PAPER

Underwater Gliders for Ocean Research

AUTHORS
Daniel L. Rudnick
Russ E. Davis
Scripps Institution of Oceanography
Charles C. Eriksen
University of Washington
David M. Fratantoni
Woods Hole Oceanographic Institution
Mary Jane Perry
Darling Marine Center, University of Maine

ABSTRACT

Underwater gliders are autonomous vehicles that profile vertically by controlling buoyancy and move horizontally on wings. Gliders are reviewed, from their conception by Henry Stommel as an extension of autonomous profiling floats, through their development in three models, and including their first deployments singly and in numbers. The basics of glider function are discussed as implemented by University of Washington in Seaglider, Scripps Institution of Oceanography in Spray, and Webb Research in Slocum. Gliders sample in the archetypical modes of sections and of "virtual moorings." Preliminary results are presented from a recent demonstration project that used a network of gliders off Monterey. A wide range of sensors has already been deployed on gliders, with many under current development, and an even wider range of future possibilities. Glider networks appear to be one of the best approaches to achieving subsurface spatial resolution necessary for ocean research.

INTRODUCTION

Henry Stommel (1989) published a piece in Oceanography that might best be characterized as highly informed science fiction. This first-person narrative, written as if the year were 2021, discussed the first quarter century in the use of "Slocums," described as floats that "migrate vertically through the ocean changing ballast … steered horizontally by gliding on wings …broach the surface six times a day to … transmit their accumulated data and receive instructions telling them how to steer through the ocean … [at a] speed [of] generally half a knot." In essence, Stommel was imagining the world after the establishment of a fleet of undersea gliders.

The fundamental concept behind Stommel's vision was one of an observing infrastructure made up of many small, relatively inexpensive platforms. Such an observational system appears the best approach to solving the central observational problem in oceanography: that of sampling a global turbulent fluid with a range of scales from the size of ocean basins, through mesoscale eddies, down to the microscales on which turbulent dissipation occurs. An advantage of the many small platform approach is that the infrastructure is inherently scalable. That is, the density of deployment can be scaled to the problem at hand; global distribution is appropriate for climate problems, while a study of, say, biophysical interactions in mesoscale eddies would require more focused deployments. A second advantage of small platforms is that they are readily portable to sample phenomena that may be intermittent and localized, such as mixing and upwelling events, and phytoplankton blooms. The scalability and portability of a fleet of autonomous platforms make them essential infrastructure for ocean research.

The global array of profiling floats known as Argo (Roemmich et al., 2004) is an excellent example of a system of many small platforms. The fundamental element of the Argo array is the profiling float, which controls buoyancy to surface periodically, transmits data and localizes via satellite, and returns to depth. As of early 2004, over 1000 floats are deployed as part of Argo, with a goal of 3000 floats by the end of 2006. Floats allow a measure of ocean currents by tracking displacement, but also take advantage of circulation to effect dispersal and achieve broad sampling.

A glider is essentially a float with wings to provide lift and allow it to move horizontally while profiling. Gliders are the natural next step in the development of autonomous float technology. Stommel was thinking of this very progression in technology, as he was well aware of the development of the first profiling float, the Autonomous Lagrangian Circulation Explorer (Davis et al., 1992). Because gliders' horizontal positions are, to a large extent, controlled, the scientist decides where profiles are to be taken. This control over horizontal sampling is the fundamental advance of gliders over floats. Gliders are now proven to work, and are beginning to be deployed in numbers, and for long periods in the open and coastal ocean.

Gliders are a technology undergoing active and rapid development. In this article, the discussion is limited to gliders that are operational in the sense that they have already been deployed to do science, to be distinguished from in-water tests of concept or engineering. A number of efforts are underway to expand the capability of existing gliders, and to design new and different gliders. With the field growing so quickly, we hope only to give an accurate snapshot of the glider enterprise at one point in time, rather than to speculate on what ongoing developments will prove successful.

The purpose of this article is to discuss the role of gliders in ocean research infrastructure. Section 2 discusses the basics of glider function, with a summary of the three current designs. Section 3 addresses basic glider capabilities, and the survey patterns possible using a single glider. The next phase in the evolution of glider observations is the deployment of many gliders in coordinated sampling systems; a coastal example of such a system is covered in Section 4. The sensors used on gliders, and future possibilities, are discussed in Section 5. The conclusion (Section 6) includes a brief summary, and a view of the role of gliders in sustained observations.

2. Glider Function

There are now three operational underwater gliders: Seaglider (Eriksen et al., 2001) built at the University of Washington, Slocum Battery manufactured by Webb Research Corp, and Spray (Sherman et al., 2001) built at Scripps Institution of Oceanography. The Slocum Thermal (Webb et al., 2001), which is propelled by extracting heat from the ocean's thermal stratification, was successfully deployed at sea in January 2003 but is not yet fully operational. Here we describe the main functional systems of the three operational vehicles: buoyancy engine, hull, energy storage, attitude sensing and navigation, gliding control, and communication. Sensors are discussed in a later section. Table 1 summarizes the specifications of the three gliders.

Gliders propel themselves by changing buoyancy and using wings to produce forward motion. Buoyancy is changed by varying the vehicle volume typically by O(100 cc) to create a buoyancy force of about 1 N. Wing lift balances the across-track buoyant force while the forward buoyant force balances drag. The ratio of horizontal speed O(25 cm/s) to vertical speed (glide slope) equals lift over drag and is typically 2 to 4, much less than for an aeronautical glider but comparable to that of a NASA Space Shuttle. Energy for gliding is supplied at the bottom of each dive cycle where work is performed to increase vehicle volume. On an O(1 km) deep dive cycle lasting several hours, the O(10 kJ) energy used to change buoyancy implies a power usage for propulsion of about 0.5W. The saw tooth flight paths of gliders naturally sample the ocean both vertically and horizontally.

The considerable range and duration of gliders is accomplished by moving slowly and by keeping down the hotel and sensor load. Since drag is roughly quadratic, halving speed roughly increases range by four. The characteristic that most clearly distinguishes gliders from other AUVs is not their means of propulsion but rather the fact that their very slow speed and consequent low drag permit long-duration operations. In the tropics, the energy needed to penetrate buoyancy change across the pycnocline is also significant, so the weak stratification of subpolar oceans results in greater range through the water. The main factors influencing range per unit energy consumption are operating speed (fast is inefficient), depth (shallow operation is inefficient), vehicle hydrodynamic drag, and the combination of ocean stratification and the difference of compressibility between the glider hull and seawater.

Electric buoyancy engines for floats and gliders fall in two categories: reciprocating hydraulic pumps and single-stroke pumps. Reciprocating (multi-stroke) pumps like those used in Seaglider and Spray are smaller and lighter than single-stroke pumps; and because today's gliders are larger than floats and operate with a larger diving buoyancy difference, this capability is important, particularly at large maximum operating pressures. A disadvantage of small reciprocating pumps is sensitivity to vapor lock, which occurs when the pump cylinder fills with gas and the compression ratio of the pump is insufficient to raise the pressure of the compressed gas to the ambient pressure. If this happens to all cylinders of a reciprocating pump, pumping ceases. Single-stroke pumps, as used by Slocum, are more robust, do not need the valving that reciprocating pumps use to provide bi-directional buoy-

TABLE 1

Specifications for the 3 operational gliders. Payload is limited by both volume and weight and figures given are typical for sensors. "Control" describes the variables used by the control program to adjust gliding; "depth" is vehicle depth and "altitude" is distance above the bottom. Vehicle cost is the purchase price for an individual unaffiliated with the developing institutions or company. Spray cost includes a CTD and either a fluorometer or an optical backscatter sensor. Slocum cost includes a CTD. Seaglider cost includes a CTD and a combination fluorometer/optical backscatter sensor.

