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Introduction to the *Limnology and Oceanography* Special Issue on Autonomous and Lagrangian Platforms and Sensors (ALPS)

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Abstract

This issue is devoted to recent developments of autonomous and Lagrangian platforms and sensors (ALPS) and their uses for solving a broad range of interdisciplinary aquatic problems. The collective papers treat a variety of problems that generally require measurements spanning a continuum of temporal and spatial scales. ALPS platforms in this issue include surface drifters, profiling and other types of subsurface floats, gliders, unmanned boats, autonomous underwater vehicles, and instrumented animals. ALPS platforms can provide access in difficult environments (e.g., under ice and in high-sea states). They are also important for emerging networked ocean and lake observing systems that require continuous measurements and near-real-time data. This introductory paper provides historical perspectives, background, motivation for the issue, and a tabular summary of papers in the present collection.

Background

Limnologists and oceanographers rely heavily upon in situ as well as remote sensing observations to develop and test hypotheses and models. Aquatic environments remain grossly undersampled for a variety of reasons despite the increasing urgency for their improved management and stewardship and their acknowledged importance to many key aspects of global climate change. Development of interdisciplinary sampling platforms and sensors has been driven in large part by societally relevant as well as curiosity-driven problems (*see* table 1 in Dickey and Bidigare 2005). The ocean and its adjacent aquatic environments are difficult to study because they are often hostile (e.g., affected by storms and large waves) and hard to reach (e.g., under ice, distant from ports). In addition, they are heterogeneous turbulent fluids that are inherently difficult to sample (Davis 1991). Aquatic scientists not only must cross disciplinary boundaries to examine phenomena and test models, but also are often required to encompass spatial and temporal scales that span 6 to 10 orders of magnitude to capture episodic events as well as document long-term trends.

This special issue on autonomous and Lagrangian platforms and sensors (ALPS) is devoted to a new class of aquatic, autonomous sampling platforms and sensors that uniquely meet some of the challenges of sampling aquatic systems over a broad range of temporal and spatial scales. The unifying feature of ALPS is that they are autonomous and deliberately mobile; they currently include surface drifters, profiling and other types of subsurface floats, gliders, unmanned boats, autonomous underwater vehicles (AUVs), and instrumented animals. Unmanned sailboats and hybrid platforms are under development as well. Used either singly or in networks, ALPS enable sampling at relevant temporal and spatial scales while providing a continuous observing presence to capture episodic events, sample adaptively, and characterize longer-term phenomena. Over the last decade as ALPS technologies matured, they have been transitioned from the engineering test phase to mainstream science applications. Results from early scientific missions are now becoming available, making this an excellent time to review how ALPS technologies can be used to address the challenge of sampling turbulent, heterogeneous fluids, and answer compelling science questions. This special issue presents examples of advances in understanding that have resulted from these efforts and offers a view into future applications of the new ALPS technologies.

A few brief historical perspectives are offered before the formal introduction of the papers that appear in this issue. Walter Munk (2000) eloquently described one of the sampling dilemmas of oceanographers, which dates back to the Challenger expeditions of the 1870s. He noted, "The first law of ocean research was to never waste your assets by occupying the same station twice. And when the law was violated and the results differed, the differences could be attributed to equipment malfunctioning." Of course, he was referring to the nonsteady-state condition of the heterogeneous ocean and the problem of undersampling in time and space. He also discussed how mesoscale variability (e.g., ocean

Table 1. List of the papers in this special issue.

Authors	Platforms	Applications	Regions
Drifters and floats			
Boutin et al.	Surface drifters	CO2 air–sea exchange	Southern Ocean
Riser et al.	Profiling float	Rainfall and wind	Indian Ocean
Martz et al.	Profiling float	Oxygen utilization and primary production	South Pacific
Boss et al.	Profiling float	Primary production in eddies	North Atlantic
Checkley et al.	Profiling float	Plankton dynamics	North Pacific
D'Asaro	Mixed-layer float	Ocean mixing	North Pacific
Gliders			
Davis et al.	Gliders	Primary production in coastal fronts and eddies	California Current
Perry et al.	Gliders	Seasonal cycle of primary production across the shelf	Washington Shelf
Glenn et al.	Gliders	Sediment resuspension under a hurricane	Mid-Atlantic Bight
Baumgartner and Fratantoni	Gliders	Whale vocalization	Gulf of Maine
Niewiadomska et al.	Gliders	Biogeochemical variability	Mediterranean
Nicholson et al.	Gliders	Oxygen utilization and primary production	North Pacific
AUVs, robotic boats, and animals			
Johnson and Needoba	AUV	Small-scale variability in nutrient and oxygen	Monterey Bay
Chao et al.	AUV	Effect of in-situ observations on model predictions	Monterey Bay
Shcherbina et al.	AUV	Population connectivity of Nassau Grouper	Caribbean Sea
Jones et al.	AUV	Plume dispersion on a fringing reef	Hawaii
Hayes and Morison	AUV	Heat and salt flux under ice	Arctic Ocean
Nicholls et al.	AUV	Ocean variability under an ice shelf	Antarctic Shelf
Forrest et al.	AUV	Temperature structure and thermodynamics of small lake	Pavilion Lake, BC
Caron et al.	Robotic boat	Mixing and anoxia in a lake	Lake Fulmor, CA
Boehme et al.	Elephant seal	Dynamics of high latitude fronts	Southern Ocean

weather on orders of 10- to 100-km scales), which contributes over 95% of the ocean's kinetic energy, had "fallen through the loose net of traditional sampling." Finally, he stated, "If I were to choose a single phrase for the first century of modern oceanography, it would be a century of undersampling."

