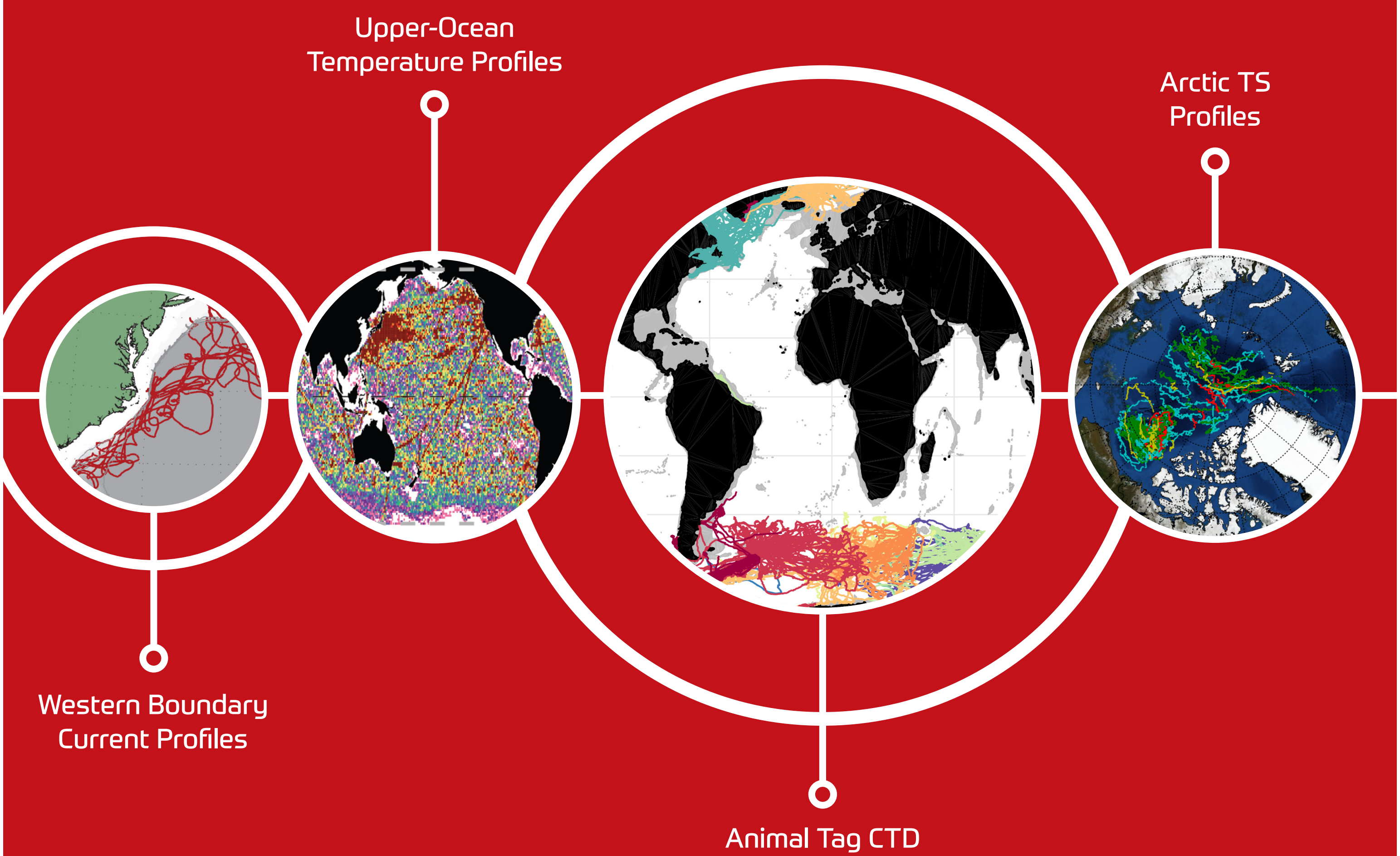
ALPS II

Autonomous and Lagrangian Platforms and Sensors



A Report of the ALPS II Workshop
Held February 21–24, 2017, La Jolla, California

The ALPS II Workshop

The ALPS II workshop was held on February 21–24, 2017, in La Jolla, California, USA, to address the question: what are the broad visions for ALPS technology, capabilities, infrastructure, and user base in the next decade, and in the coming decades?

The ALPS II Mission

1. To survey progress in autonomous platforms and sensors for ocean research since the original ALPS meeting 13 years ago.
2. To assess future prospects and challenges.

The ALPS II Steering Committee

Daniel Rudnick
Daniel Costa
Ken Johnson
Craig Lee
Mary-Louise Timmermans

Acknowledgments

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ALPS II

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Contents

Introduction

Daniel Rudnick, Daniel Costa, Ken Johnson, Craig Lee, and Mary-Louise Timmermans

The fundamental observational problem in oceanography is sampling a global, turbulent fluid where physical, biological, and chemical processes act over a wide range of scales. Relevant length scales range from the size of ocean basins down to millimeters where turbulent dissipation occurs. Time scales of interest are as small as seconds and as large as decades or centuries. An approach to this daunting problem is to use autonomous platforms, defined here as being unconnected either to a ship or the seafloor. This approach relies on many relatively **small**, inexpensive platforms. The wide range of scales favors observational systems that are **scalable**. Intermittence and regionality require observational systems to be **portable**.