Spray	
Hull	Length 200 cm, Diameter 20 cm, Mass 51 kg, Payload 3.5 kg
Lift Surfaces	Wing span (chord) 120 (10) cm, Vertical stabilizer length (chord) 49 (7) cm
Batteries	52 DD Lithium CSC cells in 3 packs, Energy 13 MJ, Mass 12 kg
Volume Change	Max 900 cc, Motor & reciprocating pump, 50 (20) % efficient @ 1000 (100) dbar
Communication	Iridium, 180 byte/s net, 35 J/Kbyte. GPS navigation
Operating	Max P 1500 dbar, Max U 45 cm/s, Control on depth+altitude+attitude+vertical W
Endurance	U = 27 cm/s, 18° glide, Buoyancy 125 gm, Range 7,000 km, Duration 330 days
Cost	Vehicle $50,000, Refueling $2850
Slocum	
Hull	Length 150 cm (overall 215), Diameter 21 cm, Mass 52 kg, Payload 5 kg
Lift Surfaces	Wing span (chord) 120 (9) cm swept 45°, Stabilizer length (chord) 15 (18) cm
Batteries	250 Alkaline C cells, Energy 8 MJ, Mass 18 kg
Volume Change	Typical 450 cc, 90 W motor & single-stroke pump, 50% efficient @ 200 dbar
Communication	Freewave LAN, 5.7 Kbyte/s, 3 J/Mbyte, 30 km range – or – Iridium. GPS navigation
Operating	Max P 200 dbar, Max U 40 cm/s, Control on depth+altitude+attitude+vertical W
Endurance	U = 35 cm/s, 25° glide, Buoyancy 230 gm, Range 500 km, Duration 20 days
Cost	Vehicle $70,000, Refueling $675
Seaglider	
Hull & Shroud	Length 180 cm (overall 330), Diameter 30 cm, Mass 52 kg, Payload 4 kg
Lift Surfaces	Wing span (av chord) 100 (16) cm, Vertical stabilizer span (chord) 40 (7) cm
Batteries	81 D Lithium cells in 2 packs, Energy 10 MJ, Mass 9.4 kg
Volume Change	Max 840 cc, Motor & reciprocating pump, 40% (8%) efficient at 1000 (100) dbar
Communication	Iridium, 180 byte/s net, 35J/Kbytes. GPS navigation
Operating	Max P 1000 dbar, Max U 45 cm/s, Control on depth+position+attitude+vertical W
Endurance	U = 27 cm/s, 16° glide, Buoyancy 130 gm, Range 4600 km, Duration 200 days
Cost	Vehicle $70,000, Refueling $1375

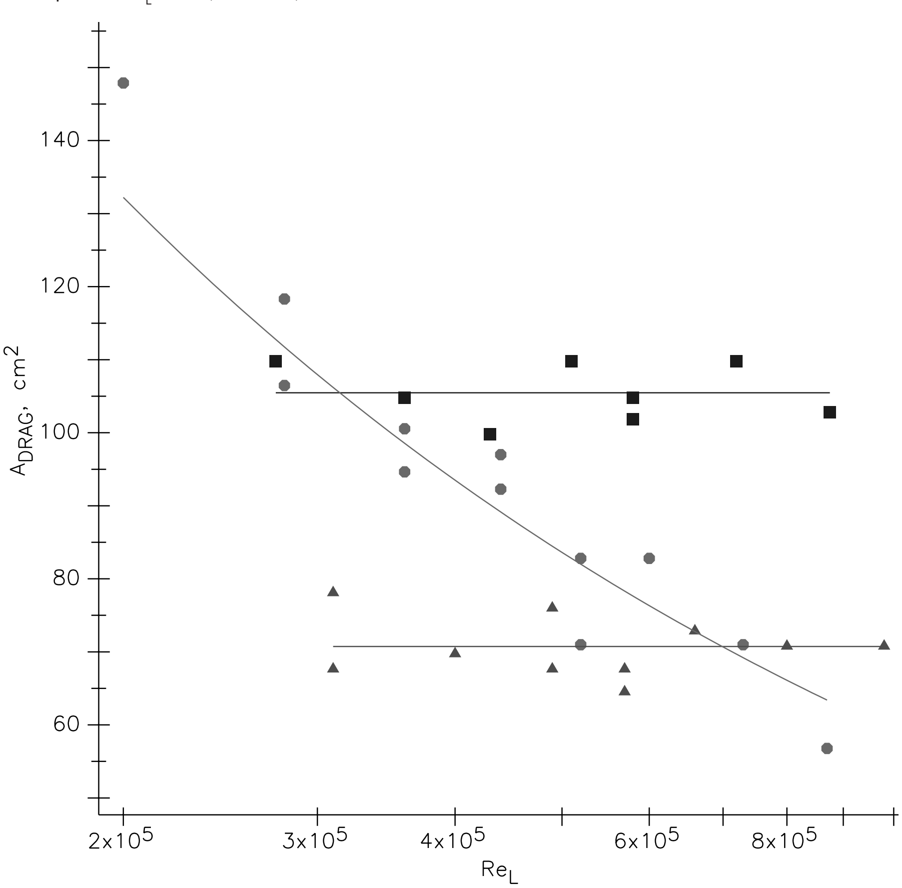
ancy control, and are effectively immune to vapor lock. Slocum is optimized for shallow and coastal operation where rapid maneuverability is important and, consequently, uses a more powerful motor than the other gliders for rapid buoyancy control.

Spray and Slocum use simple aluminum hulls to resist external pressure and provide a streamlined hydrodynamic shape. With computer controlled machining, this is an economical approach that produces a robust hull. The compressibility of these simple hulls (3.2´10^{-6} dbar^{-1} for Slocum, 3.0´10^{-6} dbar^{-1} for Spray) is, however, less than that of seawater so that extra pumping and energy are needed at the bottom of a deep dive to compensate. The Seaglider uses a compound hull with a flooded fiberglass fairing providing a streamlined laminar-flow shape while an interior aluminum hull resists pressure. The pressure hull is machined into a fluted pattern to match its compressibility to that of seawater, leading to significant energy savings, particularly at large operating depths. This compound hull increases Seaglider's volume from its 50 liter displacement to a 60 liter enclosed volume. Maximum depths of operation are 200 m for Slocum, 1000 m for Seaglider, and 1500 m for Spray.

Seaglider's laminar-flow shape gives it a drag that increases as $U^{3/2}$ rather than the conventional U^2 dependence found for Slocum and Spray. Figure 1 shows the effective drag area, based on data reported by Sherman et al. (2001) for the three hulls. Spray has a more streamlined shape than Slocum while Seaglider's drag is higher at low speeds and lower at high speed. Experience in the field shows that antennas, CTD supports, and other sensors typically add 35% to the drag.

FIGURE 1

Drag of the three glider hulls presented as the effective drag area A_{DRAG} defined so that drag force is $A_{DRAG}\frac{\rho}{2}q^2$ where is speed through the water. Symbols (Slocum: squares, Seaglider: circles, and Spray: triangles) are laboratory measurements of hull, or for Seaglider the hull and wings at zero angle of attack, plotted vs. Reynolds number based on vehicle length. Level lines are best-fit constants for Slocum and Spray. The third line is the best $Re_L^{-1/2}$ fit to Seaglider's laminar-flow drag behavior. Typical operating speed ranges correspond to Re_L of 350,000 - 600,000.



Stored energy for buoyancy control and electronics in today's electric gliders come from primary (non-rechargeable) batteries. While economics dictate using rechargeable batteries for more powerful AUVs, the extra energy density of primary batteries can be afforded when vehicle power is low and lifetimes are long. Seaglider and Spray use lithium thionyl chloride batteries, which have twice the energy per unit mass and are better built with a much longer shelf life than alkaline batteries. Slocum is designed to use alkaline batteries, which are safer and less expensive than lithium, have a lower possibility of explosive failure, and are less expensive per unit energy. Although designed for alkaline batteries, Slocum can be fitted with lithium batteries to extend life. Typically, 60-70% of the stored energy is used for propulsion with the remainder split approximately equally between communications and the onboard functions of the microprocessor controller and sensors.

Gliders dead reckon when submerged, maintaining a heading program between GPS fixes obtained at the surface. Well-trimmed gliders can fly straight through the water for a couple of hours without need for course adjustment. All three gliders sense their attitude and heading using a combination of a 3-axis magnetometer and a bubble-level. Because lateral accelerations are slight, a bubble level provides reliable readings of pitch and roll.