Earlier, Henry Stommel (1963) carefully outlined the problems of sampling the ocean from theoretical and practical points of view. He created what has become known as a Stommel diagram to depict expected variability in sea level associated with processes ranging in time from less than a minute (i.e., surface gravity waves and high-frequency internal gravity waves) to many centuries (i.e., climate and ice age variations) with important intermediate-scale phenomena including tides, geostrophic turbulence (mesoscale eddies), and annual cycles. Like Munk, he used the fishing net as a metaphor in regard to mesoscale eddies, stating that "a single net does not catch fish of all sizes; the existing net of tide gauges does not suffice for a study of geostrophic turbulence." Stommel further commented, "It is necessary to decide which part of the spectrum of each variable one wants to measure." Indeed, the Stommel diagram and other time–space diagrams forwarded by subsequent researchers (Haury et al. 1977; Dickey 1991) have been used as templates for many different field experiments. However, it also important to note that Stommel (1963), and later in biological terms, Levin (1992), as well as others, have aptly cautioned that "contamination" from other parts of the spectrum is important as variance or energy cascades to both larger and smaller scales as processes interact. Oceanographers, including Haury et al. (1977), Denman and Powell (1984), and Levin (1992), underscored the importance of pattern and scales including "patchiness" for attacking fundamental problems of ecology and the unification of population biology, biogeochemistry, and ecosystems as affected by physical and chemical forcing. These reviews dealt with various aspects and used different schematizations of the time–space diagram for wide-ranging ocean processes. Importantly, interdisciplinary data were beginning to be collected from moorings, towed instrument packages deployed from ships and drifters in the late 1970s and early 1980s. During the same period, the advent of satellite-based radiometers also revealed the level of time and space variability at the mesoscale and underscored the need for improving data density and sampling methods.

In the 20th century, ships, moorings, drifters, floats, and satellites were the major oceanographic sampling platforms; these will continue to play important roles well into the future. In particular, stationary moorings with fixed-depth and profiling instruments have served to increase our understanding of depth- and time-dependent changes at specific geographic locations (Send et al. 2001). In addition, surface drifters and subsurface floats (fixed-depth and profiling) have been effectively used to track currents and heat changes. Autonomous sampling platforms have important attributes that will increase their usage in the future, either alone or in combination with other emerging autonomous sampling platforms or in concert with more traditional sampling platforms. These capabilities enable measurements over a greater range of time and space scales, extended sampling durations, decreased cost, greater numbers of observations particularly when configured as networks of ALPS, adaptive sampling, and collection of data under extraordinarily adverse conditions such as hurricanes and typhoons (Dickey et al. 2006; D'Asaro and McNeil 2007; D'Asaro et al. 2007).

Ideas for sampling the ocean without direct use of ships can be traced back to at least the late 18th century as noted by Perry and Rudnick (2003). For example, Benjamin Franklin reported observations made with buoys and drogues in the late 1780's and Robert Whitehead has been credited with the development of an early autonomous underwater vehicle in the 1860's (AUV; e,g., see Griffiths 2003), which was called the Whitehead Automobile "Fish" Torpedo. About a century later, John Swallow used neutrally buoyant floats to track deep currents and first noted energetic mesoscale eddies.

The oceanographic community was apprised of the potential for in situ sampling of the ocean on a global scale in a futuristic paper by none other than Stommel (1989), who described the mythical Slocum mission, which utilized AUVs (essentially gliders; Eriksen et al. 2001; Davis et al. 2003) using the ocean's naturally occurring thermal gradients to vertically navigate and sample. As part of his envisioned World Ocean Observing System (WOOS), similar to the present-day Global Ocean Observing System, two classes of gliders, Slocums for research and Sentinels for monitoring, prowled the seas and transmitted their data back to scientists residing on an island offshore of Woods Hole, Massachusetts (of course!). In this vision, one-half of the 1000 Slocums were capable of measuring geochemical (including tracers) in addition to the physical variables. Interestingly, at the end of 2007, the international ARGO program reached its goal of deploying over 3000 profiling ARGO floats worldwide; these are now collecting temperature and salinity profiles daily (ARGO Sciences Team 2001; Davis et al. 2001; Schiermeier 2007). Stommel's vision was to study a host of societally important problems (e.g., pollutant trajectories, ocean heating, circulation patterns) as well as to conduct an around-the-world ocean race for Slocums that would allow phenomena to be discovered, theories to be tested, and the world populace to become engaged in and learn some oceanography (i.e., riding internal Kelvin waves). Quite obviously, Stommel anticipated precisely the sort of work described in the present ALPS issue.

