stratification and their role in the global carbon cycle. This phenomenon is difficult to sample by ships due to the unpredictable timing. Moorings can be very useful, but they are expensive and the depth resolution of most moorings is relatively poor. Satellite ocean color data are limited by cloud cover and provide no depth resolution. Autonomous profilers with simple optical sensors can effectively provide low-cost, high-resolution profiles to complement more traditional observational strategies.

To characterize thermal stratification, the development of the spring bloom, and formation of the post-bloom deep chlorophyll maximum in recurring eddies in the Sea of Japan, we deployed a Sounding Oceanographic Lagrangian Observer (SOLO) with a temperature sensor and a three-channel spectral radiometer (Figure 13). The spectral radiometer allowed estimates of spectral diffuse attenuation coefficients (K), the depth derivative of irradiance. K is well correlated with phytoplankton pigments and colored dissolved organic matter. An important advantage of the simple three-channel irradiance sensor is that it has very low power requirements and K is not affected by calibration or biofouling since K is computed as the rate of change in irradiance over small depth intervals. A disadvantage is that K can only be computed in the upper water column (~200 m) during daytime.

K-SOLO was programmed to acquire a profile of spectral irradiance and temperature in the upper 500 m near noon on alternate days. The timing of the profile was

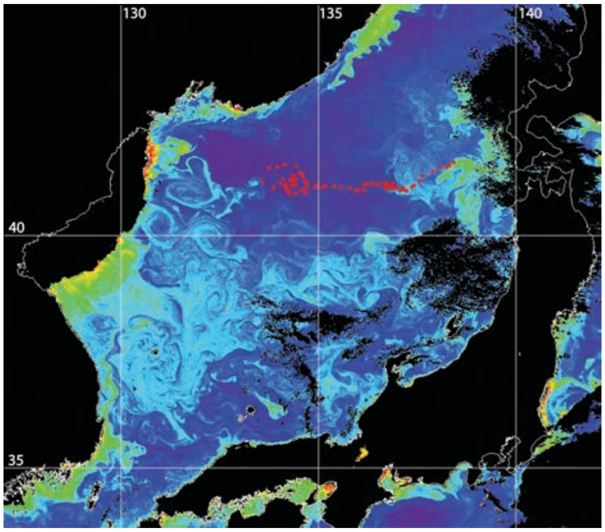


Figure 13. SeaWiFS chlorophyll a image for April 6, 2000, approximately three weeks after the autonomous K-SOLO profiler deployment. K-SOLO transmitted data every second day until August 8, 2000. K-SOLO stayed within the Japan Basin for the first 75 days and *in situ* calculations of K(490) increased from 0.06 m^{-1} to 0.15 m^{-1}. The full K-SOLO trajectory is superimposed on the image. After the spring bloom associated with the thermal stratification of the deeply mixed basin, K-SOLO drifted rapidly to the east and was eventually caught in a fishing net.

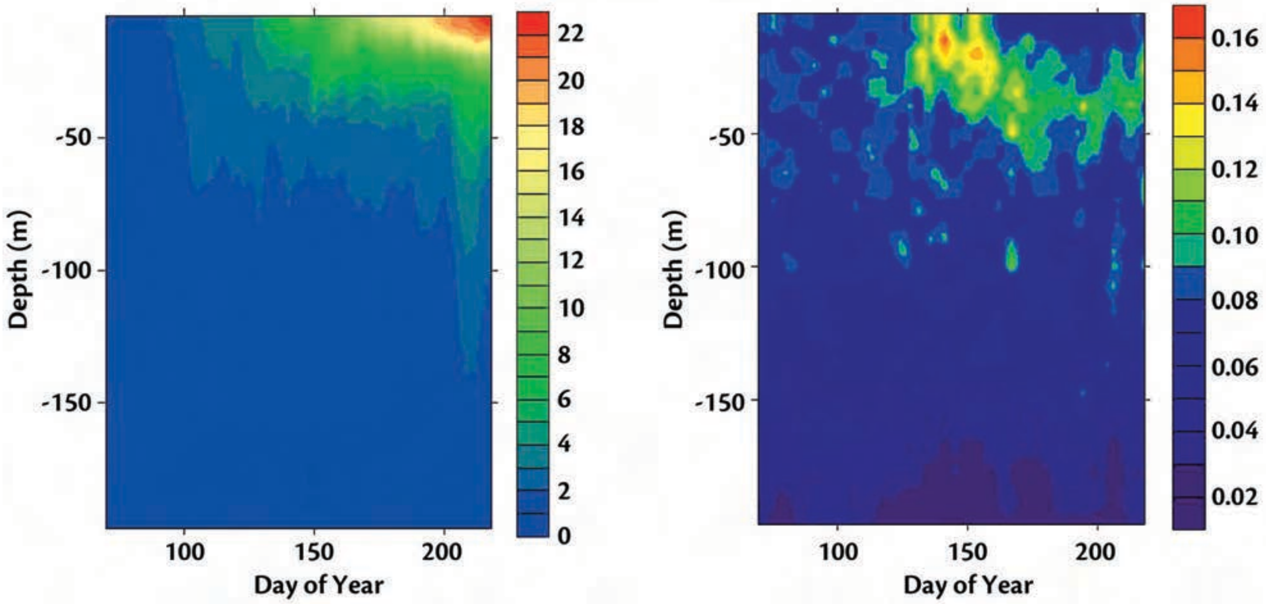


Figure 14. Time evolution of temperature (left) and K(490)—spectral diffuse attenuation coefficient—(right) in the upper 200 m during the K-SOLO experiment. Evidence of higher attenuation coefficients in the upper 100 m compared to deeper water indicates some growth of phytoplankton even in deeply mixed waters. Following strong stratification after day 125, a phytoplankton bloom occurred with maximum values observed near day 150. The increase in phytoplankton led to a strong increase in K(490) in the surface waters. Subsequently, the surface bloom declined and maximum values of K(490) were found near 50 m depth. K(490) below 150 m approached values close to the pure water value for this wavelength.

chosen to collect data simultaneously with the overpass of the SeaWiFS ocean color satellite. Resolution of temperature and spectral irradiance was 5 m in the upper 100 m and 10 m from 100-200 m; below 200 m the irradiance data were not reported and temperature resolution was limited to 10 m. These sampling compromises were required to permit data transmission via the low bandwidth System ARGOS on NOAA polar orbiting satellites. A total of 76 vertical profiles were acquired.

The time series of temperature and K(490) are shown in Figure 14. Initially, K-SOLO was trapped in the Japan Basin eddy and resolved the late winter deeply mixed system and the temporal dynamics of thermal stratification and the spring bloom. Thus, the initial deployment period, while within the eddy, can be considered a 1-dimensional experiment for evaluating the onset of the spring phytoplankton bloom in response to physical stratification. After strong stratification occurred, the K-SOLO moved east. The development of a deep chlorophyll maximum was evident, presumably caused by isolation of the mixed layer from nutrients below the pycnocline.

With higher bandwidth communications that are now possible, the integration of attenuation or backscattering meters, fluorometers , oxygen, pCO_2, and perhaps nutrient sensors can be envisioned to create inexpensive "productivity" floats to improve our understanding of physical-chemical-biological coupling and how this coupling influences biogeochemical cycles in the upper ocean. Autonomous systems should be envisioned as an inexpensive observing strategy to complement ships, moorings, and satellites. These systems should prove particularly important for high-latitude regions that are difficult to sample year round and where cloud cover severely limits satellite observations. While we were fortunate that the single unit deployed in this case study was retained in the target eddy for several months, in general, an array of similar floats should be deployed within a region to more accurately characterize the coupling between physical dynamics and phytoplankton response.

COASTAL OCEAN FLUX AND EXCHANGE

Introduction

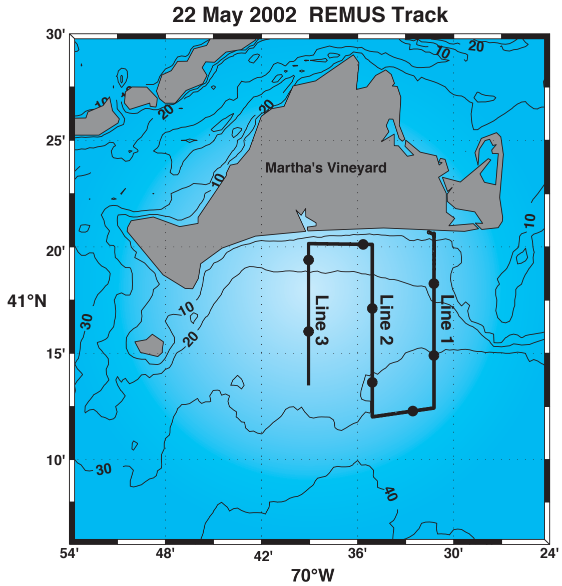
R. Kipp Shearman, Woods Hole Oceanographic Institution

ALPS will play a major role in the emerging field of coastal observatory science because they return more data per unit cost than ships or moorings, provide the needed spatial and temporal resolution, and are unconstrained by weather or ship availability.

The coastal ocean is a dynamic environment, characterized by complex spatial patterns that change on a variety of time scales. Forcing by wind and buoyancy (i.e., rivers), variations in bathymetry, enhanced mixing from relatively large tides, and the presence of fronts (e.g., the shelf-slope front in the Middle Atlantic Bight) are just a few processes in the coastal ocean that combine to create variability on short length (as little as 1 km) and time (less than a day) scales, not to mention other chemical and biological processes that add to the complexity. Observing this variability is one of the principal challenges in addressing a wide range of important oceanographic problems. The fundamental processes affecting along-shelf transport and exchange between the coastal and deep ocean of physical, biological, and chemical properties must be understood. For example, conducting search and rescue operations, dealing with environmental hazards such as oil spills or harmful algal blooms, and monitoring coastal ecosystems (processes such as recruitment) depend on knowing transport pathways in the coastal ocean.

The difficulty of obtaining measurements that capture both the spatial and temporal variability is the primary factor limiting progress in understanding the coastal ocean. In the past few decades, remotely sensed observations (e.g., satellites, airborne lidar, and shore-based HF radar) have provided detailed pictures of the characteristics of the ocean surface. However, the underlying structure remains poorly understood because of our inability to make complementary subsurface observations with spatial and temporal detail similar to the remotely sensed observations. Traditionally, oceanographers have relied on ship-based surveys and moored instrumentation to obtain observations of the ocean's structure and variability. Moored arrays of instruments can sample rapidly for several months or more, but the deployment of fixed arrays is expensive, and it is not feasible to deploy enough moorings to resolve the short spatial scales characterizing the coastal ocean. Ship-based surveys have the advantage of better spatial coverage and resolution, but they are also expensive, require the use of large oceanographic research vessels, are constrained by weather, and typically last a few weeks or less due to costs.

To advance our understanding of the coastal ocean, in particular, processes related to transport and exchange, an observational capability that merges the high spatial resolution of ship-based surveys with the endurance and temporal resolution of moorings is needed. ALPS are a cost-efficient means to achieve this goal. Fleets of gliders are an effective way of sampling large areas over long,



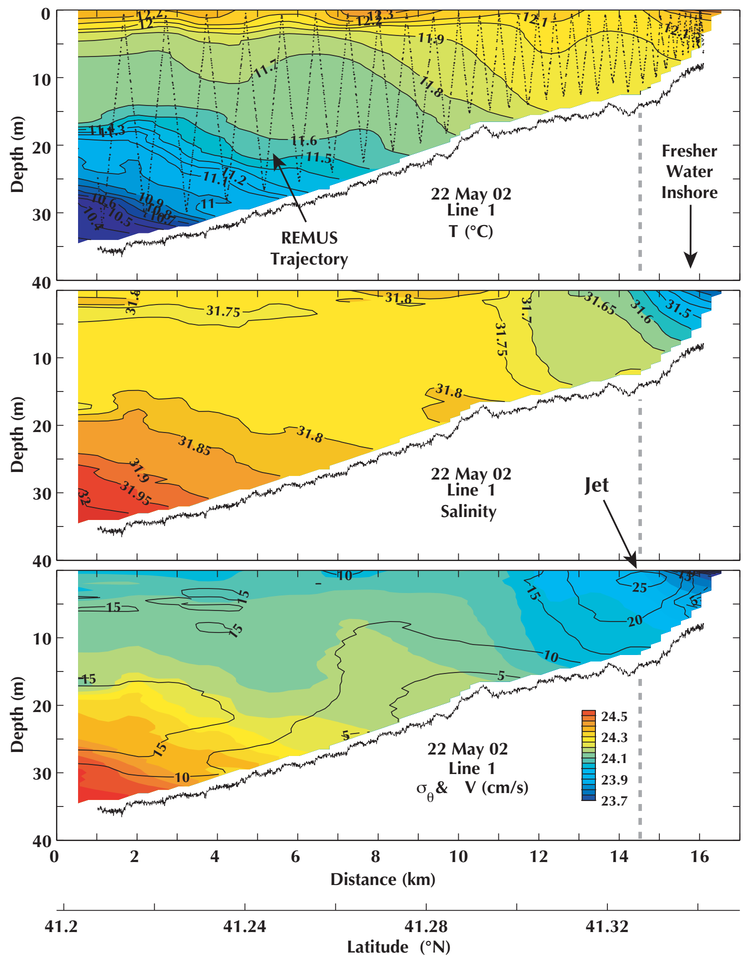


Figure 15. Above: Path of the REMUS AUV during the 22 May 02 deployment off Martha's Vineyard (dots indicate hourly intervals). REMUS was equipped with a conductivity-temperature-depth sensor, acoustic Doppler current profiler (600 kHz), and an optical backscatter sensor. Right: Observed temperature (top), salinity (middle), and density (bottom, shaded), and westward currents (contoured) along Line 1. A strong (25 cm/s), narrow (~4 km wide) current jet dominates the inshore velocity field, running westward along the 15 m isobath. The jet overlies a sharp cross-shelf density gradient associated with a buoyant plume of relatively fresh water (S<31.5) very near the shoreline. The observed vertical shear within the jet approximately matches the estimate of thermal wind shear from the measured cross-shelf density gradient. This feature and its dynamical characteristics had previously gone unobserved because traditional sampling techniques do not resolve the small spatial scales.

continuous periods, powered AUVs are useful for sampling smaller areas with a larger suite of instrumentation, and floats offer direct measurement of transport pathways. Furthermore, ALPS will play a major role in the emerging field of coastal observatory science because they return more data per unit cost than ships or moorings, provide the needed spatial and temporal resolution, and are unconstrained by weather or ship availability. Coastal observatories will likewise enhance the capabilities of autonomous platforms such as gliders and powered AUVs by providing the means to recharge batteries or download data without coming out of the water. Finally, the high-resolution synoptic data provided by platforms such as gliders and powered AUVs, in conjunction with remotely sensed surface data, are ideally suited to assimilation into models of the coastal ocean, and will improve the capabilities and validate our understanding of these models.