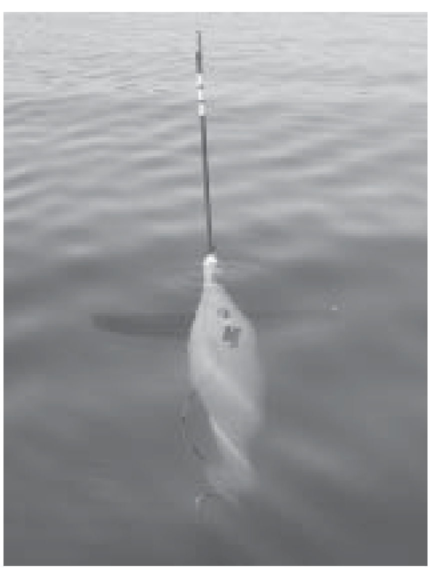
Pitch, and consequently dive angle, in all three gliders is adjusted by shifting internal mass (batteries) fore and aft. Spray and Seaglider adjust their course using roll and consequent lateral lift to change heading; rotating an eccentric weight (also batteries) around the vehicle's longitudinal axis induces roll as the center of mass stays below the center of buoyancy. Although Doug Webb pioneered this method of steering, the Slocum developed by Webb Research Corp uses a rudder to induce yaw and change heading. An active rudder was adopted to turn the glider faster than was achieved by vehicle roll. Typical turn radii of all gliders are a few tens of meters or less. Operating characteristics like waypoints, headings, emergency procedures, dive angle and buoyant forcing can typically be adjusted from shore during a mission.

Global low-power satellite communication is a key enabling technology for gliders, making it possible for them to operate worldwide sending data in near real-time. In the past, gliders have used cellular telephone, System Argos and Orbcomm for data communication but today all use two-way Iridium communication and Slocum also uses Freewave high-bandwidth Local Area Network communication when close to a receiving station. Iridium provides two-way communication with throughputs of ~200 bytes/s for an energy cost of ~40 J/Kbytes and a monetary cost of ~$0.25-0.50/kbyte. Sample density and data communication are tailored for each application and are easily adjusted through shore-to-glider communication; Iridium makes it feasible to report O(1000) samples from various sensors on each dive cycle for the order of a dollar. Local communication, like Slocum's LAN, makes it possible to relay an order of magnitude more data. Gliders typically have enough onboard memory to store more data than is relayed for subsequent analysis.

While the above basic functions of today's gliders are similar, they differ in the missions and characteristics for which they were optimized.

FIGURE 2

A Seaglider pitched down to elevate its GPS/Iridium antenna (brown cylinder at the end of the 1 m long hollow stalk). Conductivity, temperature, and dissolved oxygen sensors are visible between the (black) wings atop the (pink) fairing.



Seagliders (Figure 2) were designed to operate most efficiently in the open ocean, with dives to 1 km depth in missions of several months duration and several thousand km range. The longest mission to date covered 5 months and 2700 km; Seagliders have operated through many winter storms in the Gulf of Alaska and the Labrador Sea. To efficiently carry out surveys and to virtually moor itself at a target location, Seaglider was designed to operate with pitch angles as gentle as 10° from horizontal and as steep as 75°. Seagliders trail a 10 cm long cylindrical antenna mounted on a 1 m stalk behind the main vehicle body. This dual use Iridium/GPS antenna is raised above the air-sea interface by pitching the vehicle nose down to obtain navigational fixes and communicate. The buoyancy necessary for propulsion is normally adequate and additional pumping is not required at the surface.

Slocum (Figure 3) was optimized to operate in shallow coastal waters where high maneuverability is necessary, a limited range and duration is less of an operational hindrance, and high data rates using local communication are possible. It is designed to be readily manufactured and is available commercially. A modular payload bay centered over the vehicle's center of buoyancy is designed to facilitate sensor integration. Slocum is capable of operating in water as shallow as 5 m. Buoyancy pump gearboxes may be easily swapped according to the maximum depth required allowing optimization of torque vs. inflection speed. Successful experiments to date have included both coastal and blue-water deployments in fleets as large as 10 vehicles.

FIGURE 3

A Slocum ascending. The tail section includes the GPS/Iridium antenna and the rudder used for steering.

Spray (Figure 4) was designed for efficient deepwater performance and ease of manufacture and maintenance. It combines a low-drag hull with antennas in the wings to further reduce drag. When surfacing it rolls 90° to make one wing vertical to obtain GPS fixes or communicate through Iridium. At wind speeds above 25 knots antenna performance degrades and messages may be saved for later transmission. The aft section is a flooded compartment where sensors are easily installed. A back-up Argos antenna is often mounted in the vertical stabilizer. The main operational difficulties have been being run down by surface vessels while at the surface (a problem common to all gliders) and gas bubbles in the hydraulic pump.

3. Glider Surveys

3.1 Sections

Repeat hydrography of the upper ocean is routinely carried out using gliders (Figures 5-6). The main operational constraint is that current averaged over the depth of glider dive cycles is modest compared to glider speed. The main sampling constraint is that the decorrelation time of the surveyed fields is longer than the interval between re-

FIGURE 4

A Spray in transit to deployment. The shroud is removed from the aft flooded section exposing the external bladders that adjust vehicle buoyancy [Todd Walsh, MBARI].

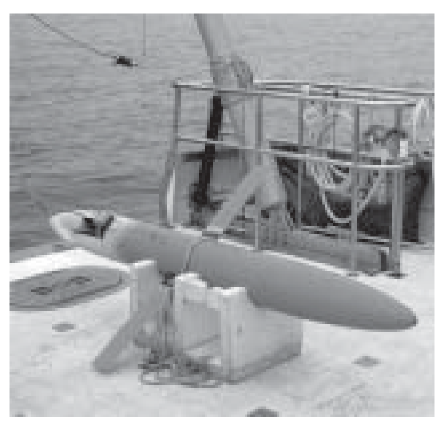
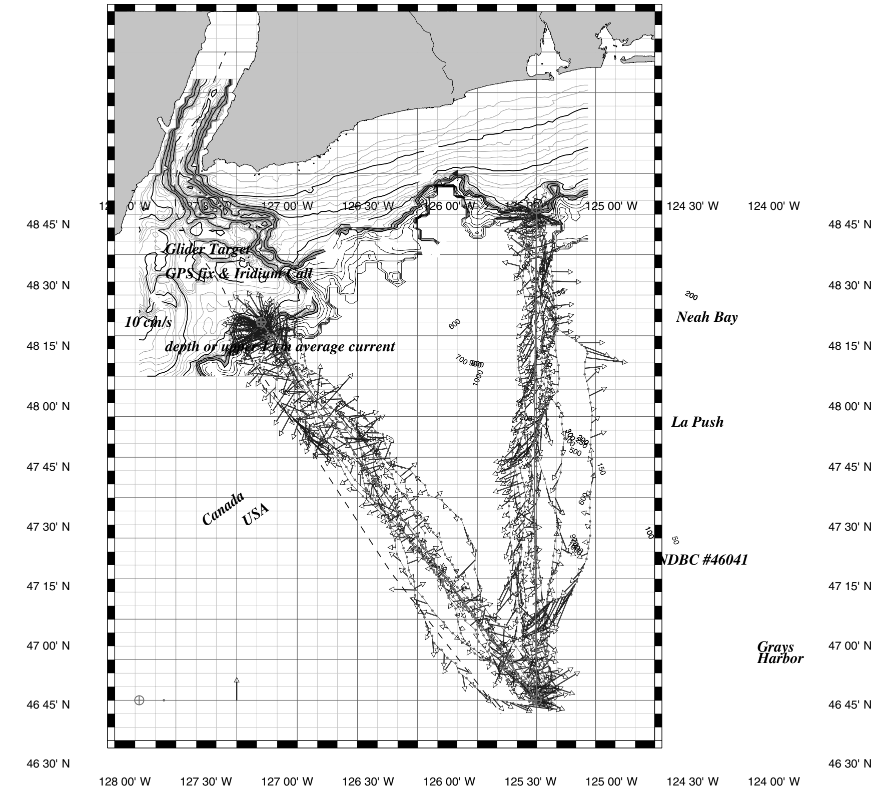