In recent years, some investigators have equipped moorings (Eulerian), drifters (Lagrangian), and floats (Lagrangian) with sensors or samplers to expand their capacity for biological, chemical, and geological as well as physical measurements (reviews by Dickey 2003; Rudnick and Perry 2003; Dickey and Bidigare 2005). Tagging of marine mammals, fish, and seabirds has provided information about both the animals and the ocean (McCafferty et al. 1999; Weimerskirch et al. 1995). As technologies have advanced during the past few decades, autonomous sampling and data telemetry from new mobile vehicles as well as Lagrangian and stationary platforms and marine animals and birds has become a reality. Some fascinating scientific papers based upon the early ALPS studies have already been published. They include Niiler 2001; Bishop et al. 2002; Yu et al. 2002; Autosub Science and Engineering Teams 2003; Oceanography, V. 17, No. 2, June 2004, Special Issue: Coastal Ocean Optics and Dynamics; Bishop et al. 2004; Riser and Johnson 2008.

In recognition of the recent advances in ALPS technologies, a workshop was convened in La Jolla, California by Rudnick and Perry (2003). This workshop represented a key step in identifying the capabilities of ALPS for addressing a host of important scientific questions, for determining means to utilize ALPS alone or in conjunction with other ocean observing tools, and for facilitating community access to ALPS technologies. This workshop was followed by special sessions at the The Oceanography Society (TOS) meeting in June 2005 on ALPS and the joint American Geophysical Union–American Society of Limnology and Oceanography–TOS Ocean Sciences Meeting in February 2006, entitled "New results from science programs employing autonomous and Lagrangian platforms." The 2006 meeting garnered large responses in the number of papers presented, concurrent press conference coverage, and participation in the session. The concept for this *Limnology and Oceanography* special issue arose, in large part, because of the interest generated by the meeting.

This *Limnology and Oceanography* special issue on ALPS presents a compendium of research papers that utilize ALPS for the advancement of limnology and oceanography. The open call for papers sought contributions on recent advances in physical, chemical, and biological studies that were enabled by ALPS on a wide range of scales. Suggested ALPS platforms included: surface drifters, profiling floats, AUVs, and gliders as well as other emerging platforms. Papers were solicited from all disciplines in the aquatic sciences, and suggested topics included current structures, heat and salt flux, ocean–atmosphere interaction, shelf exchange, sediment transport, biogeochemistry, particle flux, nutrient distribution, eutrophication, primary productivity, deep-sea geochemistry, biological dynamics, plankton structure and interaction, harmful algae, bioacoustics, animal migration, and deep-sea biota. Interdisciplinary studies enabled by ALPS and numerical modeling studies using ALPS were also welcomed.

Finally, it is worth noting that ALPS platforms will be vital for virtually all of the emerging national and international ocean observing systems (Glenn and Dickey 2003; Schofield and Tivey 2005; Babin et al. 2008) and for the development of predictive interdisciplinary data assimilation models (Hoffman and Friedrichs 2001; Robinson and Lermusiaux 2002; Dickey 2003). It is exciting to witness that Stommel's Slocum mission is indeed becoming a reality and that Munk's "century of undersampling" may become a distant memory.

Overview of the issue

Papers appearing in this ALPS issue have been placed in sequence according to platforms: drifters, floats, gliders, AUVs and robotic boats, and animals. They are summarized in Table 1.

The first group of papers is based on studies that used drifters and floats, which follow water motion and are thus Lagrangian. These devices are used for a range of applications and typically have multiple sensors and interdisciplinary objectives. Drifters have been used for many years by oceanographers; however, their utility has been vastly improved with the advent of satellite global positioning systems and a plethora of new multidisciplinary sensors. Likewise, fixed-depth floats have been commonly used for several decades in circulation and water mass transformation studies. A new generation of profiling floats has enabled observational access to vast regions of the oceans that were rarely sampled by conventional ships. Novel uses of drifters and floats are presented in this group of papers.

In the second group of papers, gliders serve as the platforms. Gliders, which can be operated over long distances and deployment periods, are constrained primarily by battery life and biofouling. In most cases, gliders have been used to collect horizontal–vertical spatial data sets; however, they can also be used to obtain time series when programmed to remain near a selected site. A variety of physical, chemical, optical, and acoustical sensors have been mounted on gliders for various scientific studies as described in this group of papers.

Papers in the final group are based on studies that used AUVs, a robotic boat, and elephant seals to carry a variety of sensors. The advantages of the individual platforms are highlighted in these nine papers, with electrical power being the greatest limiting constraint.

In summary, this issue reports progress in ALPS technologies and their novel applications to a variety of aquatic problems. The papers suggest new pathways for attacking many longstanding problems that have remained unsolved for lack of relevant data sets. It will be interesting to review advances over the next decade as ALPS technologies become more readily available and as observing networks, many with predictive modeling components using ALPS to routinely collect data in many ocean regions and in lakes, become operational.

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