The actual implementation of ALPS in the coastal ocean is in its most nascent stages. For example, in 2002 and 2003 several rapid, high-resolution sections of temperature, salinity and currents were collected at the Martha's Vineyard Coastal Observatory (Figure 15), using the AUV REMUS. The spatial resolution of the observations are unique for this region, and the observations have helped reveal previously unknown features, such as a near shore buoyant plume that strongly affects the currents and stratification over the inner shelf. Other more ambitious efforts are underway to implement comprehensive observations of the California Current, using large networks of autonomous gliders with the goal of resolving the features responsible for cross-shelf fluxes of heat, salt, and nutrients (see case study on opposite page). Also, gliders are currently being used in integrated observing systems to monitor the development of harmful algal blooms off the west Florida shelf (see case study on p. 33).

Our understanding of the coastal ocean, and especially processes that affect the transport and exchange of physical, biological, and chemical properties, depends on the development and expansion of autonomous and Lagrangian observational capabilities. Traditional observational methods will never suffice, because large ships are too few and too expensive to make the necessary frequent observations, small boat operations have limited range and are too dependent on calm weather, and moorings lack the necessary spatial resolution. For ALPS to achieve their full potential as an observational tool for coastal oceanography, several technological advances will be required. Gliders will need an expanded instrument payload, including equipment such as an Acoustic Doppler Current Profiler (ADCP), and powered AUVs will need increased endurance and range, achieved through more efficient power management, larger batteries, or connections with underwater docking stations. Finally, to fully address problems related to coastal ocean transport and exchange, advances will be required in managing the large amounts of data resulting from the deployment of autonomous platforms such as gliders, the assimilation of these observations into models, and linking together observations from various points along the coast to better understand the system as a whole.

Fluxes in the California Current System

Charlie Eriksen, University of Washington

A network of gliders observing the entire continental U.S. Pacific Coast several hundred kilometers offshore would cost annually roughly what a single oceanographic ship costs to make a month-long cruise.

The California Current System is responsible for maintenance of the ecosystem encompassing the entire Pacific coast U.S. Exclusive Economic Zone and beyond. The consequences of its structure and variability are of environmental, economic, and military importance. The fluxes of heat, freshwater, and nutrients that it controls determine how, where, and when ocean productivity takes place.

Fluxes within the California Current System are poorly known and more poorly understood. While advection within the Pacific subtropical gyre and coastal upwelling generally determine physical structure, and this physical structure in a large part determines biological productivity, the specific processes that govern the ecosystem and its variation through the seasons, El Niño Southern Oscillations cycles, and the Pacific Decadal Oscillation have not been identified or understood. How the West Wind Drift across the Pacific bifurcates into the California and Alaska Currents is not known, nor are its seasonal and interannual cycles. Coastal upwelling occurs in squirts and jets, yet its overall efficacy in supplying nutrient-rich waters to the near surface where light penetrates is not well known. The current system is richly eddied but the role of these eddies is poorly understood.

To determine how the California Current System works requires additional observations. At present, regular ship-based surveys of the system are carried out roughly quarterly along several transects. These surveys provide a description that is too coarse both temporally and spatially to answer the questions of what fluxes are carried by the current system and what implications these have for the ecosystem. The current ship-based surveys are

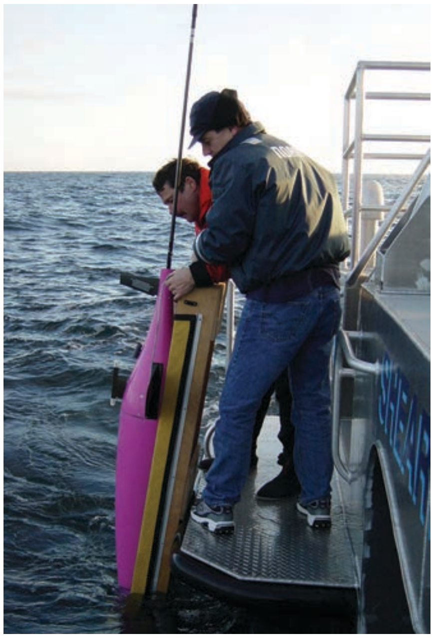


Figure 16. The Seaglider is one of several autonomous underwater vehicles that enable oceanographers to measure hydrographic, chemical, and biological fields on long sections across the oceans. This particular instrument can measure about 1000 profiles from the surface to a depth of 2 km over a track of about 6000 km. Each time it surfaces, it transmits data via satellite, at which time its course can be reset. The Seaglider is 1.8 m long and weighs 52 kg—a size and weight that allow easy launching and recovery by two people on a small boat.

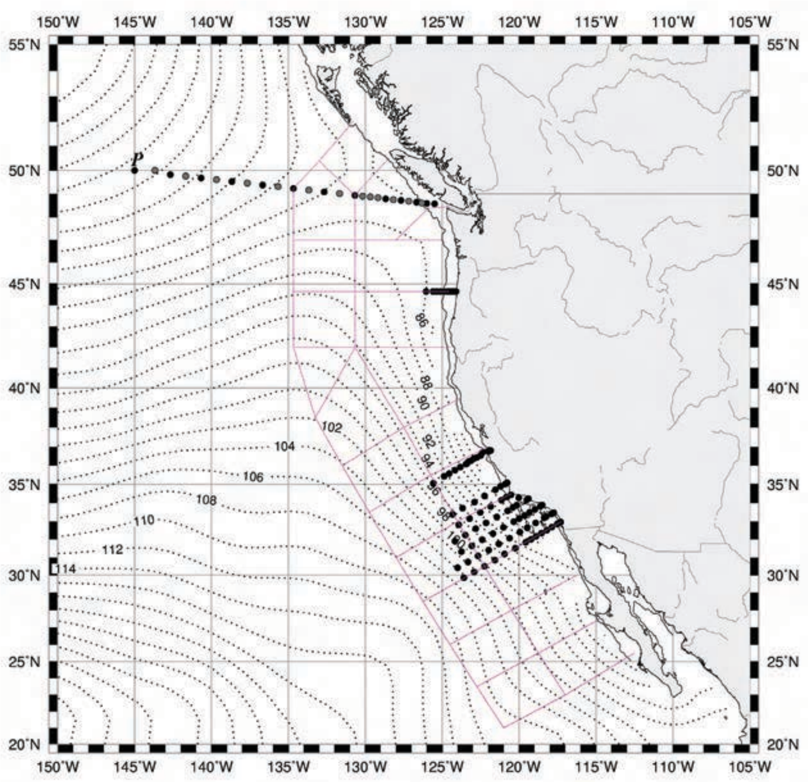


Figure 17. Schematic autonomous underwater glider sampling plan for the California Current System. Magenta sequences of dots are potential sampling tracks of a network of gliders, with locations of successive dives marked by circles 5 km apart. Solid dots show the location of the Line P, Newport, Monterey, and CALCOFI hydrographic casts made roughly quarterly by ships. Dotted curves indicate annual average dynamic topography (dynamic cm) with respect to 1 km depth. All glider transects would be repeated monthly, providing over a quarter million km of 1 km deep sections annually.

inadequate because coarse resolution in space and time contributes errors comparable to the signals. Dramatic increases in the density of ship-based observations are prohibited by cost.

Autonomous underwater gliders (Figure 16) offer an attractive solution to the problem of making regular observations across the current system extent and over seasonal and interannual time scales while resolving features of much smaller scale in space and time. A network of gliders observing the entire continental U.S. Pacific Coast several hundred kilometers offshore would cost annually roughly what a single oceanographic ship costs to make a month-long cruise. The dramatic difference in cost between ships and gliders derives from reliance on robotic machinery rather than on human labor to execute seagoing measurements. Gliders are controlled remotely from shore.

A schematic glider sampling plan of the California Current System is shown in Figure 17. The glider survey is laid out as a sequence of intersecting sections forming enclosed regions a couple of hundred km on a side. Fluxes of mass, heat, fresh water, oxygen, and chlorophyll can be estimated through the boundaries of each of these enclosed regions so that budgets of these quantities can be examined. Such sampling allows a regional map of flux convergence of the measured quantities to be constructed that covers the entire current system.

Glider surveys of the kind pictured will resolve fluxes at fine horizontal (several kilometers) and temporal (monthly) scales. Because of their low cost, a glider network can be maintained continuously for several years. Glider ranges and mission durations can be several thousand kilometers and several months, respectively. A network reaching several hundred kilometers to sea can rely on small boats on day trips from shore to maintain it. All data from the glider network would be archived in near real time.

Making Progress on Harmful Algal Blooms: Lessons from the Gulf of Mexico

Oscar Schofield, Rutgers University and Chris von Alt, Woods Hole Oceanographic Institution

Harmful Algal Blooms (HABs) directly impact human health and cause numerous trickle-down economic effects. In the western waters off Florida, blooms of the toxic dinoflagellate *K. brevis* (formerly *Gymnodinium brevis*) have occurred annually in the Gulf of Mexico 26 out of 27 years since records have been kept (K. Steidinger, pers. comm.), and the geographic extent of the blooms appears to have increased in recent years. These blooms have resulted in fish kills and reduced commercial seafood production and recreational fishing success along the coastlines of Alabama, Florida, Louisiana, Mississippi, North Carolina, and Texas. Economic impact studies showed a loss to Florida of nearly $20 M from a bloom in 1971 and more than $15 M from a 1973-74 bloom (Habas and Gilbert, 1974).

Little is known concerning the exact physical and/or chemical conditions providing for increased growth and, ultimately, accumulation of *K. brevis*. It is generally thought that *K. brevis* blooms develop offshore (Steidinger, 1975) and that physical forcing (water circulation, tides, wind) transports and concentrates cells within near-shore waters. One hypothesis suggesting offshore development is currently supported by experimental work and ship observations. The hypothesis suggests that *K. brevis* blooms are initiated 20 to 75 km offshore where the growth of another, non-toxic phytoplankton, *Trichodesmium spp.*, plays a critical role. Saharan dust transport and deposition help to fuel the growth of *Trichodesmium spp.*, which then releases dissolved organic nitrogen necessary for *K. brevis* growth. Because there are many steps that lead to *K. brevis* development, the initial steps involve low concentrations of phytoplankton throughout the water column (making bloom initiation difficult to detect by satellite), and the entire sequence may takes weeks to months to come to fruition, traditional shipboard strategies are inadequate. Integrated sensor packages on appropriate long-duration, autonomous platforms are needed to collect relevant data over the proper temporal and spatial scales. Autonomous platforms are now sufficiently robust and can maintain a continuous presence in offshore waters. AUVs could be used to characterize the phasing of *K. brevis* and *Trichodesmium* blooms in offshore waters as bio-optical instrumentation is now capable of detecting both phytoplankton species while simultaneously determining the relative concentration of colored dissolved organic nitrogen.

A competing idea is that nutrients from rivers play a role in initiating red tides. Accumulations of *K. brevis* cells are usually observed in nearshore waters. For example, blooms were located in close proximity to coastal waters associated with river discharges from Charlotte Harbor, FL (in 1998 and 1999) and northwest Florida (1999). Coastal fronts appeared to exist in locations where *K. brevis* abundance was greatest, suggesting that physical convergence fields may be especially important in increasing overall cell numbers. Terrestrial river flow may provide a secondary source of nitrogen (in the form of ammonia and/or dissolved organic nitrogen) and phosphorus, which fuels the *K. brevis* blooms. Again, developing a robust capability to continuously map meandering river plumes over a time scale of a month is difficult using traditional shipboard sampling strategies.

To make further progress on the *K. brevis* problem, observations need to be nested. Offshore measurements are required over temporal scales of at least a month, and over spatial scales of hundreds of kilometers. Nearshore, high-resolution spatial (meters) and temporal (hours) maps are required to define the physical and biological mechanisms associated with frontal boundaries and river plumes in coastal waters. Ideally, these observing platforms should be able to effectively cross frontal boundaries to provide high-resolution physical, chemical, and biological data. Moorings provide time series but do not provide the required spatial data. Drifters provide a Lagrangian perspective, ideal data for characterizing the temporal evolution of a feature within a water mass, but lack control when cross-frontal data are required. Autonomous vehicles provide the spatial/temporal data required for documenting the factors associated with *K. brevis* bloom dynamics across hydrographic gradients. Long-duration gliders and drifters are ideally suited for sampling this problem, and the sensor suites for optical properties and fluorescence are rapidly maturing (e.g., Figure 18).

To increase our understanding of the *K. brevis* problem, we need spatially coherent data to map the evolving structures over time. If the data are not spatially coherent, the spatial gradients for the dynamical balances cannot be resolved. Moored and fixed platforms will provide independent time series allowing the scientist to ask "what" happened, but they will not provide the data necessary to answer "why" it happened. It is clear that a combination of autonomous and Lagrangian platforms will be required to address this important scientific issue.

References

Habas, E.J. and C.K. Gilbert, 1974, The economic effects of the 1971 Florida red tide and the damage it presages for future occurrences, *Environ. Letters*, 6, 139-147.

Steidinger, K.A., 1975, Basic factors influencing red tides, In, V.R. LoCicero, ed., *Proceedings of the First International Conference on Toxic Dinoflagellate Blooms*, Massachusetts Science and Technology Foundation, 153-162.

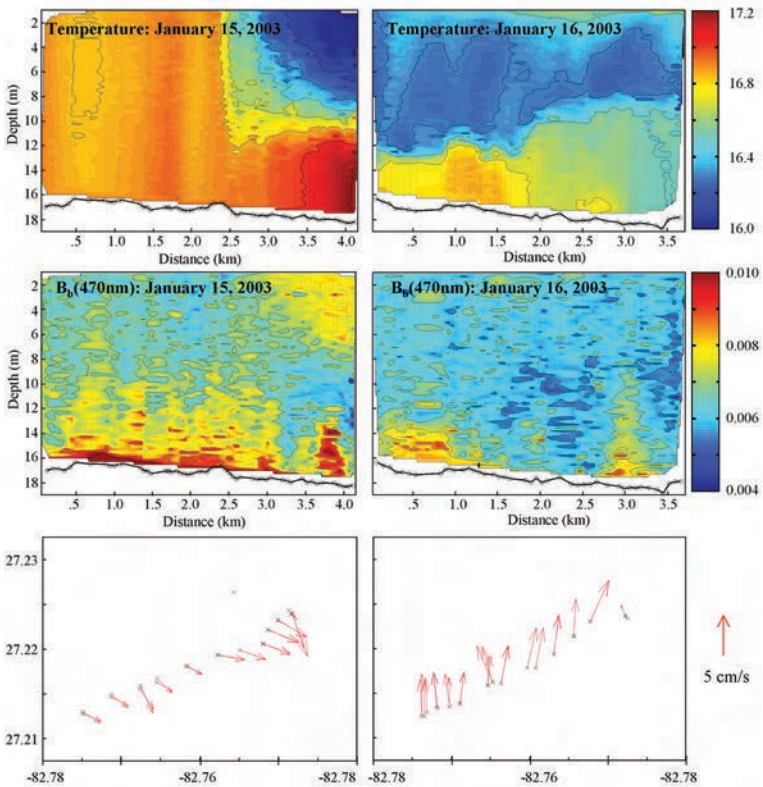


Figure 18. The Ecology of Harmful Algal Blooms (EcoHAB) program site on the West Florida Shelf provided a perfect setting for field trials of Slocum gliders to evaluate their ability to detect and monitor harmful algal blooms during Operation Gulfcast (January 12 – 16, 2003). Based out of Mote Marine Laboratory in Sarasota, FL, a team of Rutgers University and Mote Marine Laboratory scientists conducted daily glider deployments on a historical EcoHAB transect line during a red tide event. The gliders mapped physical and optical features over a 3.5 – 5 km transect and transmitted real-time data back to the R/V *Eugenie Clark*, where the information was immediately processed and displayed (left). Data showed that a storm event altered local hydrography, currents, and *in situ* particle loads.