FIGURE 5

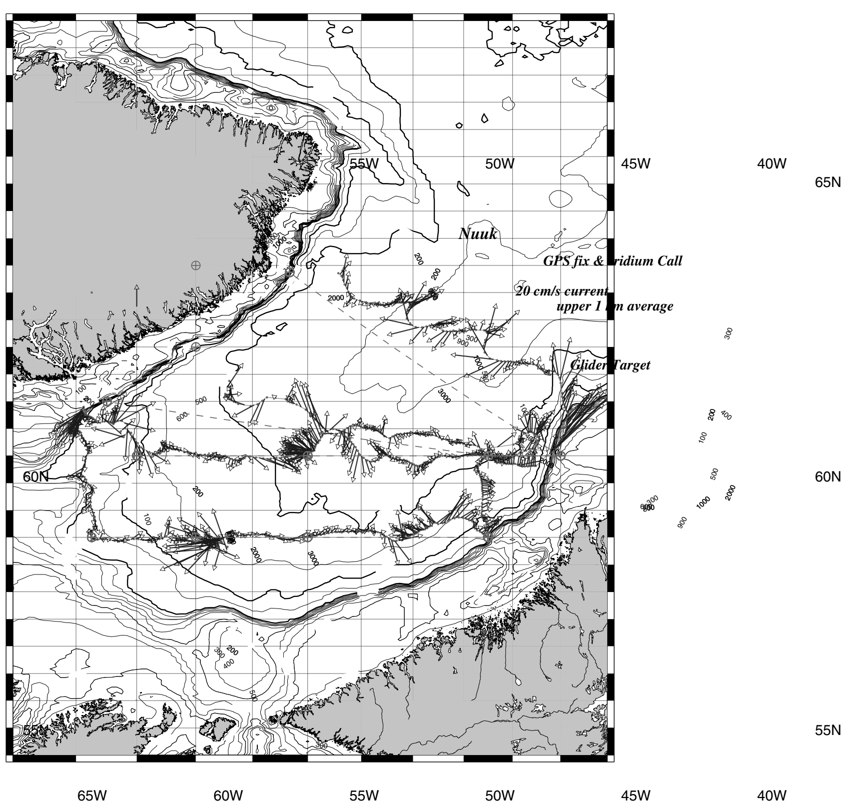
Tracks from two successive 5-month Seaglider missions off the Washington coast (22 August 2003 - 34 June 2004) together with current estimates averaged over the shallower of 1000 m and water depth. Sections are fortnightly. Dive cycles average 8 hr in duration and 6 km in lateral extent.



An example of the use of gliders to perform repeat sections is given in Figure 5, where the track of successive Seaglider deployments seaward of the continental shelf edge off the Washington coast is shown along with average current estimates over 1000 m or the bottom depth, whichever is shallower. The ten-month time series covering nearly 5000 km to date is composed of two five-month missions. A third planned of equal length has recently begun. The gliders have been sent to targets 240 km apart to form a pair of sections each roughly normal to the coast traversing part of the California Current system. Results have documented a seasonal reversal in alongshore current extending about 180 km seaward of the shelf break (poleward in winter, equatorward in summer) and the abrupt disappearance of corresponding subsurface maxima in chlorophyll fluorescence and dissolved oxygen in peat occupations. While glider economy increases with mission duration, repeat section interval is proportional to section length and inversely proportional to glider speed. Glider missions in the open deep ocean are more efficient than, for example, over the continental shelf, both because buoyancy engines are more efficient at depth and depth averaged currents tend to be smaller. Operations in strong surface currents present the complicating factor that surface drift during communication may be a significant component of glider displacement over each dive cycle. While gliders need not necessarily surface or communicate after each dive cycle, failure to do so introduces uncertainty in where measurements were made, prevents the calculation of depth-averaged current, and wastes the energy expended to become buoyant. The strategy of using the spatial structure of current systems to navigational advantage may be effective.

FIGURE 6

Tracks of two Seagliders in the Labrador Sea from 2 October 2003 through 9 February 2004, plotted as in Figure 5, but with half the current scale. Gliders were launched 75 km west of Nuuk, Greenland from a chartered tourist boat on a day trip taking advantage of a brief calm between week-long stormy periods.



autumn and reappearance in spring. These gliders have so far not shown evidence of performance degradation due to fouling.

An example of a larger scale survey is given in Figure 6, where the tracks of two Seagliders crossing the Labrador Sea in winter are shown. While stratification was considerably weaker than off the Washington coast, depth averaged currents were sometimes strong enough to cause these gliders to deviate substantially from the planned courses. Nevertheless, they were successful in completing a pair of 1000 km long shelf-edge to shelf-edge surveys across the Labrador Sea along 55°W and 58°W, respectively, execute a half dozen crossings of the Labrador Current, and nearly complete return sections. The partial section from the Labrador shelf to near the southern tip of Greenland, in particular, demonstrates how a glider traveling at 0.21 m/s through eddies with depth averaged flows sometimes nearly double that can be taken off course. These gliders observed convection deepen the surface mixed layer by ~300 m over their 4 months of operation. Compact flash memory file corruption errors impaired operation during their last month of operation and are suspected of leading eventually to vehicle loss.

3.2 Virtual Mooring

As long as currents are not stronger than glider speed, a glider can be programmed to perform repeated profiles while holding horizontal position nearly constant. In this mode of sampling, which has come to be known as the "virtual mooring," a glider can hold station as well as the surface buoy of a mooring, on the order of 1 km (Weller et al., 1990). A glider may be deployed to transit to a predetermined location, virtually moor itself for a time, and later return to be picked up close to shore. Like a profiling mooring, but unlike a standard mooring with fixed sensors, a virtually moored glider provides profiles essentially continuous in depth. The principal advantages of moorings with fixed sensors are that simultaneous measurements at different depths allow high frequency phenomena to be sampled. Other advantages of moorings are that large, hydrodynamically rough instruments can be deployed on them, and that surface meteorology can be measured from a surface buoy. Sophisticated moorings require more material resources and labor than a glider to install and operate, mainly due to size and dependence on ship operations.

The few examples of virtual moorings suggest that the technique holds promise. In an early demonstration of glider performance in 1999, a Spray was virtually moored in an underwater canyon off Monterey (Sherman et al., 2001). In 11 days, a total of 182 profiles were completed from the surface to the 380 m bottom. In another example, a pair of Seagliders was stationed 1.5 km apart across a 3 km wide fjord (part of Puget Sound) in 2001, from which along channel current profiles were calculated geostrophically. The Seagliders chose course and speed to maintain their positions based on the predictions of a Kalman filter that assimilated diurnal and semidiurnal tidal and mean currents from the difference between dead-reckoned and absolute displacements over each dive cycle. In May 2004, as a technology demonstration for the U.S. Naval Oceanographic Office the WHOI Glider Lab ran a fleet of 5 gliders in the western tropical Pacific 500 km east of Luzon Strait. This is a mid-ocean site near the subtropical front rich with mesoscale eddies. Most of the vehicles were deployed in a virtual moored array within a 100 km box. This two-week experiment (whose results are not yet available at the time of the writing of this manuscript) continues the demonstration of utility of glider networks.

3.3 Comparison to Other Modes of Sampling

To begin to understand what part of the ocean's temporal and spatial spectrum gliders sample, it is useful to compare them to established sampling methodologies. In a typical deployment a glider may profile from the surface to 500 m at a horizontal speed of 0.25 m s^{-1}, repeating a cycle once every 3 km in 3.3 h. The horizontal resolution and vertical range compares to that of the SeaSoar (Pollard, 1986) towed vehicle, which profiles to a depth of typically 350 m at a tow speed of 4 m s^{-1}, repeating a cycle every 3 km in 0.2 h. Thus, while spatial sampling is similar from a glider or a SeaSoar, the survey speed and resolved time scales are quite different. SeaSoar observations suggest that spatial structure tens of kilometers in size changes on time scales of days to weeks. Thus even a relatively short glider section will confuse temporal variability as spatial structure, and it is probably not appropriate to consider a glider section to be a snapshot of ocean conditions.

The sampling from a glider can also be compared to that of its predecessor technology, the profiling float. In a typical use, a float can be programmed to profile continuously the upper 500 m in the same 3.3 hours as a glider. The float moves horizontally with the 500 m depth-average velocity, yielding a semi-Lagrangian time series of profiles. The key advantage of using a glider in the same application is that the horizontal position of the glider is, within limits, controllable. Consider an observational program focused on a specific region of the ocean. While a float deployed in the region may be advected outside the region by ocean currents, a glider may be programmed to provide profiles at desired locations within the region. Thus gliders may be appropriately considered as profiling floats whose horizontal positions are controllable.

4. A Coastal Glider Array

The Autonomous Ocean Sampling Network (AOSN) program is a sustained research effort that is responsible for the three electric-powered gliders described here. AOSN sprang from the vision of Tom Curtin of the Office of Naval Research who saw Henry Stommel's concept of buoyancy-driven autonomous vehicles as a path to a network of observing platforms linked by real-time communication to form an array that could adapt its strategy according to observations it made (see Curtin et al., 1993). AOSN has sponsored a number of exercises (Davis et al., 2003), the most recent of which is discussed below.

In the summer of 2003 the AOSN program mounted an ambitious month-long observational effort spanning an area of roughly 100 km on a side centered on Monterey Bay that combined a wide variety of observing assets from ships and high-speed AUVs to slow long-duration underwater gliders. The broad goal was to blend these assets into an adaptive array reporting physical and bio-optical parameters to two data-assimilating numerical models so that they could forecast conditions out to a few days in advance. Coastal upwelling is vigorous along the central California coast in this season with upwelling events typically separated by periods of weak alongshore winds. Warm well-stratified water that accumulates during "wind relaxation" periods is swept offshore during wind events as the thermocline first surfaces at the coast and then the surface outcrop moves offshore until the wind slackens. Questions of concern included how this essentially two-dimensional process develops across the mouth of Monterey Bay and the substantial bathymetric perturbation of the underwater canyon.

Five Spray gliders and ten Slocum gliders were available for the experiment. The superior maneuverability of Slocum is particularly useful operating in shallow water close to the coast while the extra duration and greater operating depth of Spray is most useful in deep offshore waters where vehicle turnaround operations are more difficult. Consequently Slocums were operated nearshore along a series of "racetracks" (Figure 7) while Sprays occupied 80-100 km long lines perpendicular to the coast (Figure 8). Each Slocum carried a Sea Bird CTD and a Wetlabs chlorophyll-a fluorometer and two-wavelength optical backscatter sensor. Each Spray supported a Precision Measurement Engineering CTD and a Sea Point chlorophyll-a fluorometer or an optical backscatter sensor. Both gliders operated at effective survey speeds of 25-30 cm/s, Slocum reaching the lesser of the water depth or 200 m while Spray generally operated to 400 m (or the bottom) with daily excursions to 750 m for CTD intercomparison. The effective survey speed is a function of both vehicle speed through the water and the frequency and duration of surface intervals.

FIGURE 7

Sampling near Monterey Bay carried out by 10 Slocums over one month. The 11341 profiles were to 200 m depth or the bottom.

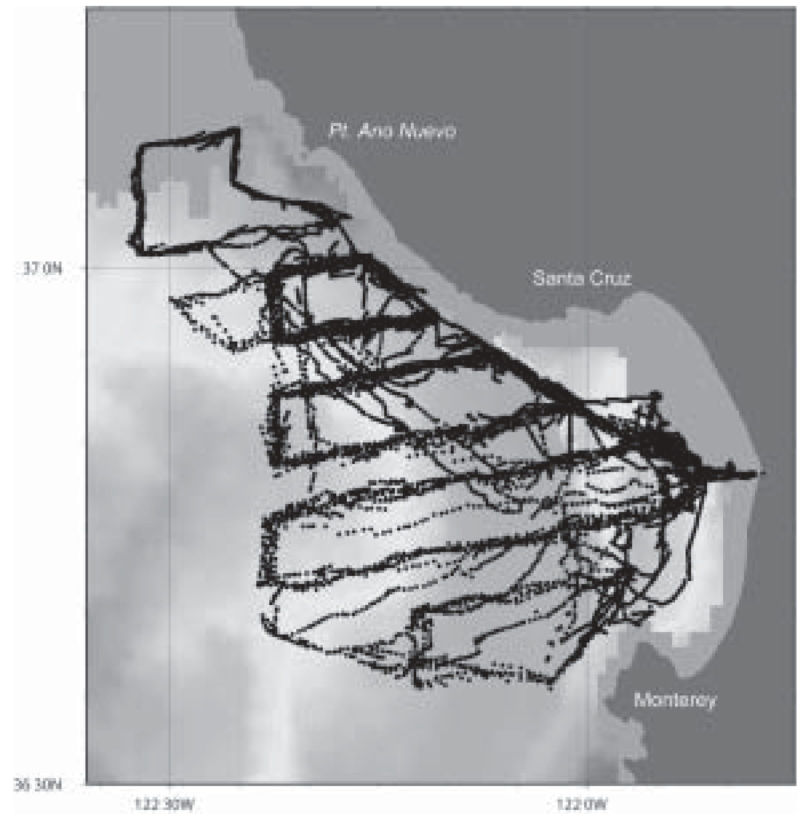
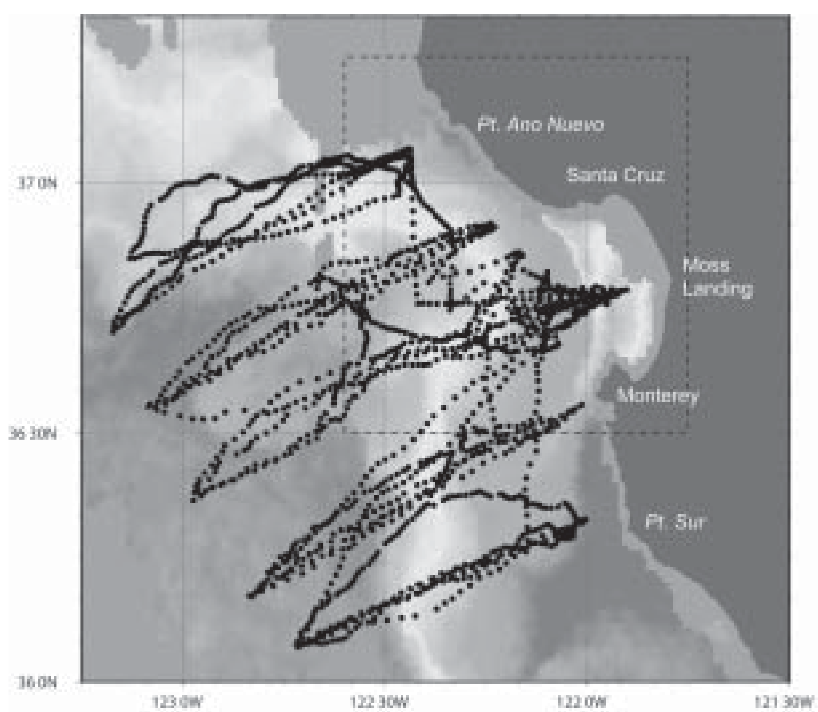


FIGURE 8

Sampling near Monterey Bay carried out by 5 Sprays over one month. Most of the 2075 profiles are to 400 m, some to 750 m.



Slocum data were acquired and reported at high resolution (approximately 40 cm in the vertical and 1 km laterally). The resultant rapid vertical cycling and significantly higher data transmission volume coupled with a lower stored energy capacity required that Slocums be recovered for re-powering approximately every 12-14 days. The Sprays, with more stored energy, lower drag, and a lower relayed data rate (approximately 6 m vertical resolution) operated for up to 5 weeks while exhausting less than 20% of their stored energy.

By comparing through-water speed and direction with distance made good between surfacing, gliders provide direct measurements of the vertically averaged velocity over the glider's operating range. Figure 9 portrays velocity averaged over the upper 400 m during the first 10 days of extensive Spray coverage during a protracted wind relaxation event. The strong flow to the northwest is apparently a manifestation of the California Undercurrent.

At the start of the 2003 AOSN field trial the scales of variability near Monterey Bay area were not well known, so the glider-sampling array (Figs. 7 & 8) was established without benefit of the kind of mapping error analysis needed to ensure that energetic features would be adequately sampled. Although the resultant array was not designed to provide spatial mapping of synoptic features, it did provide data from which the scales of variability could be roughly estimated. Figure 10 shows the homogeneous isotropic space- and time-lagged correlations of 100-150-m-average temperature from all the Spray data. The gliders resolved e-folding scales of the order 2 days and 20 km. These scales suggest that too few gliders were deployed to provide accurate mapping over the entire region. Because gliders travel less than 3 correlation space scales over the time scale of 2 days, they are the sampling equivalent of no more than 3 fixed-point time series during this experiment. It follows that about 8 gliders would be needed to map a 100 km^2 region, as such a region can be divided into 25 sectors of size the 20 km^2.