Introduction

Mary Jane Perry, University of Maine

In science as in life, perspective is everything. Nets and sampling bottles have been mainstays of plankton and nekton sampling from the inception of biological oceanography. The picture that they have painted in space is decidedly sparse. It has been a struggle on the time axis to provide a moving picture more highly resolved than seasonal or diurnal. The bane of sampling design and implementation in ecosystem and food-web ecology is the rare but significant event. Most rare events are missed with traditional sampling. As discussed in the case study on p. 37, the role of unpredictable events in influencing planktonic community processes is recognized, but difficult to quantify.

Traditional sampling has influenced food-web perspectives in more subtle ways. The diversity of plankton organisms can readily be seen with new imaging systems such as the Video Plankton Recorder (Figure 19). Automated image analysis of video images can provide information on species abundance more rapidly than traditional analysis. Nets often damage fragile organisms during collection. Gelatinous zooplankton, for example, were usually discarded from net hauls because they not only preserved poorly but also "slimed" their better-preserving net-mates and made them hard to identify.

Satellite remote sensing has added a large-scale, rapidly updated context for point samples, and towed optical sensors have filled in missing information in the depth dimension. Although the satellite context is invaluable, its scale is far removed from the scale of individual interactions that define food webs and constitute the flows along them. Tow tracks are usually designed to limit aliasing that confounds temporal and spatial variability.

Autonomous vehicles and drifters mark both dramatic and subtle shifts in perspective. Lagrangian floats are planktonic, and AUVs and gliders are nektonic by the usual scaling of ambient horizontal velocity of currents to propulsion velocity. Constraints on sampling by these instruments parallel similar constraints in plankton and nekton themselves (see case study on p. 39). Simply working with data records that might have been gathered by attaching sensors to planktonic or nektonic animals will give greater understanding of the constraints under which such animals operate.

More subtly, ecological interpretation of data records from floats, gliders, and AUVs must deal with the same issue of encounter rate faced by submarines searching for targets or animals searching for food. Interpretations and predictions of optimal behavior in both cases hinge on underlying models. Synergies can be expected between the evolution of modern resource-patch models and interpretation of data records from platforms that are not truly Lagrangian but follow motions choreographed by the investigator. Foragers maximizing their respective rates of gain are predicted and found to spend more time in high-density patches of resources. Particular turning rules are effective in keeping hungry foragers in patches (Grünbaum, 1998), and particular movement rules of a glider or AUV will serve a data-hungry instrument.

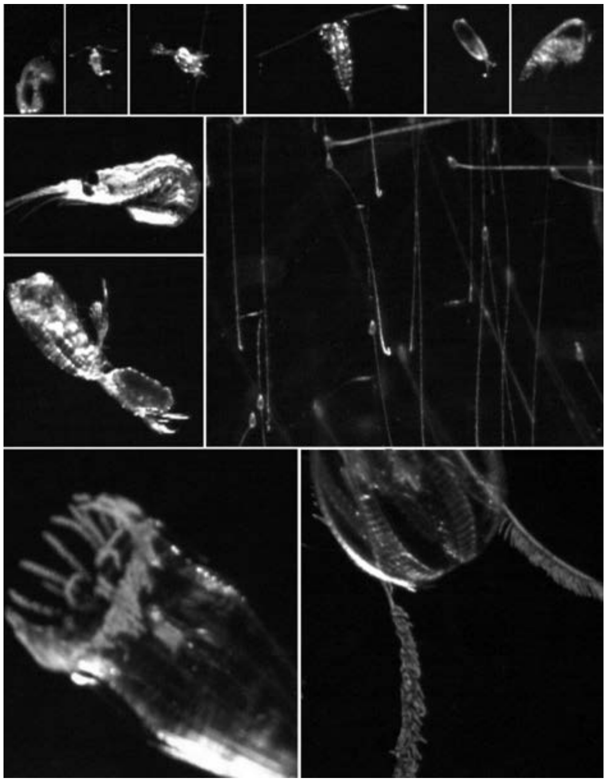


Figure 19. New imaging systems such as the Video Plankton Recorder (VPR), ZOOVIS, and SIPPER are capable of documenting the distributions of meso- and macro-planktonic organisms with spatially coregistered environmental data on fine scales. These VPR images illustrate just some of the diversity of zooplankton present in the Gulf of Maine. Spatially explicit data on the distributions of predators, competitors, prey, and hydrography are an essential precursor for deciphering the complex interactions that occur within planktonic communities. Image courtesy of Mark Benfield, Louisiana State University.

Patches are only available to be utilized by a forager or sampled by a platform if travel time to reach them is shorter than the longevity of the patch (Grünbaum, 2002). This simple but powerful conclusion goes a long way toward explaining food-web connections, i.e., which patches of which species can be accessed by a forager with particular movement rules. Conversely, analogous models will reveal the patch dynamics that are available to instruments traveling in particular ways. Patch growth and demise are virtually impossible to characterize from ship. Study of these critical ecological phenomena will benefit immensely from the new technologies.

Consumers as well as their resources aggregate. As groups of AUVs or gliders operate together, they will face similar problems and synergies as do schooling animals. Ambient water motions may either enhance or hinder the schooling behavior (Flierl et al., 1999), and self-organization emerges from simple rules (Parrish et al., 2002). Developing algorithms for coordinating AUVs or gliders will again transfer intuition both to and from the analysis of schooling foragers. We are learning to swim with the sharks and float with the plankton.

References

Flierl, G., D. Grünbaum, S. Levin and D. Olson, 1999, The interplay between behavior and physics, *J. Theor. Biol*, 196, 397-454.

Grünbaum, D., 1998, Using spatially explicit models to characterize foraging performance in heterogeneous landscapes, *Am. Nat.*, 151, 97-115.

Grünbaum, D., 2002, Predicting availability to consumers of spatially and temporally variable resources, *Hydrobiol.*, 480, 175-191.

Parrish, J.K., S.V. Viscido, and D. Grünbaum., 2002, Self-organized fish schools: An examination of emergent properties, *Biol. Bull.*, 202, 296-305.

CASE STUDY

Understanding Planktonic Ecosystems

Mark C. Benfield, Louisiana State University and Timothy J. Cowles, Oregon State University

Planktonic components of marine communities are critically important. These taxonomically diverse groups (Figure 19) mediate biogeochemical cycling and carbon flux, and have a strong influence on the population dynamics of higher trophic levels, including those that are fished. Although the importance of planktonic communities is well accepted, understanding of the physical, chemical, and biological conditions that regulate the distribution and abundance of planktonic biomass is limited, and little information exists on the *in situ* growth and mortality rates of the populations of organisms that constitute that biomass. To understand the processes that regulate the distributions, abundances, and rates within planktonic assemblages requires knowledge of the "ecosystem rules."

Determining ecosystem rules is particularly difficult in planktonic communities. In a recent review, McCarthy et al. (2002) emphasized that, "We do not yet know which are the dominant processes and which are the scales of interaction that give rise to any particular configuration of a marine ecosystem and its environment." They viewed this ignorance as a central problem in contemporary, interdisciplinary ocean science. Planktonic communities have a strong influence on the configuration of marine ecosystems yet they operate in a Lagrangian framework on time (seconds to days) and space (centimeters to hundreds of kilometers) scales that are difficult to document. To truly understand how planktonic systems function, requires an extended Lagrangian presence in these communities. This presence must provide observations and measurements of biology, chemistry, and physics on the time and space scales that are important to planktonic organisms.

Much of the current knowledge of planktonic systems has come from isolated samples collected by ships, towed systems, or from laboratory experiments. Ocean-observing systems have also provided new insights albeit from an Eulerian framework. Sampling from point platforms is limited to brief periods when vessels and working conditions are favorable. There is an increasing recognition that periodic energetic events, particularly those that introduce new nutrients into the mixed layer and euphotic zone, can have profound influence on the composition of planktonic communities and their concomitant biogeochemical processes. Such events are difficult to predict and frequently occur at times when sea states limit observational abilities. We need to supplement shipborne studies with a continuous monitoring presence among the plankton.

New sensors and platforms make an extended observational presence in the plankton feasible and cost-effective. Autonomous Lagrangian platforms are the only tools that can provide an observational time-series of phytoplankton and zooplankton activities (e.g., growth, species succession, behavior, grazing, molting, mating, predation) within defined parcels of water. Eulerian sampling of water parcels provides only "snapshots" in time and space, and requires the assumption that the Eulerian observations are representative of the "mean" condition. Moreover, quasi-synoptic sampling of a local domain (e.g., 10 x 10 km) is feasible and cost effective with a pod of autonomous vehicles—thus permitting a better understanding of spatial scales of coherence of planktonic distribution patterns. Observations will be coupled in both time and space on the spatial scales that are important. For example, we will be able to measure changes in nutrient concentrations in conjunction with changes in fluorescence and phytoplankton abundance. Avoidance artifacts associated with behavioral responses to the sampling platform will be reduced.

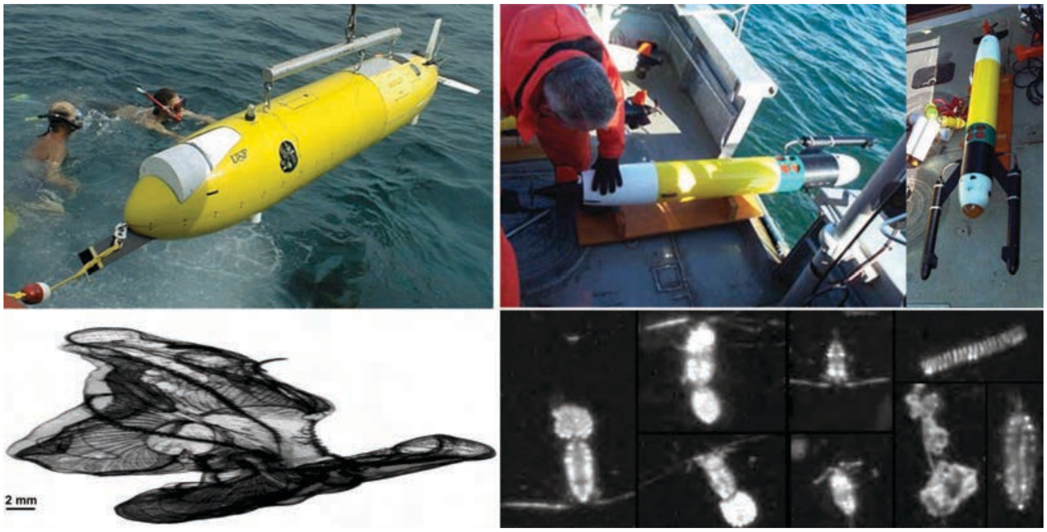


Figure 20. AUVs are already carrying imaging systems to quantify planktonic communities. Upper Left: Florida Atlantic University's *Ocean Explorer* AUV equipped with the SIPPER imaging system developed by the University of South Florida (Photo courtesy of Chad Lembke). Lower Left: a lobate ctenophore imaged by SIPPER (Image courtesy of Andrew Remsen). Upper Right: Deployment of the Woods Hole Oceanographic Institution's REMUS AUV equipped with a Video Plankton Recorder (VPR) (Photo courtesy of Cabell Davis). Lower Right: Examples of planktonic copepods, marine snow, and a diatom imaged by the VPR on REMUS. Wavelet compression produces small files that can still be correctly classified using automated recognition software (Images courtesy of Cabell Davis).

Lagrangian platforms open a broad range of potential research avenues. They include time-series sampling for phytoplankton and zooplankton biomass through the monitoring of changes in bio-optical and bio-acoustical properties (including spectra for both) permitting resolution of intermittent events and the ecological responses to such events. Lagrangian observations on relevant scales (centimeters to hundreds of meters) within the mixed layer are an exciting possibility. These observations likely need to be nested within larger contexts (kilometers), complementing point observations from ships, limited 3-dimensional observations from towed platforms, and essentially 2-dimensional synoptic observations from satellites, aircraft, and acoustics. ALPS systems can provide 4D (x, y, z, time) observations of processes, distributions, and abundances over extended periods. ALPS systems could also benefit from repeated passes of moored sensor systems, or through a domain that is well resolved by remote-sensing systems. Finally, the community's capability to run assimilative models in real- or near-real-time using telemetry from oceanographic sensors has advanced. Coupled biological-physical models based on improved ocean circulation models have the potential to provide insights into processes that cannot be easily measured. Such models will require sea truth and reparameterization from ALPS data.

To make optimal use of autonomous Lagrangian platforms, sensor miniaturization, particularly of optical sensors, is required. There are also needs for: more efficient and powerful energy storage systems; incorporation of other sensors (e.g., electromechanical sensors) into pumped sensor streams to protect systems from fouling; and systems based on micro- and nano-technology capable of detecting the signatures of biomarkers left behind by living organisms. Improved technologies for maintaining neutral buoyancy by sensor packages are essential for development of discrete sampling systems that can repeatedly sample within narrow depth ranges.

References

McCarthy, J.J., A.R. Robinson, and B.J. Rothschild, 2002, Chapter 1: Introduction - biological-physical interactions in the sea: emergent findings and new directions. In, *The Sea*, Volume 12, edited by Allan R. Robinson, James J. McCarthy, and Brian J. Rothschild, John Wiley and Sons, New York.

Days in the Lives of Fishes

Mark C. Benfield, Louisiana State University

Mobile marine organisms such as pelagic fishes, cephalopods, and Antarctic krill make up a large proportion of global fisheries landings. Most commercially fished stocks are at, or beyond, maximum sustainable levels of exploitation. Moreover, recent data suggest that fisheries for large, predatory species have dramatically reduced the abundances of these highly mobile taxa (Meyers and Worm, 2003). New and innovative observing platforms are needed that will permit study of mobile nekton in their habitat, while they are moving, and over extended periods. Such data are essential for effective management of these stocks.

Study of this mobile nekton poses unique challenges. Many species, such as tunas, migrate over long distances, developmentally as well as seasonally. Fish and other nekton interact with their environments on a wide variety of time scales, ranging from seconds and minutes (e.g., predator-prey interactions), hours (e.g., diel vertical migration, schooling and dispersal), days (e.g., spawning aggregations), to weeks and months (e.g., feeding and spawning migrations). The mobility of these organisms permits them to operate on space scales that range from tens to hundreds of meters (school dimensions) through kilometers (daily movements) and hundreds to thousands of kilometers (annual movements). In addition, these animals possess highly developed sensory systems that allow them to detect and avoid most sampling systems. Hydroacoustic techniques have been used to census fish schools, but the information that such techniques provide is generally qualitative and may be biased by avoidance of survey vessels and failure to resolve mixed species and size classes.