The WHOI glider fleet collected more than 11,000 vertical profiles during the AOSN-II along approximately 5,600 km of track line. Operations consisted of a combination of grid-based surveys, automated gradient-following experiments (Leonard et al., 2004), and human-directed (subjective) adaptive sampling. Programmatic objectives and a general aversion to entanglement in kelp limited glider observations shoreward of the 50 m isobath.

Some of the most interesting profiles indicated the existence of thin layers of chlorophyll fluorescence associated with strong gradients in potential density (Figure 11). These layers, often no more than a few meters thick, can contain a substantial fraction of the vertically integrated biomass (e.g. Cowles, 2003). Osborn (1998) describes finestructure in both physical and biological properties as resulting primarily from the differential lateral movement of water, and further suggests (based on the earlier work of Eckart, 1948) that the horizontal scales of features resulting from lateral intrusions are significantly larger than their vertical

FIGURE 9

Map of absolute velocity near Monterey Bay averaged from 0 to 400 m measured by 5 Sprays over a ten-day time period.

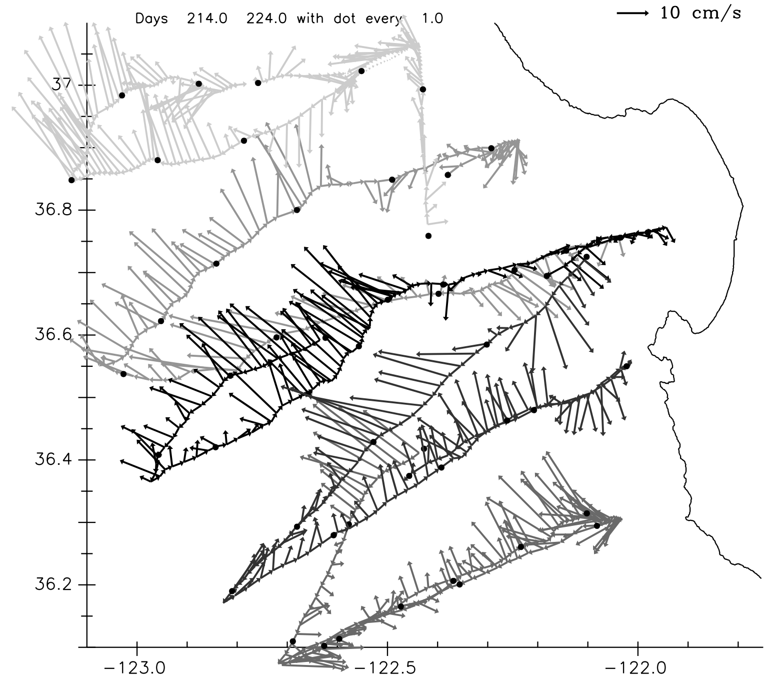
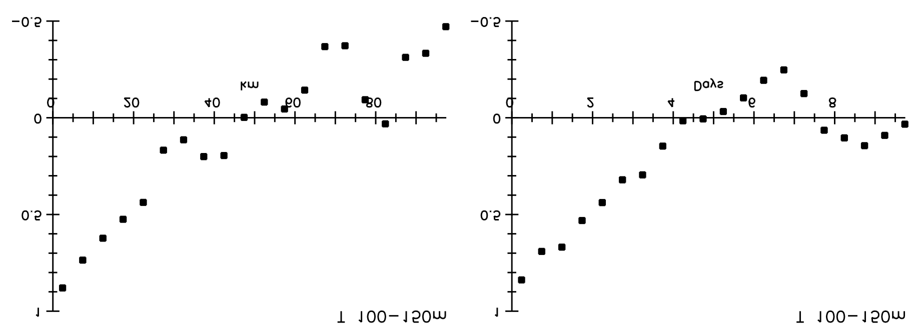


FIGURE 10

Homogeneous-isotropic correlations of temperature averaged from 100 to 150 m vs distance (left) and time (right) from Spray data in Monterey Bay.



scale. As a consequence of their relative shallow glide angle and high endurance, a fleet of gliders is intrinsically well suited to identify and study features with relatively small vertical scale and arbitrary horizontal extent. During AOSN-II the WHOI glider fleet was able to map the occurrence of thin layers over most of Monterey Bay and through the several upwelling/relaxation cycles. Spatial clustering of layers was observed near fronts associated with the cool, nutrient-rich plume of upwelled water south of Pt. Año Nuevo and near the head of Monterey Canyon (Figure 12).

5. Sensors

Perhaps more than any other unattended observing platform, gliders have the most stringent constraints as to the types of sensors that they can carry. The primary requirements for glider sensors are small size, low weight, and stingy power consumption. In the current generation of gliders, extra space beyond that devoted to the operation of the glider itself, and the batteries that power the sensors, is minimal. Ideally, glider sensors should be small, but also should not protrude beyond the external surface of the glider. If protrusion cannot be avoided, sensors should be designed and located on the surface in a way that minimizes hydrodynamic drag. Bulky sensors have been strapped externally to the glider body, but at the cost of reduced mission length. Many glider missions to date have been experimental, testing the capacities of both the platform and the sensor. As the usage of glider increases, options will likely evolve that allow for integrated sensor systems on gliders used for specific types of missions as well as modular systems that allow the user to easily reconfigure the sensor packages for diversity of tasks.

Sensor weight is important because of limits in glider payload and the need to maintain centers of mass and buoyancy within the glider. Low power consumption of sensors is critical because, to a large extent, the power budget determines the length of the glider deployment. It is ultimately the power budget that forces tradeoffs among mission length, sampling frequency, num-

FIGURE 11

Locations of 140 profiles exhibiting thin layers in chlorophyll fluorescence during the August 2003 AOSN-II experiment in Monterey Bay. The contours represent bathymetry, 50-200 m in steps of 50 m (dashed), and 500 m and deeper with intervals of 500 m (solid). Observations were limited to depths greater than 50 m (green dashed contour). Thin layers were objectively identified from a population of more than 11,000 profiles by their intensity (greater than 3 times background), their thickness (less than 5 m), and by the number of discrete samples spanning the layer (n>5). Less stringent selection criteria resulted in considerably more layers. Spatial clustering of thin layers was observed near fronts associated with a cool, nutrient rich plume of upwelled water. A substantial number of thin layers were also observed near the head of Monterey Canyon.

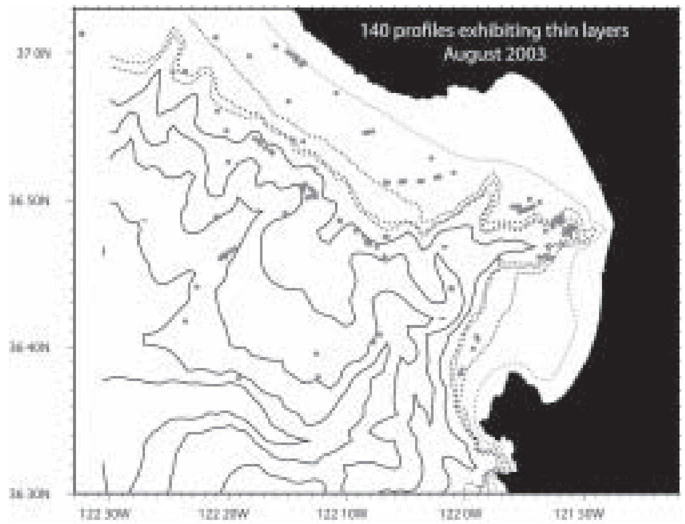
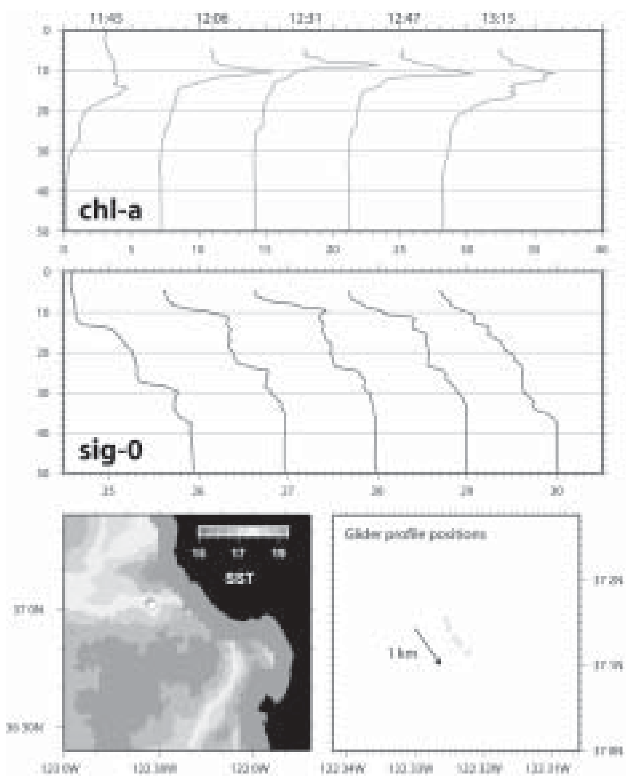