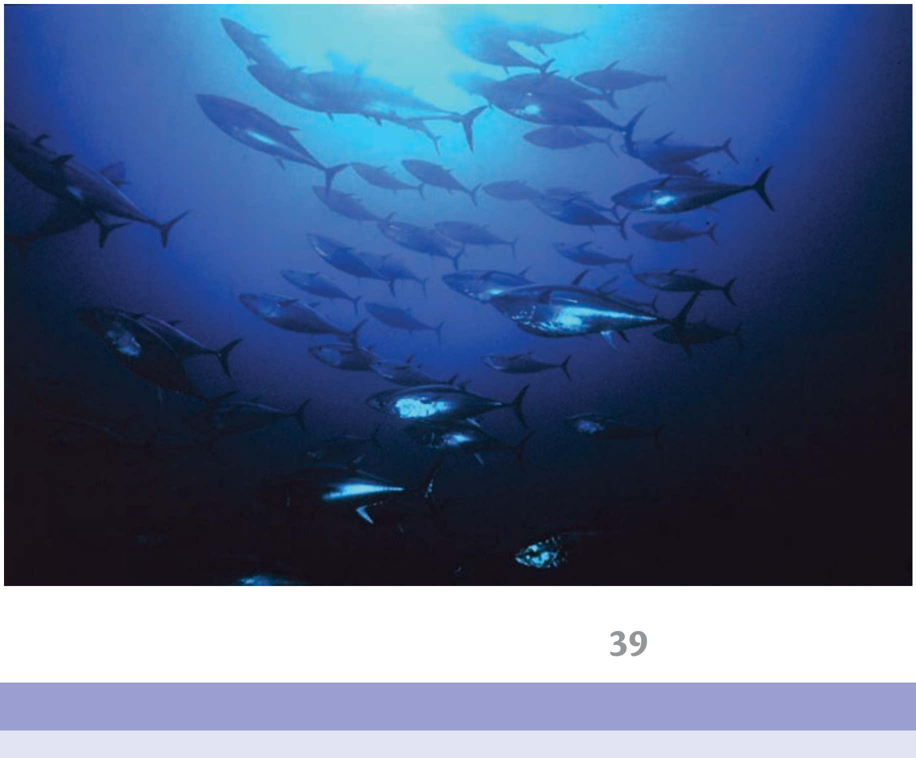


Figure 21. Studying the ecology of highly migratory pelagic fishes such as these tunas poses unique challenges for biological oceanographers. Their mobility requires platforms that are capable of keeping up with the fish during their daily movements without altering their behavior. Rapid AUVs capable of high endurance may soon be able to follow fish marked with acoustic tags. Image courtesy of the NOAA Photo Library, Photo Credit: Danilo Cedrone.

Predictions of standing stock, reproductive success, and survivorship could be improved with more information about how these mobile organisms interact with their environments, including how and where they spend their time and what cues they exploit to find food and mates and to avoid predators. Obtaining this information requires means of studying their activities and migrations that are non-invasive and capable of surveying their environments on time and space scales relevant to their ambits. AUVs and new tagging technologies offer means to accomplish these objectives. Deployment of groups of AUVs in the vicinity of fish schools containing acoustically tagged individuals would allow tracking of movements and behaviors of pelagic fishes while documenting their biological and physical ambits. AUVs have the potential to follow fish schools, particularly when individuals within the school have been tagged with active or transponding tags. When the data stream produced by the tags includes depth information and the AUVs have an estimate of their positions, it will be possible for them to follow schools while measuring environmental characteristics within the depth stratum favored by the school. Though it is unlikely that AUVs could keep up with rapid swimmers such as the Atlantic bluefin tuna, drifters equipped with GPS and hydrophones could be seeded along likely migratory routes to provide a record of the times and locations that tagged individuals were detected. High-speed, surface, snorkeling vehicles or submersible AUVs capable of increased endurance (e.g., Ferguson et al. 1999) will likely produce a generation of systems that are capable of keeping up with rapidly swimming fishes.

AUVs equipped with scientific echosounders could perform acoustic surveys of fish schools while restricting avoidance of the survey platform by its targets (see *Autosub* case study on p. 45). Multibeam acoustic systems are emerging as a potentially valuable tool in fisheries and zooplankton ecology. AUVs have already been equipped with multibeam echosounders (George et al. 2002). Properly calibrated multibeam systems capable of recording water-column backscattering intensity could undertake stealthy volumetric fish stock and distribution assessments. Migrations through the open ocean or within coastal boundary currents could be mapped using drifters equipped to listen for implanted acoustic tags. Combination of ALPS with more conventional platforms (ships) and emerging technologies (such as lidars) to locate pelagic fish schools (Brown et al. 2002), will vastly improve ability to quantify and understand nektonic organisms.

To make further progress on this problem, requires: propulsion and energy storage systems that improve AUV speed and endurance; technologies to reduce hydrodynamic and propulsive noise; smaller, internally recording echosounders operating at multiple acoustical frequencies; higher-bandwidth and more powerful acoustic modems for data transfer among AUVs and between AUVs and other platforms; artificially intelligent control software to improve tracking capabilities for rapidly moving targets; and improved and smaller implantable tags to telemeter physiological and environmental data from fishes.

References

Brown, E.D., J.H. Churnside, R.L. Collins, T. Veenstra, J.J. Wilson, and K. Abnett, 2002, Remote sensing of capelin and other biological features in the North Pacific using lidar and video technology, ICES *J. Mar. Sci.*, 59, 1120-1130.

Ferguson, J., A. Pope, B. Butler, and R. Verrall, 1999, Theseus AUV - Two record breaking missions, *Sea Technology*, 40, 65-70.

Meyers, R.A. and B. Worm, 2003, Rapid worldwide depletion of predatory fish communities, *Nature*, 423, 280.

George, R.A., L. Gee, A.W. Hill, J.A. Thomson and P. Jeanjean, 2002, High-resolution AUV Surveys of the Eastern Sigsbee Escarpment, *Proceedings of the 2002 Offshore Technology Conference*, Houston, Texas, 6–9 May 2002, OTC 14139, pp. 1-12.

HIGH-LATITUDE SCIENCE ISSUES

Introduction

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ALPS technologies offer critical paths for extending observational capabilities to regions subject to seasonal or permanent ice cover.

The high-latitude oceans serve as freshwater sources and heat sinks for the global thermohaline circulation, exerting significant influence on ocean general circulation and climate variability. Warm surface flows carry heat toward the poles where intense heat loss to the atmosphere drives densification and produces an equatorward return flow of intermediate and bottom waters. This exchange establishes the meridional overturning circulation (MOC) which, when combined with the inter-basin exchange permitted by the zonally unbounded Southern Ocean geometry, supports the global thermohaline circulation. High-latitude convection thus ventilates the many mid- and low-latitude density layers that outcrop in the polar/subpolar oceans, setting subsurface density structure and removing carbon to the ocean interior.

In contrast, net precipitation in the polar regions produces an equatorward freshwater flux that is largely confined to the upper ocean. Freshwaters exiting the Arctic can form a low-density surface barrier that inhibits convective overturning at the deep water formation sites in the Labrador and Greenland Seas, modulating the strength of the MOC and thus the exchange of heat from equator to pole. The high-latitude freshwater balance plays additional roles in the climate system. For example, the combination of Arctic riverine discharge and brine rejection during sea ice formation generates a strong halocline which insulates the ice from the warmer waters below. Processes that impact high-latitude heat and salt balances (and thus circulation) exert strong influences on global climate through this series of connections and feedbacks.

Geographic remoteness, severe operating conditions, and issues associated with ice cover have hindered high-latitude measurement efforts and thus limited our understanding of polar and subpolar regions. Icebreakers, aircraft, and occasionally submarines provide access for hydrographic and mooring programs, but are costly and unable to operate in many areas of interest. The presence of permanent or seasonal ice cover makes year-round time series extremely difficult to obtain. There are relatively few ice-capable ships, and these cannot readily access difficult regions such as the Canadian Basin. Weather and available daylight restrict aircraft operations to narrow time windows. Likewise, though many critical processes occur in the upper ocean, the threat posed by overhead ice prevents moored instruments from sampling the region directly below the ice bottom. The resulting paucity of data has left many broad, fundamental questions unanswered and places some aspects of polar oceanography on an exploratory footing reminiscent of earlier periods of lower latitude science. Important outstanding issues include:

- Mapping the hydrography, pathways, and inter-basin connections that characterize Arctic regional circulation.
- Exploring the dynamics and variability of the Arctic Ocean boundary current, which carries Pacific water through to the Atlantic and transports heat from the Atlantic into the basin interior.
- Understanding freshwater exchange with the Arctic and its response to decadal-scale climate fluctuations.
- Quantifying ice draft variability and the role of ice in the freshwater balance.
- Investigating the processes governing circulation and watermass transformation beneath Antarctic ice shelves and along Arctic and Antarctic ice margins.
- Understanding the dynamics that govern circulation over broad, shallow Arctic shelves and the processes that drive exchange with the adjoining basins.

Efforts to address these issues might range from the intensive, short-duration process studies (time scales of hours/days and spatial resolutions < 1 km) required to quantify the fine-scale dynamics governing watermass transformation to long-term (years to decades) basin-scale programs aimed at understanding the response of freshwater exchange to climate variations.

Application of developing ALPS technologies could ease many of the cost and accessibility issues that currently hinder high-latitude measurement programs. Autonomous floats have been successfully employed in studies of deep water formation in the Labrador Sea (Lavender and Davis, 2002; Steffen and D'Asaro, 2002) and exchange across the Antarctic Circumpolar Current (Gille, 2003), providing an extensive set of measurements that would have been impossible to obtain using combinations of ship-based surveys and moorings. These deployments illustrate the use of ALPS technologies to collect measurements over extended time periods (2 years or longer) in remote, operationally difficult (though not inaccessible) locations.

ALPS technologies offer critical paths for extending observational capabilities to regions subject to seasonal or permanent ice cover. Quasi-synoptic survey capability, similar to that used in investigations of mesoscale and fine-scale dynamics in ice-free regions, would facilitate many important process studies. A growing class of powered AUVs (e.g., *Autosub*, *Bluefin Odyssey* and the Atlantic Layer Tracking Experiment (ALTEX) vehicle) promises the ability to conduct limited-duration surveys (hours to days) beneath the ice. The Lead Experiment (Morison

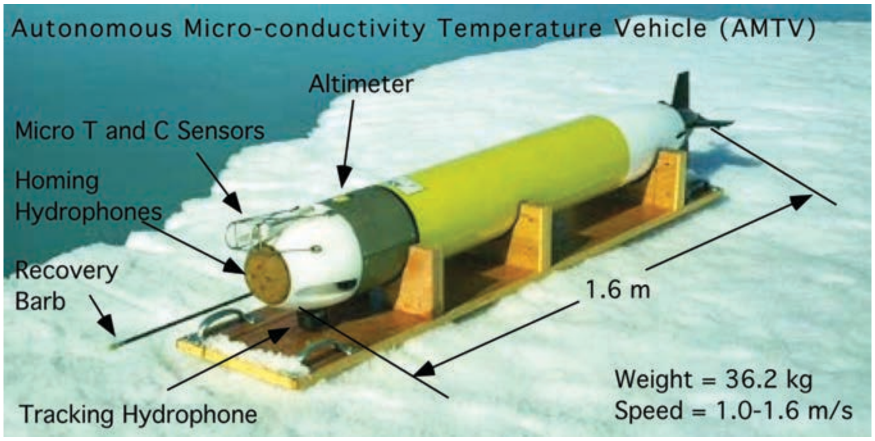

Figure 22. An opening in the sea ice cover (lead) results in strong spatial variation of the surface fluxes of salt, heat, and momentum. The Autonomous Micro-conductivity and Temperature Vehicle (AMTV) was developed to study spatial variability by obtaining horizontal sections of mean and turbulent quantities under open water, thin ice, and thick ice. The AMTV is based on an early version of the REMUS vehicle to which rapid-response ocean sensors, upward-looking sonar (for ice draft measurement), and an inertial motion sensing unit were added. The AMTV was used in a study of summer leads during the Surface Heat Budget of The Arctic Ocean (SHEBA) experiment in 1998. Figure courtesy of James Morison, APL/University of Washington and Dan Hayes, British Antarctic Survey.

and McPhee, 1998) and the Surface Heat Budget of the Arctic Ocean program (Hayes and Morison, 2002) provide pioneering illustrations of how AUVs might be used to conduct process studies beneath the ice (Figure 22). These vehicles execute preprogrammed patterns, profiling in the vertical, following the underside of the ice, or tracking a specific property surface. Inertial navigation can be employed for short-range missions, eliminating the need to deploy a separate array of navigation beacons. Though range-limited (typically < 100 km), these platforms offer unprecedented access to the ice shelf boundaries and could be employed in studies of shelf dynamics, watermass transformation processes, and shelf-open basin exchange. The vehicles could also be carried into basin interiors to access regions far beyond the ice edge. Because these operations require ships, an effective strategy might be to combine ship-based surveys with AUV deployments, using the AUVs to provide three-dimensional context and extend observational "reach" to the underside of the ice. The Autonomous Polar Geophysical Explorer (APOGEE) project illustrates another AUV-based strategy for providing access to ice-covered regions. This vehicle will land an ocean bottom seismometer on the Nansen-Gakkel Ridge where it will winter over, returning to meet a recovery vessel the following year.

Adaptations of extended-endurance platforms such as autonomous gliders (Eriksen et al., 2001; Sherman et al., 2001), profiling floats (Davis et al., 2001), and heavily instrumented Lagrangian floats (D'Asaro, 2003) offer promising avenues for leveraging ALPS technologies to access ice-covered regions. Relatively low cost and long mission durations (months to years) make these platforms ideal for circulation studies and long-term monitoring efforts. Begun in 1979, the International Arctic Buoy Program (IABP) provides an early example of drifter technology applied to long-term monitoring of ice-covered environments. Buoys mounted on the ice surface drift with the ice while providing near-real-time measurements of position (and thus ice motion), surface pressure, and air temperature. Gliders can also hold station (acting as profiling moorings) or transit between prescribed way points, executing tightly spaced (kilometers) profiles along the route. Significantly, this class of platforms can periodically profile upward to the ice bottom while spending the balance of their time deep enough to be protected from collisions. Typically, these platforms navigate using GPS and employ satellite telemetry (e.g., ARGOS, Iridium, and ORBCOM) to exchange data and instructions with shore-side command centers, making them highly dependent on surface access. Efforts are currently underway to integrate RAFOS navigation into gliders and floats, which will enable them to determine their position by triangulating from an array of moored sound sources. High-latitude salinity stratification creates a surface sound channel that forces rays to reflect off the ice bottom, producing large transmission losses that depend on ice bottom roughness and water depth. When operating beneath the ice, RAFOS frequency (260 Hz) sources achieve ranges of only 150-300 km (Jin et al., 1994; Manley et al., 1989), an order of magnitude poorer than typical mid-latitude performance. These relatively short ranges place practical limitations on the size of the ensonified region. A modest number of sources can provide navigation for regions spanning several hundred kilometers, facilitating studies of straits, ice shelves, and select regions of major basins. Large-scale circulation studies and trans-Arctic sections would require either an extensive network of sources or an alternative technology. Although RAFOS navigation eliminates the need to surface, it does not address telemetry issues. Under-ice deployments thus require a high degree of vehicle autonomy and depend on post-mission interrogation via satellite (upon encountering open water) or physical recovery to access the data stored aboard. Ice-capable floats and gliders can also be used in tandem with conventional moorings and ship-based operations to provide complementary measurements. Consider, for example, the monitoring of an ice-covered strait. A moored array could provide Upward Looking Sonar (ULS) and Acoustic Doppler Current Profiler (ADCP) measurements for estimating ice draft, ice velocity, and upper ocean currents. Gliders could contribute high-resolution spatial coverage, collecting profiles of physical, optical, and (eventually) biogeochemical variables that extend upward to within a few meters of the ice bottom. The combined system would provide year-round characterization of liquid and ice fluxes that would be impossible to obtain using a single platform.