FIGURE 12

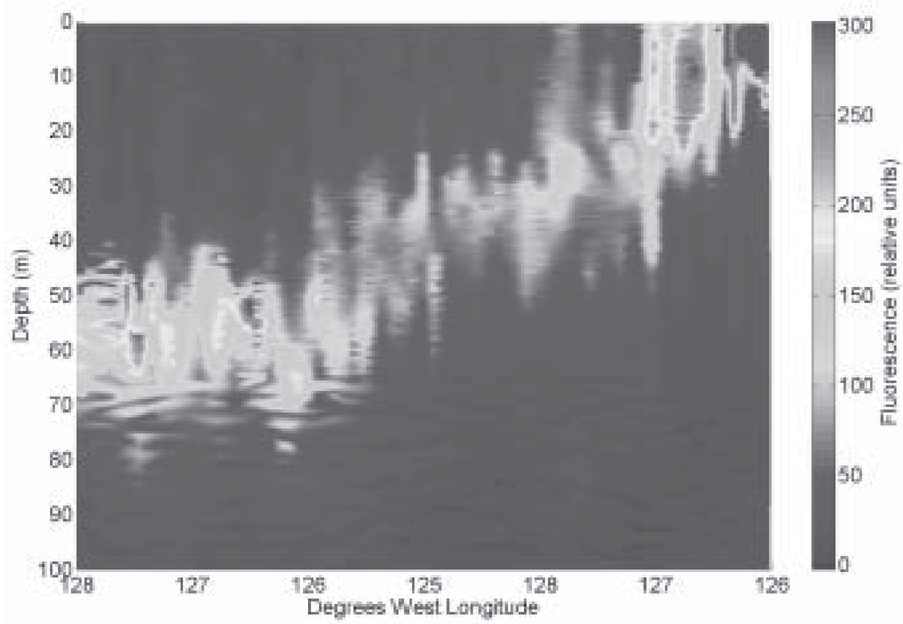
Five consecutive chlorophyll and density profiles collected by a single Slocum glider near an upwelling front, August 25, 2003. Note the substantial change in structure and intensity of both the phytoplankton layers and the underlying stratification during the 1.5 hour / 1 km span of these measurements. The locations of the profiles relative to the coastline and SST observations (left) and in detail (right) are indicated in the lower panels.



ber and types of sensors incorporated into or attached onto gliders. For some applications, endurance is key; for others, the key is the ability to measure specific variables, even if the sensors are not optimized for gliders. Power restrictions also influence the quality of data collected by some sensors. For example, in traditional applications of conductivity and oxygen sensors, pumps deliver water to the sensing surface at constant rates. The power consumption of currently available pumps is a serious constraint, but their use on gliders is being investigated. Water flow through sensors depends on glider motion, and hence is variable, reducing the accuracy of the data, although efforts are underway to model the responses of various sensors on gliders. Some sensors that have been flown on gliders are commercially available, while others are in various stages of development, or optimization for gliders, at academic institutions or industry. The natural evolution of oceanographic sensors has been reduction in power and size without sacrificing performance, and the extreme technological challenges of sensing on gliders have accelerated the development of a new generation of small sensors specifically designed for gliders that will also be highly applicable for other autonomous observing platforms (Rudnick and Perry, 2003).

FIGURE 13

Fluorescence section measured by a Seaglider off the coast of Washington (Figure 5).



5.1 Sensors Used to Date

Despite the constraints of size, weight, and power, an impressive diversity of biological, chemical, and physical sensors have already been deployed on gliders. Temperature, salinity, and pressure sensors form the basic suite of sensors that have been integrated into all gliders; because of the low power consumption of these sensors, temperature and salinity can be continuously monitored. Daly et al. (2004) provide an overview of chemical and biological sensors, their stage of development, and present capabilities for gliders and other platforms. In the last few years a number of optical sensors have been developed that meet glider size and power constraints, and a diversity of optical sensors have been deployed on Seaglider, Slocum, and Spray. Passive radiometers measure apparent optical properties (AOPs) and depend on sunlight as the source of light; their power consumption is low, but the major disadvantage is that they cannot operate at night or below the photic zone. A small cosine PAR sensor (i.e., Photosynthetically Active Radiation, visible wavelengths) developed by Fucile at WHOI was used on Slocum gliders during the AOSN experiment in summer 2003. Sensor placement is important, particularly for AOP sensors; scalar irradiance sensors that measure ~ 4 pi steradians many be preferable for gliders and obviate the need to correct of variability in glider orientation during dives. A small prototype bioluminescence sensor, primarily for detection of dinoflagellate bioluminescence, has been deployed on gliders by WHOI. Active optical sensors, consisting of internal light sources and detectors, are able to collect data at night and below the photic zone, but at the cost of greater power consumption relative to passive sensors. The active sensors measure inherent optical properties (IOPs = absorption, scattering, and attenuation coefficients) and fluorescence of chlorophyll, phycoerythrin and CDOM (chromophoric dissolved organic matter); these variables serve as proxies for concentrations of phytoplankton, suspended sediments, and particulate and dissolved organic carbon. The Rutgers University and Mote Marine Laboratory groups have tested a liquid capillary waveguide on gliders to measure hyperspectral particulate absorption coefficients, similar to the instrument used to measure CDOM absorption (Kirkpatrick et al., 2003), with the goal of identifying harmful algal species. The WET Labs ECO Pucks, small flush-face sensors that can be integrated into the body of the glider, offer options for measuring optical backscattering at one or several wavelengths, backscattering at one or several angles, or a combination of backscattering and fluorescence. Data in Figure 13 were collected with a fluorescence/optical backscatter ECO Puck during the second leg of the 2003 Seaglider deployment off the Washington coast (Figure 5; from 47N, 128 W landward to 47N, 125W). The subsurface phytoplankton layer is persistent in offshore waters from spring to early autumn. Although undetectable by ocean color satellites, this subsurface layer dominates the annual net productivity of these offshore waters.

Oxygen sensor technology and issues related to calibration and stability are reviewed in Daly et al. (2004). The Sea-Bird oxygen sensor, based on a modified Clark polarographic membrane, is currently used on Seaglider; because water is not pumped across the surface of the membrane at a constant rate, calibration is more difficult than for pumped systems. A completely different type of oxygen sensor, available commercially from Aanderra, will soon be tested on gliders. Optode technology is based on fluorescence quenching: the fluorescent emission of a fluorophore is reduced as a function of oxygen concentration. The use of oxygen optodes in the oceanographic community is relatively new, and assessment of the performance of these sensors is an area of active research.