The many unresolved high-latitude science issues suggest future development paths for ALPS technologies. Operation of powered AUVs and gliders in ice-covered regions requires robust autonomy, especially for extended missions that are subject to a wide range of environmental conditions. Designing and implementing appropriate behavior is a difficult, ongoing task. Development of a basin-scale navigation system for under-ice operations would dramatically improve the utility of AUVs, gliders, and floats. Such a system would facilitate extensive float/glider efforts, which could efficiently characterize basin-scale circulation. The availability of data telemetry during under-ice operations would dramatically reduce experimental risk, as platform loss would no longer be synonymous with catastrophic data loss. The ALTEX AUV employs data capsules designed to melt through overhead ice to gain access to the surface, though alternative approaches might include periodic transfer to moored data depots or to other vehicles. Current platforms impose strong restrictions on payload size and power consumption, severely limiting the selection of acceptable sensors. Simultaneous development of new sensor technologies, especially for biogeochemical properties, and of vehicles with enhanced endurance and payload capability, would facilitate interdisciplinary observational efforts. Ideally, biological and chemical measurements would be conducted with the same spatial and temporal resolution as the simpler physical (e.g., temperature and conductivity) measurements. Careful attention must be paid to issues of size and power consumption when developing sensors for autonomous platforms. Shallow, high-latitude shelves remain resistant to measurement efforts. Ice scouring poses a serious threat to bottom-mounted instrumentation while the region between the ice and the seabed is often too narrow to permit AUV, float, or glider operations. The instrumenting of shallow, ice-covered shelves presents a difficult challenge that will likely require a combination of conventional (trawl-resistant bottom landers) and ALPS technologies. System designs may need to be capable of tolerating significant losses while still providing useful data return.

References

D'Asaro, E.A., 2003, Performance of autonomous Lagrangian floats, *J. Atmos. and Ocean. Tech.*, 20, 896-911.

Davis, R.E., J.T. Sherman, and J. Dufour, 2001, Profiling ALACEs and other advances in autonomous subsurface floats, *J. Atmos. and Ocean. Tech.*, 18, 982-993.

Eriksen, C.C., J.T. Osse, R.D. Light, T. Wen, T.W. Lehman, P.L. Sabin, J.W. Ballard, and A.M. Chiodi, 2001, Seaglider: A long-range autonomous underwater vehicle for oceanographic research, *IEEE Journal of Oceanic Engineering*, 26, 424-436.

Gille, S.T., 2003, Float observations of the Southern Ocean. Part 2: Eddy fluxes, *J. Phys. Oceanogr.*, 33, 1182-1196.

Hayes, D.R. and J.H. Morison, 2002, Determining turbulent vertical velocity, and fluxes of heat and salt with an autonomous underwater vehicle, *J. Atmos. Ocean. Tech.*, 19, 759-779.

Jin, G., J.F. Lynch, R. Pawlowicz, and P. Worcester, 1994, Acoustic scattering losses in the Greenland Sea Marginal Ice Zone during the 1988-89 Tomography Experiment, *J. Acous. Soc. Amer.*, 96, 3045-3053.

Lavender, K.L. and R.E. Davis, 2002: Observations of open-ocean deep convection in the Labrador Sea from subsurface floats, *J. Phys. Oceanogr.*, 32, 511-526.

Manley, T.O., J.-C. Gascard, and W.B. Owens, 1989, The Polar Floats Program, *IEEE Journal of Oceanic Engineering*, 12, 186-193.

Morison, J.H. and M.G. McPhee, 1998, Lead convection measured with an autonomous underwater vehicle, *J. Geophys. Res.*, 103, 3257-3281.

Sherman, J.T., R.E. Davis, W.B. Owens, and J.R. Valdes, 2001. The autonomous underwater glider "Spray," *IEEE Journal of Oceanic Engineering*, 26, 437-446.

Steffen, E. and E.A. D'Asaro, 2002, Deep convection in the Labrador Sea as observed by Lagrangian floats, *J. Phys. Oceanogr.*, 32, 475-492.

Information on the Web

MARVOR floats (PALACE floats with RAFOS receivers):
www.ifremer.fr/dtmsi/produits/marvor/marvor.htm

APOGEE
www.whoi.edu/science/PO/arcticgroup/projects/apogee.html

AUTOSUB
www.soc.soton.ac.uk/SOES/MSC/OC/CEO/aui/aui.html

Observing Under the Ice with the *Autosub* AUV

Gwyn Griffiths, Southampton Oceanography Centre, UK

When the UK Natural Environment Research Council (NERC) began its support for the *Autosub* program back in 1989 it was clear that one of the key science areas that would benefit enormously through the use of an AUV was polar oceanography. It is to the credit of polar oceanographers that they kept faith for over a decade while the engineers developed the vehicle, as *Autosub's* first under-ice missions did not take place until 2001. When working together—engineers, scientists, and funding agencies—a collective vision can drive marine science forward.

Within NERC's *Autosub* Science Missions thematic program (1998-2001), Drs. Brierley, Fernandes, and Brandon's USIPS project combined studies of pelagic fisheries in the North Sea (Fernandes et al., 2000a,b, Brierley and Fernandes, 2001) with studies of krill (*Euphausia superba*) distribution and sea-ice thickness in the Weddell Sea (Brierley at al., 2002, 2003). While this combination might seem strange, it made excellent sense in that the key observations for the three studies were to be made with one instrument—the EK500 scientific echo sounder. Thus, the risk of failure due to sensor problems during the Antarctic campaign would be reduced through prior experience in the North Sea.

This strategy worked well. Brierley et al. used the *Autosub* to test the null hypothesis that there was no difference in the distribution of krill in open water and under sea ice. The vehicle made the observations with its upward-looking EK500 sounder at 38 and 120 kHz by cruising at a typical depth of 150 m from north of the ice edge, under the marginal ice zone and beneath more consolidated pack ice for 20-25 km (maximum penetration 27 km in to the ice covered zone) before returning to open water for recovery (Figure 23). In the meantime, on the RRS *James Clark Ross*, an identical sounder was used to make observations of krill distribution on reciprocal tracks in open water. Seven such missions were carried out to establish the degree of confidence in the observations. The results were clear—in a band from 1 to 13 km from the ice edge, the under-sea ice krill population was over five times that in open water (Brierley et al., 2002).

While gathering krill echo information from the water column, the sounder also measured the travel time (distance) to the under side of the sea surface or sea ice. When combined with the pressure sensor data for vehicle depth, this enabled Brandon to estimates sea ice draft, hence thickness. Observations of ice draft from over 250 km under sea ice are currently being studied.

The successful outcomes of the USIPS project under sea ice were an important factor in NERC's decision to fund a subsequent thematic program—*Autosub* Under Ice (AUI). AUI (2002-2006) has as its focus multidisciplinary studies under floating ice shelves in Antarctica and Greenland. Here, the ice is not meters thick and discontinuous, as sea ice, but hundreds of meters thick and continuous, being the floating parts of continental ice sheets. The AUI program aims to study, *inter alia*: water mass properties, melting, and refreezing; seabed morphology; the stratigraphy of the upper sediments; the morphology of the underside of the ice shelf; the distribution of macrobenthos and the relationships between ice shelf, polynya, and sea ice. The program comprises three

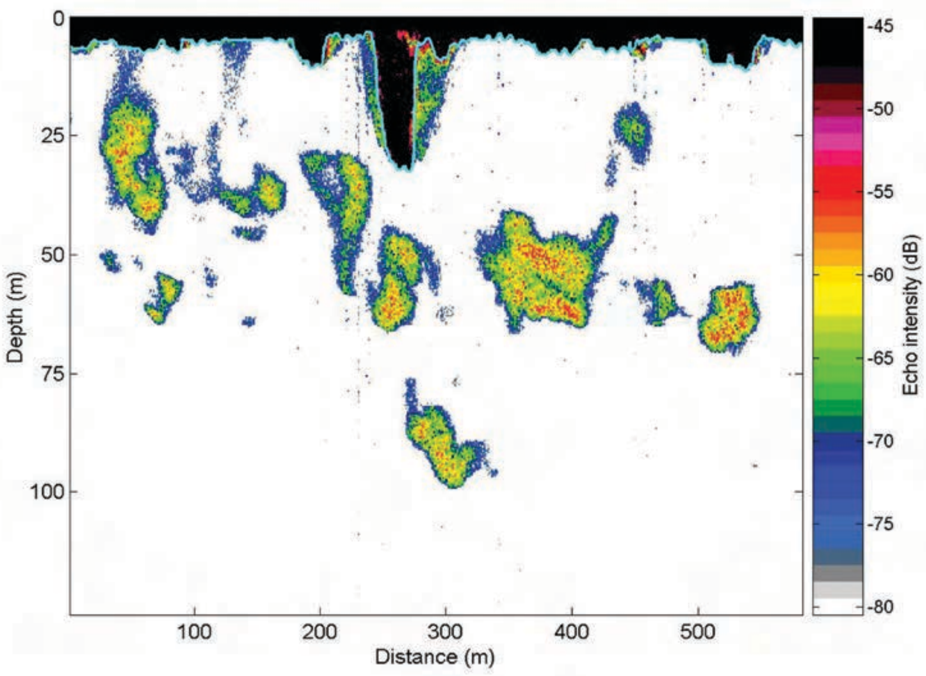

Figure 23. An echogram from the 38 kHz Simrad EK500 upward-looking echo sounder installed on *Autosub* for a cruise in February 2001. The vehicle was travelling at a depth of 150 m. The color scale represents echo intensity, where the patches in mid water were due to swarms of krill. The black trace represents echoes from the underside of the sea ice, from which ice draft can be estimated. For the *Autosub* Under Ice program, the *Autosub* instrument suite was expanded to include: (1) 200 kHz swath bathymetry (EM2000); (2) chirp sub-bottom profiler (Edgetech); (3) 150 kHz downward-looking ADCP for navigation and longer range current profiles (RDI workhorse navigator); (4) fiber-optic gyrocompass for precision heading at high latitudes; (5) still camera and lighting for seabed photography; and (6) water sampler for 50 samples (Envirotech).

expeditions: to Pine Island Bay Glacier, Amundsen Sea in March 2003, eastern Greenland in boreal summer 2004, and the Filchner-Ronne ice shelf in February 2005.

The first expedition to Pine Island Bay Glacier brought mixed fortunes. Technical difficulties with the vehicle, including intractable connector problems, meant that the vehicle was not allowed, under its risk assessment, to dive deep enough to penetrate the ice shelf cavity. In parallel, ice conditions, and the lateness of the season, would have made access to the front of the ice shelf hazardous and the retreat even more so. Consequently, *Autosub* observations were confined to under-sea ice studies, over some 200 km of track, while the ship carried out CTD and swath bathymetry surveys in support of the more general science objectives of the parties.

Future under ice missions for *Autosub*, beyond AUI, would benefit from new developments in sensors including rapid response, *in situ* chemical analyzers for nutrients, swath acoustic sounders for 3-dimensional water column acoustic backscatter characterization, and range-gated underwater lidar for fluorescence profile measurements and for estimating phytoplankton on the underside of sea ice.

References

Brierley, A.S., and P.G. Fernandes, 2001, Diving depths of northern gannets: acoustic observations of Sula bassana from an autonomous underwater vehicle, *The Auk*, 118(2), 529-534.

Brierley, A.S., P.G. Fernandes, M.A. Brandon, F. Armstrong, N.W. Millard, S.D. McPhail, P. Stevenson, M. Pebody, J. Perrett, M. Squires, D.G. Bone, and G. Griffiths, 2002, Antarctic krill under sea ice: elevated abundance in a narrow band just south of ice edge, *Science*, 295, 1890-1892.

Brierley, A.S., P.G. Fernandes, M.A. Brandon, F. Armstrong, N.W. Millard, S.D., McPhail, P. Stevenson, M. Pebody, J.R. Perrett, M. Squires, D.G. Bone, and G. Griffiths, 2003, An investigation of avoidance by Antarctic krill of RRS *James Clark Ross* using the *Autosub-2* autonomous underwater vehicle, *Fisheries Research*, 60, 569-576.

Fernandes, P.G., A.S. Brierley, E.J. Simmonds, N.W. Millard, S.D. McPhail, F. Armstrong, P. Stevenson, and M. Squires, 2000a, Fish do not avoid survey vessels, *Nature*, 404, 35-36.

Fernandes, P.G., A.S. Brierley, E.J. Simmonds, N.W. Millard, S.D. McPhail, F. Armstrong, P. Stevenson, and M. Squires, 2000b, Addendum to Fish do not avoid survey vessels, *Nature*, 407, 152-152.

TRANSIENT AND RAPIDLY EVOLVING EVENTS

Introduction

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The ocean is very large compared to our ability to sample it. Accordingly, most routine oceanographic sampling attempts to cover wide areas with a limited number of measurements spread widely in space and time. For example, the WOCE hydrographic survey criss-crossed the world ocean with section lines. Along each line a ship made measurements roughly every 50 km. The survey was planned years in advance and took about ten years to complete. The Argo program (see case study on p. 18) attempts to improve upon this by deploying thousands of autonomous floats across the world ocean. The average float spacing will still be roughly 300 km and measurements will be taken only once every ten days. Oceanographic measurements are, of course, not confined to sampling these large scales alone. Scientists commonly address much smaller scales, typically with intensive ship surveys or with arrays of moored instruments. However, these campaigns are almost always planned far in advance with the exact time of sampling strongly influenced by administrative and logistical concerns. Satellite remote sensing can sample a large range of scales globally, but can only sample the ocean surface.

Many important oceanic phenomena can slip through this sampling net. For example, hurricanes have a large effect on the upper ocean (Price, 1981) and continental shelf (Chang and Dickey, 2001), both physically and ecologically. They typically affect ocean areas several 100 km across, and last about a day. Blooms of harmful algae can develop offshore and be rapidly carried onshore by ocean currents with dramatic effects on harvestable shellfish and other nearshore organisms. The blooms are often only kilometers in size, can reside kilometers to tens of kilometers offshore and can move onshore in a few days. The Weddell polynya (Figure 24) was a large hole in the wintertime Antarctic ice cover that persisted for three years (1974-1976). At its largest, it measured 350 km by 1000 km. This was a major climatic event, destroying the local ocean stratification and cooling the ocean to 3000 m depth. No measurements were made within the polynya. Although we do not know how the polynya was formed, it is clear that the ocean must have played a large role in melting the sea ice and keeping it from refreezing.

ALPS technologies are particularly well suited to sampling these transient events. Hurricanes are difficult to sample from ships, both because they cannot safely operate and because the rigid schedules of research ships cannot easily adapt to the unpredictable occurrence of hurricanes. The likelihood of a fixed mooring sampling a hurricane in any given year is low. In contrast, nearly 150 measurements of hurricane passage have been made by the Atlantic Argo float array from 1997 to 2001. The probability of a given float sampling a storm is still low, but the large number of floats allowed these infrequent events to be sampled many times. Air-deployment of floats and drifters into hurricanes is an effective sampling technique (see case study on p. 49). ALPS techniques should be similarly effective in measuring the recurrence of the Weddell polynya. Some of the Southern Ocean Argo floats would undoubtedly make their way into the polynya and provide limited information, particularly if

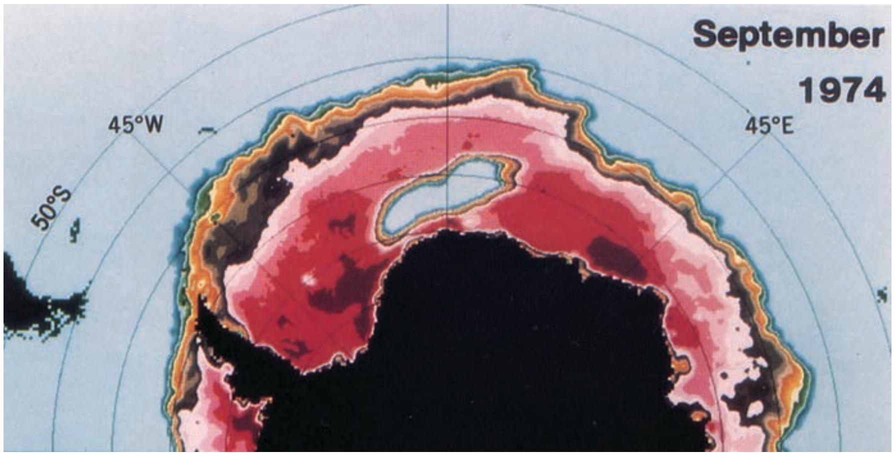

Figure 24. An enormous ice-free region (polynya) amid the ice cover near the Weddell Sea formed during three consecutive Southern Hemisphere winters. The satellite image shows the concentration of sea ice surrounding Antarctica (black). Dark red regions are almost completely covered by ice. Blue regions are ice-free. Despite this being a major climatic event, which clearly involved the ocean, no measurements were made within the polynya. By deploying ALPS, there is a hope of capturing any recurrence. Image from NASA SP-459, Antarctic Sea Ice 1973-1976.

some provision was made for them to survive surfacing under ice. More effective, however, would be air-deployment of floats and drifters into the polynya. Such an array could be deployed for far less cost than a single icebreaker cruise into the polynya, would maintain a presence for many months or years, and could be rapidly deployed. Finally, for harmful algal blooms (see case study on p. 52), gliders and AUVs are well-suited to make the small-scale intensive surveys necessary to sample the blooms. These can be easily deployed from small boats or even launching ramps, bypassing the rigid schedules of research vessels and thus providing the timely and detailed information necessary to track the blooms.

The use of ALPS instrumentation to intensively sample transient events is particularly effective when combined with techniques that can provide timely targeting information. For example, hurricanes can be readily detected and tracked with a variety of remote sensing techniques; the success of aircraft-based hurricane studies, including float and drifter deployments, depends on the ability to vector aircraft directly to the storm. Similarly, microwave remote sensing of sea ice, as shown in Figure 24, provides reliable and real-time measurements of the location and size of polynyas. For HABs, however, remote sensing signatures are ambiguous at best. Here, the best strategy will be to used fixed stations, both moored and on the beach, to act as sentinels for the presence of toxins. These would act as triggers for more intensive AUV or glider surveys when necessary. Operationally, these measurements are best used in the context an integrated observing system that combines data of all types within a dynamically based model.

There exist some technological obstacles to the routine use of ALPS sensors to sample transient events. The suite of available sensors, although growing, is still quite limited. Opportunistic sampling requires speed and flexibility in both operations and deployment. Such continuous operations are difficult to maintain within a typical research group. For global sampling, the fastest and most economical way to reach a given location is by aircraft. Although the techniques of air deployment are well developed and have been adapted to some varieties of floats, drifters, and small AUVs, much remains to be done to make air deployments routine.

References

Chang, G.C. and T. D. Dickey, 2001, Optical and physical variability on timescales from minutes to the seasonal cycle on the New England shelf: July 1996-June 1997, *J. Geophys. Res.*, 106, 9435-9453.

Gordon A, L. 1978. Deep Antarctic convection west of Maud Rise, *J. Phys. Oceanogr.* 8, 600-612.

Capturing Air-Sea Interaction in Hurricanes

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Hurricanes are among the most deadly geophysical phenomena; a 1970 storm in Bangladesh killed over a half million people. Over the last century, increasing skill in prediction has dramatically reduced the deaths in North America despite large increases in coastal populations during this same period (Willoughby, 2000). Uncertainties in present hurricane forecasts, particularly at times longer than 48 hours, continue to cause unnecessary and expensive coastal evacuations, while often providing warnings too late for effective preparations. Hurricanes significantly increase the air-sea flux of $C0_2$ (Bates, 1998), have large impacts on coastal ecosystems, and have potentially important feedbacks on climate (Emmanuel, 2003).

Hurricanes draw their energy from warm ocean waters. The ocean plays two important roles in this process. First, hurricane intensity is limited by the rate at which enthalpy and momentum can be exchanged across the air-sea surface (Emmanuel, 1986). The exchange coefficients are only poorly known at hurricane wind speeds, where spray effects play a large role (Andreas and Emmanuel, 2001). Second, hurricane winds set up strong currents in the ocean mixed layer, which causes mixing between its warm water and the much colder underlying water. The resulting drop in sea surface temperature (Figure 25a, c) can significantly reduce the intensity of hurricanes (Emmanuel, 1999).

Ocean observations are necessary to address these issues. Ship-based methods cannot be used under hurricane conditions; even if they could, ships cannot move rapidly enough to routinely intercept hurricanes. Although long-term moored observations occasionally are overrun by hurricanes (Dickey et. al. 1998), many years typically elapse at a given site between such events. Most measurements of hurricanes are made from aircraft. About a dozen NOAA and Air Force planes are dedicated to hurricane reconnaissance and research during each season. Expendable probes deployed from these aircraft have been the basis of almost all detailed studies of the ocean beneath hurricanes (Price, 1981; Jacob et. al., 2000). However, these can only make profiles of temperature, salinity, and velocity when an aircraft is present. ALPS instrumentation, deployed from existing aircraft, can provide an opportunity to make sustained measurements of a variety of quantities within the ocean beneath hurricanes.

In August 1999, three Lagrangian floats were air deployed ahead of hurricane Dennis using a chartered skydive aircraft (D'Asaro, 2003a). These floats (Figure 25d), designed and built at the Applied Physics Laboratory, University of Washington, follow the three-dimensional motion of water parcels to an accuracy of about 0.01 m/s (D'Asaro 2003b) using a combination of neutral buoyancy, controlled compressibility, and high drag. Float depth was measured from pressure. The temperature of the surrounding water was measured to an accuracy of about 1mK. For the first day after deployment the float equilibrated at 60 m, adjusting its density to match that of the surrounding water. It then moved into the mixed layer and began its four-day-long scientific mission. Data were returned via the ARGOS satellite system.

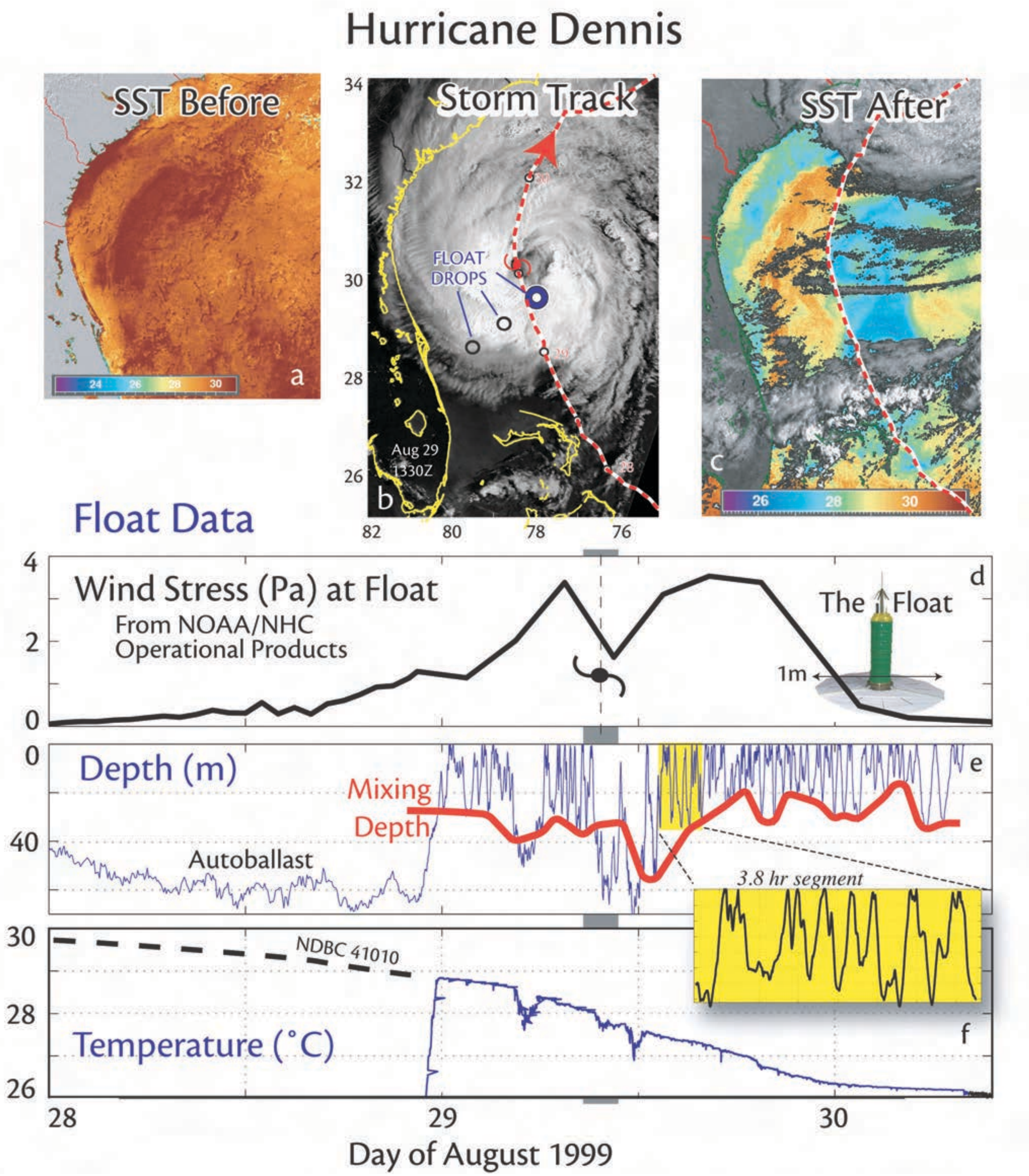

Figure 25. Autonomous Lagrangian instruments were used to make key measurements (three-dimensional water particle motion, temperature, and depth) in Hurricane Dennis—a highly transient and hostile feature—within an environmental framework defined by satellite, aircraft, and operational weather measurements. The AUV measurements were possible because other measurements could define the location of the hurricane in real time, the Lagrangian instruments could be quickly and flexibly deployed by aircraft to the correct location, and these instruments were robust enough to operate in the hurricane. These data confirm the key role of the oceans in hurricane dynamics. Additional measurements using floats equipped with sensors measuring oceanic shear, gas exchange, surface waves, and bubbles will be carried out as part of the CBLAST program during the 2003 and 2004 hurricane seasons.

Figure 25e, f shows data from the one float that sampled the ocean beneath the high wind region near Dennis' eye (Figure 25b). Maximum winds (Figure 25d) exceeded 30 m/s; the estimated wind stress exceeded 3 Pa. The float repeatedly transited the mixed layer (Figure 25e and yellow insert) carried by the turbulent eddies that mixed the upper ocean. Typical vertical speeds were 0.05 m/s with peak speeds of 0.2 m/s. The depth to which the float moved, combined with its temperature measurements, defined a mixing depth (red line in Figure 25e) that varied from 30-50 m.

Satellite sea surface temperature (SST) images (Figure 25, a and c) show the 3-4˚C cooling in Dennis' wake. The float data (Figure 25d) show similar cooling. The combination of float vertical velocity (w) and temperature (T) allows the vertical transport of heat due to mixing to be directly measured from their average product <wT>(z). Other terms in the heat budget can also be computed. The total cooling of the upper 30 m is equivalent to 3800 W/m^2 during August 29. Of this, only 15% (600±200 W/m^2) is due to the air-sea flux and thus goes to power the hurricane. The rest is due to vertical (1600±250 W/m^2) and horizontal (1800±600 W/m^2) mixing. Thus, ocean mixing, driven by the hurricane winds, removed most of the ocean heat energy available to the hurricane, thus confirming the key role of the ocean in hurricane dynamics.

Coupled air-sea models are now routinely used for hurricane forecasting. These are run with minimal oceanographic data for initialization or verification. The routine deployment of floats measuring profiles of temperature, salinity, and velocity in front of selected hurricanes could provide the data necessary to verify and thus improve these models.

References

Andreas, E. L. and Emanueal, K.A., 2001, Effects of Sea Spray on tropical cyclone intensity, *J. Atmos. Sci.*, 58, 3741-51.

Bates, N. R., A.H. Knap, and A.F. Michaels, 1998, Contribution of hurricanes to local and global estimates of air-sea exchange of CO_2, *Nature*, 395, 58-61.

D'Asaro, Eric A. 2003a, The Ocean Boundary Layer below Hurricane Dennis. *J. Phys. Oceanogr.* 33, 561-579.

D'Asaro, Eric A. 2003b, Performance of Autonomous Lagrangian Floats. *Journal of Atmospheric and Oceanic Technology*, 20, 896-911.

Dickey, T., Frye, D., McNeil, J., Manov, D., Nelson, N., Sigurdson, D., Jannasch, H., Siegel, D., Michaels, A., Johnson, R., 1998. Upper ocean temperature response to Hurricane Felix as measured by the Bermuda Testbed Mooring, *Monthly Weather Review,* 126, 1195-1201.

Emmanuel, K., 1999, Thermodynamic control of Hurricane intensity, *Nature*, 401, 665-69.

Emmanuel, K, 2003, Tropical Cyclones, *Ann. Rev. Earth Planet. Sci*, 31, 75-104.

Emmanuel, K., 1986, An Air-Sea interaction theory for tropical cyclones, Part I, *J. Atmos. Sci.*, 42, 1062-71.

Jacob, D.S., L.K. Shay, A.J., Mariano, P.G., Black, 2000, The 3D Oceanic Mixed Layer Response to Hurricane Gilbert. *J. Phys. Oceanogr.,* 30, 1407-1429.

Price, J.F., 1981, Upper Ocean response to a hurricane, *J. Phys. Oceanogr.*, 11, 153-75.