5.2 Current Developments and Possibilities

One genre of sensors that has not yet been deployed on gliders, because of size and power requirements, is the nutrient sensor. Measurement of macronutrients—nitrate, nitrite, ammonium, phosphate, silicate—and trace metals is central to biogeochemical studies as well as to water quality assessment. In-water nutrient sensor technology is rapidly evolving and the size of wet chemical sensors for quantifying them is diminishing. Recent developments have made it possible to measure nitrate in seawater, without traditional colorimetric analysis or pumps, based on its UV absorption spectrum (Johnson and Coletti,2002). Continued advances in opto-electronics, such as UV-light emitting diodes, are necessary to reduce the power consumption of the UV nitrate sensor. The development of low-power pumps is critical to wet chemistry, as well as to the performance of other sensors. Long-term deployments of gliders that carry nutrient sensors will only be possible if power consumption is reduced by several orders of magnitude, and the technology is moving in that direction (cf. Table 2, Daly et al., 2004).

To date, acoustic methods for zooplankton biomass assessment have not been attempted on gliders, largely due to the weight and power consumption of these sensors. The development of high-quality, low-power acoustic for measuring zooplankton, and fish, are sorely needed for marine food web studies and to track individuals or schools for extended periods of time. We know relatively little about how organisms react to small-scale changes in the physical, biological, and chemical conditions of their habitat.

Velocity observations are now derived from gliders by dead-reckoning between profiles. These depth-average velocities are essential to the control of gliders, as well as being valuable data. A current development is the deployment Acoustic Doppler Current Profilers (ADCPs) on gliders. ADCPs would provide depth-dependent velocity profiles, making possible the calculation of fluxes of other observed parameters, such as heat, salt, and chlorophyll. A fully successful deployment of an ADCP on a glider is likely within the next year or two.

Gliders should be ideal platforms for measuring turbulence because they move slowly with little vibration or platform noise. The turbulence sensors now in use on tethered and autonomous profilers could be deployed on gliders. Fast-response thermistors and conductivity sensors, optical sensors, and pitot tubes are all legitimate possibilities. The high data rates of these sensors would call for relatively short deployments with most data recorded internally, but not communicated in real time.

Biofouling remains an issue that affects the performance of many sensors. The general term biofouling encompasses organic, bacterial and microalgal films, macroalge (typically filamentous), barnacles and bivalves. A major question on long-term deployments is when biofouling began and how the instrument behavior changed over time. Glider missions that entail only shallow dives in biological-rich waters experience heavy biofouling within one to several weeks. In contrast, gliders that perform only deep dives in less productive waters can operate for months with minimal fouling. Issues of biofouling, long-term stability, and evaluation of changes in unattended sensor performance with time will require creative solutions, but the payoff is tremendous as networks of gliders sense a multiple of physical and biogeochemical state and rate variables on the same space and time scales.

6. Conclusion

Gliders are a new technology in active development. Each of the three glider designs has proven successful in their own manner. Improvements in design are ongoing as experience indicates where better performance is needed. A variety of sensors has been deployed on gliders, and many more sensors are in the process of being integrated, with great promise for the future. The results so far suggest that gliders will be an important observational tool in the coming decade (Schofield et al., 2002).

The three glider designs discussed herein constitute only the first generation of this new mode of observation. The development of new gliding vehicles, including those with substantially greater payload capacity, increased depth capability, and higher survey speed, is ongoing. These future glider designs may bear little resemblance to Spray, Seaglider, and Slocum, yet will embrace the same design challenges of versatility, economy, and endurance.

The next stage in the use of gliders for ocean research is the deployment of many units in a coordinated fashion matched to the scales of interest. An example of such a deployment is the 2003 AOSN exercise in the coastal waters off Monterey Bay. The first results suggest that gliders can resolve the relevant temporal (2 days) and spatial (20 km) scales. A time series of maps was not possible with the AOSN glider network, because it was too sparse, but the requirements for such a network are being established. Thin layers of chlorophyll coherent with regions of strong density stratification, for example, are observable with a glider network.

A legitimate, open question is what will gliders eventually contribute to our observational capacity, especially in comparison to established platforms and techniques. In this article, we have offered a few comparisons to moorings, ship surveys, and floats, but we have not designed performance metrics (Wilcox et al., 2001), nor made detailed cost/benefit analyses. Any cost/benefit analysis is intricately dependent on the oceanographic process or phenomenon to be observed. Given the relevant scales of the process, the optimum mix of observational platforms may be determined, usually through trial and error. The value of gliders will emerge naturally as they are increasingly used to do science in the coming years.

Observing the ocean is a challenging endeavor, made difficult by the wide range of time and space scales that must be resolved. Excellent resolution in time (from seconds to years) has been possible for the past thirty years, using moorings developed and operated by many institutions. Satellites effectively sample the surface ocean, globally and with good spatial resolution. The frontier in ocean observation is adequate and sustained spatial sampling of the subsurface ocean. Networks of autonomous platforms, such as floats (Roemmich et al., 2004) and gliders seem the best way to conquer that frontier.

Acknowledgments

The support of the Office of Naval Research (ONR) and the National Science Foundation (NSF) is gratefully acknowledged through the following grants: NSF OCE0300208, NSF OCE9819530 (DLR); ONR N000140310429 (RED); NSF OCE0095414, NSF OCE9911036, ONR N000140210791 (CCE); ONR N000140210846 (DMF); NSF OCE9911037 (MJP).

References

Cowles, T. J. 2003. Planktonic Layers: Physical and Biological Interactions on the Small Scale. Handbook of Scaling Methods in Aquatic Ecology: Measurement, Analysis, Simulation. CRC Press, in press.

Curtin, T. B., J. G. Bellingham, J. Catipovic and D. Webb. 1993. Autonomous oceanographic sampling networks. Oceanography. 3:86-94.

Daly, K. L., R. H. Byrne, A. G. Dickson, S. M. Gallager, M. J. Perry and M. K. Tivey. 2004. Chemical and biological sensors for time-series research: Current status and new directions. Mar Tech Soc J. 38(2):[**pages ?**].

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.

Davis, R. E., C. C. Eriksen and C. P. Jones. 2003. Autonomous buoyancy-driven underwater gliders. In: Technology and Applications of Autonomous Underwater Vehicles, ed. G. Griffiths, pp. 37-58. Taylor and Francis.

Eckart, C. 1948. An analysis of the stirring and mixing processes in incompressible fluids. J Mar Res. 7:265-275.

Eriksen, C. C., T. J. 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 J Oceanic Eng. 26:424-436.

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 Res. I, 49:1291-1305.

Kirkpatrick, G. J., C. Orrico, M. A. Moline, M. Oliver and O. M. Scholfield. 2003. Continuous hyperspectral absorption measurements of colored dissolved organic material in aquatic systems. App Optics. 42:6564-6568.

Leonard, N. E., R. Bachmayer, P. Bhatta, E. Fiorelli, D. Paley and D. M. Fratantoni. 2004. Design and implementation of multi-AUV control methodologies for adaptive sampling in a dynamic and uncertain environment. [**Proceedings of?**] IEEE Oceanic Engineering Society, Autonomous Underwater Vehicles 2004, Sebasco Estates, ME.

Osborn, T. 1998. Finestructure, microstructure, and thin layers. Oceanography. 11:36-43.
Pollard, R. 1986. Frontal surveys with a towed profiling conductivity/temperature/depth measurement package (SeaSoar). Nature. 323:433-435.

Roemmich, D., S. Riser, R. Davis and Y. Desaubies. 2004. Autonomous profiling floats; workhorse for broadscale ocean observations. Mar Tech Soc J. 38(2):(**pages?**).

Rudnick, D. L. and M. J. Perry, eds. 2003. ALPS: Autonomous and Lagrangian Platforms and Sensors, Workshop Report. 64 pp.

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

Sherman, J., R. E. Davis, W. B. Owens, and J. Valdes, 2001: The autonomous underwater glider "Spray". IEEE J Oceanic Eng. 26:437-446.

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

Webb, D. C., P. J. Simonetti and C. P. Jones. 2001. SLOCUM: An underwater glider propelled by environmental energy. IEEE J Oceanic Eng. 26:447-452.

Weller, R. A., D. L. Rudnick, N. J. Pennington, R. P. Trask and J. R. Valdes. 1990. Measuring upper ocean variability from an array of surface moorings in the subtropical convergence zone. J Atmos Oceanic Technol. 7:68-84.

Wilcox, J. S., J. G. Bellingham, Y. Zhang and A. B. Baggeroer. 2001. Performance metrics for oceanographic surveys with autonomous underwater vehicles. IEEE J Oceanic Eng. 26:711-725.