Willoughby, H. E., 2000, *Costs and Benefits of Hurricane Forecasting, 24th Conference on Hurricanes and Tropical Meteorology*, 29 May - 2 June, 2000, Ft Lauderdale, American Meteorological Society.

The Challenges of Detecting Harmful Algal Blooms

Chris Scholin, Monterey Bay Aquarium Research Institute

Harmful algal blooms (HABs) are linked to serious human and ecosystem health impacts and pose significant and recurrent economic concerns. Only a few dozen of the thousands of algal species present in the oceans are considered harmful and/or toxic (Smayda, 1997). Collectively, HAB species comprise a very diverse group of organisms representative of most major classes of microalgae, other protists, and prokaryotes. These species occur across a diverse range of habitats from the pelagic zone to the benthos, and many inhabit U.S. coastal waters.

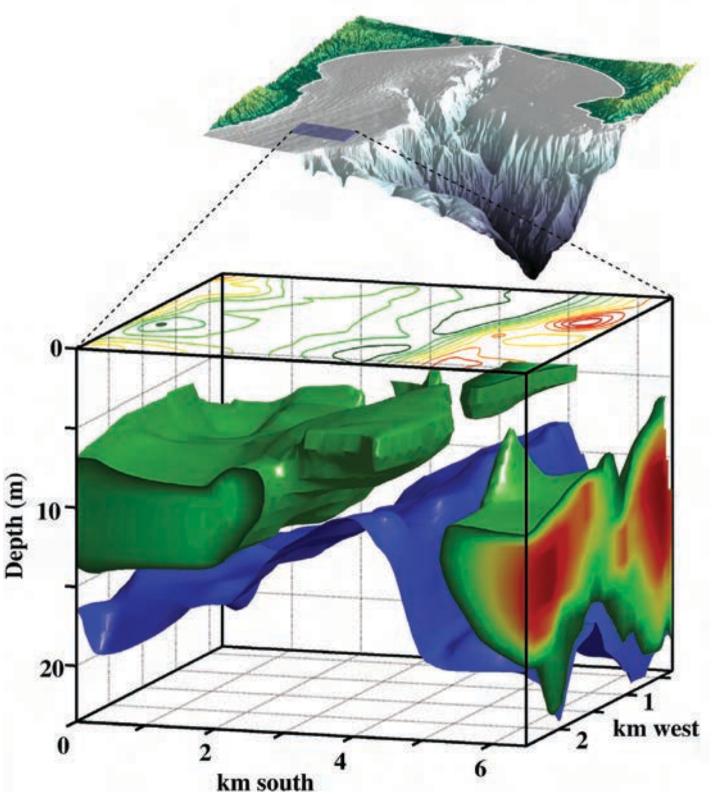

Figure 26. A 3-D view of a phytoplankton layer dispersed along a ridge in the density field and seemingly concentrated in a trough observed using an AUV in August, 2000, in Monterey Bay, CA. The layer of phytoplankton contained *Pseudo-nitzschia australis*, a toxigenic diatom liked to illness and mortality of marine wildlife. Figure courtesy John Ryan, MBARI.

Harmful algal species have historically been distinguished based upon differences in cell morphology and ultrastructure by using light and electron microscopy. However, traditional detection methods that rely on microscopy can be logistically difficult to implement when hundreds of samples must be processed in near real time. Source populations of organisms that ultimately give rise to HABs in coastal areas may occur offshore and be subsurface, sometimes in thin layers, and therefore are often difficult to detect using traditional ship surveys, and even remote sensing (e.g., Figure 26). Efforts to study, manage, and mitigate the negative impacts of HABs demand species-level cell identification and quantification, an understanding of how blooms are driven by and/or respond to chemical and physical properties of the water column, and how toxins produced by some of these organisms propagate through the food web. For these reasons, the study and management of HABs would benefit tremendously from the development of remote, *in situ*, real-time observing systems capable of detecting specific HAB species and associated toxins.

Some HAB species exert their negative effects only upon reaching high cell concentrations, sometimes leading to overt discoloration of the water ("red tides"). These high biomass blooms are associated with harmful effects, such as fish kills (e.g., Steidinger et al., 1998; Taylor, 1993). For such species, direct optical observations can provide a tractable means of detecting bloom events. This approach

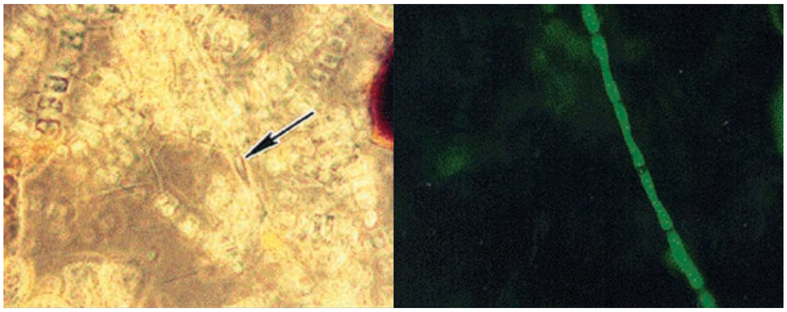

Figure 27. Example of detecting a toxigenic diatom in a natural sample using a fluorescently labeled DNA probe in whole-cell format. Left: transmitted light image of a dense group of cells collected on a filter. Right: corresponding epiflourescence image showing location of a single chain of cells labeled with a species-specific DNA probe. Arrow indicates location of that chain of cells in the transmitted light micrograph. (Miller and Scholin, 1998. Reproduced with permission of the *Journal of Phycology*.)

is being adopted to study red tides that occur in the Gulf of Mexico using an optical sensor fitted onto a Slocum glider (Figure 4, p. 9). However, many other HAB species exert harmful effects at concentrations far below those that lead to visually discolored water and may represent only a small fraction of the total number of cells present in the environment. Moreover, because it is not always possible to discriminate harmful from benign organisms based on inherent or apparent optical properties, other techniques that provide species or even "strain" level resolution are required.

Application of molecular probes is one means of accomplishing that goal (Scholin et al., 2002; Figure 27). Nevertheless, when the problem organisms are rare, relatively large samples are required (100's mL – L's) and multi-step chemical processing of that material is needed to reveal target species or toxins of interest given the techniques available currently. Therefore, successful application of molecular probe sensing technology for remote HAB species detection on autonomous platforms will require instrumentation that both accommodates large sample volumes and provides the means for processing that material prior to delivery to the detector itself. While such systems are emerging (e.g., http://www.mbari.org/microbial/ESP), it is not likely in the short term that they will provide data at rates comparable to those of physico-chemical sensors, such as a CTD. Consequently, near-term application of HAB biosensors fielded on autonomous platforms will likely be tightly integrated with other sensors that trigger an analytical event in adaptive fashion based on environmental gradients readily detectable at high frequency and previously identified as favorable for HAB formation. Powered AUVs are an attractive platform for developing, testing, and refining this capability.

References

Miller, P.E. and C.A. Scholin, 1998, Identification and enumeration of cultured and wild *Pseudo-nitzschia* (Bacillariophyceae) using species-specific LSU rRNA-targeted fluorescent probes and filter-based whole cell hybridization, *J. Phycol.*, 34, 371-382.

Scholin, C.A., F. Gulland, G. Doucette and others, 2000, Mortality of sea lions along the central California coast linked to a toxic diatom bloom, *Nature*, 403, 80-84.

Scholin, C.A., E. Vreiling, L. Peperzak, L. Rhodes, P. Rublee, 2002, Detection of HAB species using lectin, antibody and DNA probes. In: G.M. Hallegraeff, D.M. Anderson A.D. Cembella (eds), *Manual on Harmful Marine Microalgae*, in press, Paris, Intergovernmental Oceanographic Commission, UNESCO (Vol. 11. Second Edition).

Smayda, T.J., 1997, Bloom dynamics: Physiology, behavior, trophic effects, *Limnol. Oceanogr.*, 42, 1132-1136.

Steidenger, K.A., G.A. Vargo, P.A., Tester, C.R. Tomas, 1998, Bloom dynamics and physiology of Gymnodinium breve with emphasis on the Gulf of Mexico. In: D.M. Anderson, A.D. Cembella and G.M. Hallegraeff (eds), *Physiological Ecology of Harmful Algal Blooms*, Heidelberg, Springer-Verlag (NATO-Advanced Study Institute Series, Vol. 41), p. 133-153.

Taylor, F.J.R., 1993, Current problems with harmful phytoplankton blooms in British Columbia waters, In: T.J. Smayda and Y. Shimizu (eds), *Toxic Phytoplankton Blooms in the Sea*, Amsterdam, Elsevier, p. 699-704.

Further Reading

http://www.whoi.edu/redtide/
http://www.chbr.noaa.gov/CoastalResearch.html
http://www.nwfsc.noaa.gov/hab/
http://www.mote.org/~pederson/phyto_ecol.phtml
http://www.floridamarine.org/
http://www.habwatch.org/

INTEGRATING ALPS WITH OTHER PLATFORMS

New fixed and mobile ocean-observing systems are an essential complement to ships and satellites, and must be deployed if critical events are to be captured.

Ocean Sciences at the New Millennium

The vision of a modern ocean observing system that emerged from the ALPS workshop is one that combines ALPS with a variety of other platforms, as each has its own unique capabilities. Three spatial dimensions plus time must be resolved for a complete and unambiguous description of the ocean. Any one platform can typically resolve well at least two of these four dimensions, often leaving the remaining dimensions poorly observed. A thoughtful deployment of the broad array of different platforms will form the paradigm for the ocean observing systems of the future.

The anchors of some regional observing systems will be cabled moorings. The ample power and bandwidth of cabled systems permit a diversity of sensors, and excellent coverage in time and with depth, albeit at a limited number of locations. ALPS complement moorings by providing expanded resolution for spatial sampling. Moorings also act as effective sentinels, their continuous presence detecting phenomena on all time scales. ALPS can then be deployed to improve resolution during relevant transient events.

Ships are the traditional, and most capable, platforms for collecting ocean observations. Ships provide people direct access to the sea with many of the same laboratory capabilities that are available on land. ALPS improve the efficiency of ship operations by extending their reach in space and time. While scientists on board a ship make detailed observations, a network of ALPS can be operating independently in the surrounding water. When a ship departs from a region, ALPS can continue making observations long afterwards. ALPS observations can also be used to infer more difficult-to-measure quantities. Ships are essential to the development of *in situ* sensors for autonomous platforms, as measurements made on board ships are necessary to ascertain the quality of data measured from new sensors on ALPS. The combination of ALPS and ships provides a model for expeditionary and process-oriented observations of the ocean.

Satellite observations, which provide excellent spatial and temporal coverage of sea surface temperature, height, color, and winds have proven to be especially important for understanding the ocean at large spatial scales. Methods for measuring additional variables, such as salinity, continue to be developed for measurement from space. High-frequency radars, with shore-based installations along U.S. coasts, are providing tantalizing views of surface velocity. However, all of these remote observations are limited to the surface as a consequence of the ocean's opaqueness to electromagnetic waves. ALPS complement these remote observations by collecting information about the ocean beneath its surface and by providing ground truth for remotely sensed data.

Figure 28. The Autonomous Ocean Sensing Network (AOSN) in Monterey Bay uses a variety of modern platforms to produce a comprehensive view of the ocean. An exercise during summer 2003 used gliders, AUVs, drifters, floats, satellites, ships, moorings, and aircraft. Noteworthy was the deployment of a fleet of over 20 gliders of two different designs. Data were made available within hours to computer models, which in turn provided input into decisions on continued sampling from the array of platforms. The success of AOSN is a harbinger for future regional ocean observing systems. Figure courtesy of David Fierstein, Copyright 2001, MBARI.

One of the challenges in interpreting ALPS data is space-time aliasing. For example, a glider may move so slowly that its survey pattern cannot be completed at a time scale necessary to observe a particular ocean process. While this problem may be addressed through deployment of more gliders and appropriate data analysis, a more efficient approach could involve moorings to provide temporal resolution. The problem of synthesizing these data has a variety of solutions, from relatively simple objective analysis through sophisticated assimilation into numerical models. Data assimilation will see increasing use as ocean observing systems allow for accurate ocean prediction. The view that emerged from the ALPS workshop is that a holistic approach should characterize ocean observations. The combination of ALPS, moorings, ships, remote sensing, and models offer a compelling vision for the future of ocean observations (Clark and Isern, 2003; Figure 28).

Reference

Clark, H.L. and A. Isern, 2003, Overview, *Oceanography*, 16 (4), 5.

FUTURE PLATFORMS AND SENSORS

ALPS technologies have progressed rapidly in recent years, and there is every reason to believe that significant advances will continue in the future. The ALPS workshop identified several needs for more-capable platforms, summarized below.

- **New platform designs.** The present platforms are expected to evolve. Larger floats for testing new sensors, micro floats to mimic larval dispersal, AUVs for under ice exploration, and hybrid AUV-gliders are but a few of the new ideas for ALPS. See box on opposite page for details.

- **New sensors.** The potential suite of acoustical, biological, chemical, optical, and physical sensors that could be deployed on ALPS is impressive. These sensors measure both state and rate variables. Many sensors, particularly chemical sensors, remain in the prototype stage for want of the investment necessary to graduate them into robust and reliable sensors. See box on p. 59 for details.

- **Greater sensor payload is required on all platforms.** The desire to solve interdisciplinary problems drives the need for simultaneous measurement of more variables and hence greater sensor payloads. An increased sensor payload, additional power to support sensors, and robust on-board data processing algorithms to reduce data transmission loads for high data-density sensors such as the UV nitrate sensor are clear needs. The need for simultaneous measurement of many variables may necessitate larger platforms, or an alterative approach of using multiple platforms that communicate and share sampling responsibilities, each with its own subset of sensors.

- **New modes of operation for adaptive sampling and biological studies.** As control theory and self-organizing sensor networks evolve, gliders, and AUVs could operate in ways radically different from the traditional survey or station-keeping modes. Swarms of interacting underwater vehicles, communicating and sharing information with each other, could track biomarkers or pollutant signatures much more efficiently than vehicles operating independently. The detection and characterization of transient features such as harmful algal blooms could be automated with vehicles that alternate between survey monitoring and adaptive sampling strategies. Networks of ALPS could be used in new sampling designs to study zooplankton and larval processes. For example, a network of platforms with zooplankton imaging or acoustics could both track a planktonic species of interest and determine abundances of different stages, while simultaneously monitoring environmental conditions. Currently, little is known about the factors that guide zooplankton and fish through the oceans; the envisioned sampling network could new provide insights into a day in the life of a copepod.

- **Increased reliability and endurance at lower cost.** The various autonomous and Lagrangian platforms in development and use today are at different levels of maturity. All ALPS platforms have a general need for improved reliability, increased endurance, and reduced costs of acquisition, deployment, and maintenance.

- **Improved two-way platform-to-shore communication.** This will be a continuing issue with widely distributed platforms, with increased bandwidth at lower cost the primary goal. Global telecommunication will likely be driven by forces outside oceanography, but we must do what we can to encourage improvements.

- **Energy sources with increased power density and efficiency.** Improved batteries with increased power density and efficiency would facilitate interdisciplinary work on ALPS, as well as longer missions. Developments with semi-fuel cells, fuel cells, and combustion-based energy sources may lead to far higher specific energy. Energy from the environment, for example, from thermal and solar sources, is worthy of continued investigation. Docking stations powered by a range of energy sources could supply AUVs and

New Platform Designs

A number of specific ideas for new platforms arose in workshop discussions. One anticipated development is a hybrid glider/AUV that combines the endurance of a glider with the speed and maneuverability of an AUV. The strength of gliders lies in their stingy power consumption and efficiency, so missions of thousand of kilometers over months will be possible. This efficiency comes at a cost in speed and controllability, as gliders typically can move at 0.3 m/s, and thus can be affected by strong ocean currents. AUVs, in contrast, are highly maneuverable but have relatively short deployment durations. A hybrid glider/AUV would be able to cover long distances efficiently by gliding. When it arrives at a location of interest, it could then sample intensively in the manner of an AUV. As all the technology to develop such a hybrid exists, the development is only a matter of identifying and funding the appropriate team of scientists and engineers.

Short-term, large, robust, recoverable floats would be ideal platforms for newly developed sensors not yet ready for long-term deployment as well as for use in conjunction with ship-based processes studies. New sensors tend to be large—in physical size, power consumption, and cost—making such sensors inappropriate for deployment on the typical floats in use today. Floats capable of deployments of a month or less would be suitable companions for a research cruise. While scientists on board the ship would undertake the kind of measurements only possible in a laboratory, as in a biogeochemical process study, the recoverable floats would expand the range of observations, with minimal investment in ship time. These floats would most likely need to be large, with considerable capacity for buoyancy adjustment to accommodate voluminous sensors. The floats would be designed to be robust and easily recoverable, as the sensors on board also could be expensive prototypes. This model contrasts with most floats in use today, which are designed to be inexpensive and easy to deploy, but difficult to recover, as their eventual loss is assumed. Finally, a standardized electronic interface between the float and sensors would ease integration.

Small floats capable of true water-following would be able to track the trajectories of pollutants and passively advected organisms. For example, a cluster of floats could be released from a known spawning site to address issues of recruitment. To mimic the behavior of zooplankton, floats could be designed to profile vertically on a daily cycle, similar to the diurnal migration pattern of zooplankton. As these floats would be deployed in concentrated groups, a challenge would be to track them, presumably acoustically. The payoff would be substantial, as these "micro" floats would provide a new view of the ambits of a range of organisms.

gliders. The oceanographic community is not the key driver of some of these technologies, but we stand to gain from further development.

- **Improved ships and aircraft for deployment and recovery.** A small, fast, inexpensive UNOLS vessel dedicated to ALPS would be desirable. As global ALPS operations continue, an aircraft, for example a C130, would allow for wide deployment. As new platforms are developed, the engineering should reflect the potential for airborne and other types of rough deployment.

- **Standardized interfaces for a "plug and play" capability.** The integration of new sensors on platforms is always challenging. The communications aspect could be made simpler with standardized interfaces between sensors and platforms, and where possible within similar-sized sensors, the physical shape and weight distribution should be standardized.

- **Reduction in sensor cost.** Similar to the need for less-expensive platforms is the need for lower-cost sensors. Smart sensors that share common light sources, detectors, pumping systems, etc. could be developed to reduce the measurement cost per variable, as well as conserve space on a platform. Some optical sensors have been successfully miniaturized; that trend should be continued for all ALPS sensors. Developments in the emerging area of microsystems, in which electronics, sensors and actuators are merged on the micron scale, should be closely watched. Analogous to the situation with battery and satellite communication technology, although ocean sciences is not the key driver of the field, ALPS should be ready to take advantage of advances in appropriate microsystems arenas.

- **Sensor stability and calibration.** There is a need for biological, chemical, and optical sensors that are stable over a range of temperatures and number of years. Associated with this need for stability is also the need to develop a set of calibration protocols among laboratories that deploy ALPS; these protocols would include both laboratory and at-sea procedures. For example, a self-calibration routine for nitrate sensors might include monthly measurement of nitrate at 2000 m, a depth where nitrate concentrations change only on very long time scales. A more challenging engineering activity is the development of devices to enable sensor self-calibration at sea, particularly during extended missions. For optical absorption coefficients, for example, a self-calibration protocol might rely on injection of a known volume of a standard dye that is carried on the platform and integrated into the sensor system.

- **Biofouling of biological and chemical sensors.** Fouling is a major problem for most sensors; the culprits can be macroalgae, bivalves, barnacles, and films of organics, bacteria or microalgae. The development of creative means to avoid fouling or renew the sensors or sensor surfaces is essential for long-term deployments in the open ocean as well as for short-term deployments (~ several weeks) in biologically rich coastal waters. Incorporation of sensors into a pumped CTD stream would allow some types of sensors to be protected from fouling while still exposing them to a controlled flow of new water. Automated replacement of disposable sensors, particularly microsystems, would provide extended measurement durations.

- **Water sampling, on-board processing, and sample storage for later laboratory analysis.** There will always be measurements that can only be carried out on samples in the shore-based laboratory. Efficient means for collecting water samples, separating or concentrating the chemicals or particles of interest, and storing the samples is an important goal. By using micro-fluidic samplers, it might be possible to store thousands or more samples until the platform was recovered.

New Sensor Designs

Measurement of macronutrients and trace metals are central to biogeochemical studies; simple and inexpensive sensors for nitrate, nitrite, ammonium, phosphate, silicate, and iron are needed. A few chemical sensors for nutrients exist as prototype instruments, but few are sufficiently robust for routine unattended use. Recent developments have made it possible to measure nitrate in seawater, without traditional colorimetric analysis or pumps, based on its UV absorption spectrum. Continued advances in opto-electronics, such as UV-light emitting diodes, are essential to reduce the power consumption of the UV nitrate sensor. Long deployments with high sampling rates will be feasible only if power consumption is reduced by several orders of magnitude.

Another area that requires improved sensors is the direct measurement of dissolved gases—oxygen, carbon dioxide, methane and hydrosulfide—and their air/sea flux. Present sensors are susceptible to fouling and sensor drift, thereby limiting their time frame for reliable measurement. Alternative approaches, such as fluorescence quenching for oxygen sensing and thin films for methane measurement, are being explored but require considerable investment in both understanding the chemistry and in developing sensor and self-calibration systems. Improved sensors for pH, total inorganic carbon, pCO2, and titration alkalinity are needed to improve characterization of the marine carbon system. Also needed are better sensors to assess rates of primary productivity.

Molecular sensing provides an approach for identifying specific organisms, inferring metabolic potential and function, and indicating stress. Many of the diagnostic procedures for detecting molecular signatures share an overlapping set of requirements such as concentrating, preserving, and disrupting cells, applying a series of reagents in a timed sequence, and detecting and quantifying the signals with optical and electrochemical transducers. The rapid advances in microfluidic and microelectromechanical systems lead to such developments as the "lab-on-chip" which, in concept, is highly compatible with ALPS. DNA and protein arrays have the potential to simultaneously detect many genes and their products in a single sample. Molecular sensors hold great promise for answering long-standing questions in oceanography, although much basic research remains to be done.

The development of high-quality, low-power acoustic and optical systems for measuring zooplankton and fish are sorely needed for marine food web studies. Small echosounders with high bandwidth and improved optical imaging systems to identify individual species could be deployed on ALPS to track individuals or schools for extended periods of time. Improvements in these technologies would also benefit analysis of bottom characteristics. A low-power optical sensor for microstructure should be developed; this optical approach would allow turbulent-scale density fluctuations to be directly measured. Measurement of velocity microstructure from a pitot tube should also be explored because of its relatively insensitivity to mechanical vibrations.

Development of autonomous sensor systems typically progresses from bench-top prototypes, to research systems that are operated *in situ*, and finally to production of commercial systems that are accessible to the broad community. The long time frames needed to bring new sensor systems to operational status require that sustained commitments to development be made.

ENABLING ACTIVITIES

Because ALPS are relatively inexpensive it is possible to deploy many units in focused process experiments, in regional observing systems, or in global arrays. An ALPS observational network can resolve scales and processes that are otherwise difficult, or impossible, to observe. The ALPS network then acts as a single entity, and would be appropriate for funding as a large enterprise, rather than as many small, individual projects, as is typical now. Workshop attendees proposed a number of models to continue technology development, and to broaden community access to the best ALPS available.

- **Status quo.** Currently, ALPS expertise is distributed throughout the country with each group pursuing its own engineering and science goals, operating within the constraints of funding agency objectives and resource availability. This independence has resulted in the diversity of ALPS existing today. There is much to be said for the freedom allowed by the current mode of operation. However, small research and development groups have little capability or incentive to offer access to a broader community.

- **Private vendor.** Components of many ALPS technologies are produced commercially. With technology that has been developed to a reliable operational level, and with an adequate customer base, it is reasonable for a company efficiently to build and market many identical units. Private industry provides ready access to anyone with sufficient funds. However, private companies are usually unwilling to invest in or produce highly innovative systems, or one-of-a-kind instruments, even if these have a high long-term potential. The model of innovative development to the prototype and demonstration stages by research groups, followed by commercialization, is much more common.

- **Government-funded facility.** Groups of engineers and technicians can be formed into regional centers of excellence to make ALPS available to all whose science would benefit. Existing facilities can be examined for their relative benefits and liabilities, as we design an approach uniquely suitable for ALPS. Shipboard technical services, run by ship operators, supply the standard instrumentation on oceanographic cruises. A drawback is that such large ocean-going operations are often not on the cutting edge of technology, partly because of the large amount of time at sea required of employees. Other models worthy of study include facilities that support remotely operated underwater vehicles, marine geology and geophysics, and research aircraft. An effective plan will have to deal with the sometimes different goals of facilities and research scientists.

- **Special mission.** Small collectives of engineers and scientists with diverse expertise could band together to design new platforms, integrate sensors, and perform initial operations. This team approach, similar to how NASA operates, but less common in oceanography, is effective because it aligns the goals of all involved. A similar approach has recently been used in the development of *Autosub* (case study on p. 45) in the UK. A mission model is flexible, can take many forms depending on the maturity of the technology, and is worthy of further study.

Toward Implementation

An effective plan for nurturing and distributing ALPS will likely be a blend of all of the approaches discussed above. A few issues must be addressed to make any of the models work:

1. ALPS technologies vary in maturity, sophistication, and technical support requirements so that different models may be appropriate for different platforms.
2. Training of scientists and support staff in the use and possibilities of ALPS is a high priority. Such training takes time, money, and the cooperation of experts who will have to provide these activities at the expense of personal productivity.
3. The professional aspirations of all involved scientists and engineers must be recognized.

A complete implementation plan is too complex to achieve at a single workshop. A next step is to form an implementation group made up of technology originators and users. An ALPS implementation group would consider the models developed at the workshop, and work up a comprehensive plan for continued development, training, and sustained operations. The ultimate goal is to make ALPS available to all interested ocean scientists.

RECOMMENDATIONS

The vision that emerged from the workshop was of an ocean-observing network of flexible scale and scope, comprising many relatively inexpensive platforms outfitted with the most advanced sensors, to enable new views of the ocean. ALPS, uniquely among all observational systems, hold the promise of solving the fundamental oceanographic problem of spatial sampling. It is time to move forward so that all oceanographers can share in the technological advancements achieved to date and can participate in future activities. Action now will foster accelerated and coordinated growth of both platforms and sensors, and will allow ALPS to play a major role in the future of oceanography. Specific recommendations follow.

- **Resources.** Funding ALPS as infrastructure will effectively foster sustained, innovative development of the technologies and will broaden access to a wider scientific community. By enabling investigators to deploy ALPS acquired through infrastructure funding, individuals can pursue their own specific scientific goals as well as contribute to building an overall network. Although a single ALPS may have a limited lifetime, as does each component of any oceanographic observing system, the ALPS network and technological support will endure.

- **Implementation group.** A diverse group of technology innovators and scientific users must be formed to develop an implementation plan and to provide a forum for continuing community input. The key to success is sustained engineering innovation with expanded access for a broader scientific community.

- **New platforms.** The platforms of tomorrow must be designed today. Likely candidates include a robust, recoverable, multidisciplinary float; a hybrid glider/AUV; and water-following micro-floats.

- **New sensors.** Prototype sensors, particularly for chemistry, should be rapidly brought to commercialization; development of sensors for food web studies and molecular markers should receive high priority. Miniaturization and cross-platform compatibility must be a paramount consideration in new sensor development. Sustained investment in instrument development is essential.

- **High priority systems.** Existing platforms and sensors could be combined in new ways to create ALPS that will be of immediate use. For example, a basin-scale network, similar to the Argo array, of biogeochemical profiling floats with sensors for chlorophyll fluorescence, optical scattering, oxygen, and nitrate could address variability of organic carbon production and its export. An optically instrumented HAB glider (p. 52) using adaptive sampling behavior could contribute to significant advances in understanding the development of algal blooms.

- **Pilot projects.** A mechanism for supporting pilot projects must be established to promote ALPS technology development within the context of meaningful scientific goals. Science questions need to drive technological developments. The best way to ensure that ALPS technologies effectively address interdisciplinary problems is to promote the wider use of these technologies, early in their development, by high-quality interdisciplinary scientists. This recognition of the interdisciplinary potential of ALPS should not preclude innovative disciplinary work.

- **People.** Workshops, short courses, training programs, fellowships, and CAREER awards are needed to address the critical shortage of trained engineers and scientists to develop and support ALPS systems.

APPENDIX 1
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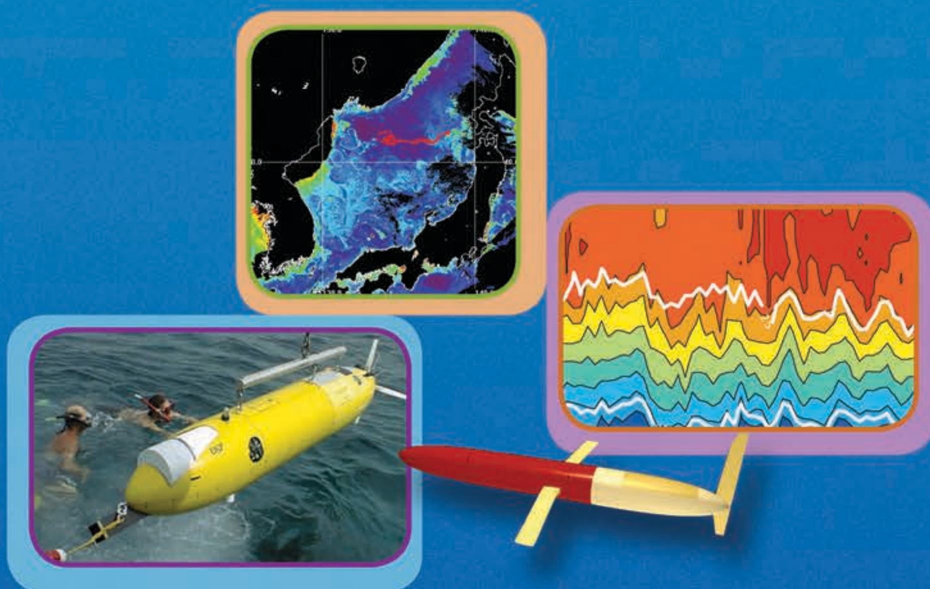

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