The notion of an observing system of small, scalable, and portable devices was the driver of the first Autonomous and Lagrangian Platforms and Sensors (ALPS) meeting in 2003. This meeting took place during a time in the early 2000s when there were several competing ideas on how to observe the ocean. Resources for observing were relatively abundant at the time, and there were many planning exercises based around the turn of the millennium. There were already a number of successes in the early 2000s, with the Global Drifter Program and the Argo profiling float array getting underway. Underwater gliders were just beginning to be used for science as opposed to engineering tests. Propeller driven autonomous underwater vehicles (AUVs) were starting to see wide use. The trend toward miniaturization was leading to sensors for a wide range of physical and biogeochemical variables. Whether by design or luck, the ALPS meeting presaged the rapid growth in autonomous observation that has fundamentally changed observational oceanography.

The ALPS-II meeting took place in early 2017, 14 years after the first ALPS meeting. Given the growth in the ALPS enterprise, the topics of interest had grown to include autonomous surface vehicles, unmanned aerial vehicles, and animal borne sensors. Applications of ALPS had also grown, especially in concert with the improvement in numerical ocean forecasts and state estimates. The topics covered in ALPS-II were thus much broader than 14 years ago. The collection of brief articles in this report reflects the breadth of discussion at the meeting.

The articles are roughly grouped into collections on ALPS Technologies, Global and Regional scientific issues, and Infrastructure. This introduction includes a distillation of the ideas about these topics derived from breakout groups at the meeting. The appendices include the workshop agenda, participants, and a list of white papers that were solicited from workshop participants prior to the meeting.

Technologies

ALPS technologies include both platforms and sensors. Lagrangian platforms move with the water, including drifters that track the surface horizontal flow, and neutrally buoyant floats that are capable of three-dimensional trajectories (D'Asaro). Unmanned aerial vehicles (Reineman) and animals as platforms (Roquet and Boehme) have exploded in use in recent years, and were not considered during the original ALPS meeting in 2003. Optical sensors find special application in ALPS for biological studies as of the carbon pump (Estapa and Boss).

Lessons from the past 14 years focus around the importance of sustained observations to establish reliability. Experimental tools are often tried first in more targeted studies. Technology development for sensors must extend through quality control and data management to achieve the greatest impact.

In general, platform development has outpaced improvements in sensors. Needed investments in sensors should target Essential Ocean Variables (www.goosocean.org/eov). Devoted centers might be considered to encourage sensor development. Sensors for measuring throughout different trophic levels would contribute to marine resource management. Finally, education in the use of new sensors could be improved through summer schools or webinar series.

A major challenge for sensors is the continuing need to improve quality and accuracy. Progress requires cooperation between manufacturers and practicing scientists. This ongoing quest for improvement is sometimes not as attractive for funding, but is essential. While a fine goal is a set of standardized protocols for each sensed variable, an open question is whether this is an oversimplification or an impediment to creativity.

Global

The use and value of ALPS on a global scale have grown significantly over the past decade. Key applications include global maps and trends of physical parameters (Gray), numerical state estimates and network design (Nguyen and Heimbach), global-scale assessments of small-scale processes (Cole), and air-sea interactions (Thomson).

The most effective employment of ALPS for global assessments requires filling regional sampling gaps. Essential undersampled areas include coastal shelves, boundary currents, polar regions, the deep ocean, the near-surface atmospheric boundary layer, and remote environments such as at ice-sheet ocean boundaries. Filling these gaps also requires higher sampling resolution for the global array in some cases, and a committed integration effort to ensure connectivity between boundary regions and the interior ocean to produce a single global data set. It is important to recognize the value of multi-platform experiments, which require making the distinction between programs (e.g., Argo) and sensor platforms (e.g., floats).

In the coming decade, global ALPS systems will be invaluable tools for event detection and resolution. For example, Argo data enabled the detection (in 2013) and monitoring of a large mass of warm water in the Pacific Ocean. Sustained systems for identification of such global anomalies will be key to understanding climate processes and making reliable projections. Adaptive sampling needs to be an important capability of ALPS platforms in the global array.

The biggest achievements with respect to global ALPS have been largely physical. There is an immediate need to extend global maps and trends to properties like biomass and inorganic carbon. Plans for biogeochemical studies on global scales (BGC-Argo; biogeochemical-argo.org) are presently being implemented. Global standards for biogeochemical sensing remain to be fully developed. In the coming decade, it is anticipated that there will be significant progress using ALPS to link biogeochemical changes to changing physics on a global scale.

Other key focus areas over the coming decade should include identifying and maintaining core parameters for global ALPS systems (e.g., the physical ocean data set is critical for continued monitoring of climate change and viable projections). Community needs should be defined for individual sensors, encompassing physical, biological, and chemical properties; for example, air-sea fluxes, waves and velocity measurements are immediate needs for global ALPS. Other focus areas should be continued improvements in data services for better accessibility of ALPS data, and robust uncertainty estimates (both for global maps and trends as well as for individual data). Novel and unanticipated uses of these global ALPS will continue to be made possible by open-access quality-controlled data. Along with essential public access to data for advancing science, there is the need to educate users by providing guidance on appropriate use and limitations. Finally, there is a continual obligation for training of early career scientists to maintain quality and reliability of data over the duration of an observational system.

Regional

Because ALPS are scalable and portable, they are uniquely suited to regional studies. The scientific and societal motivations depend on the region, as do the mix of platforms and approaches. Because the time and length scales of regional processes can cover such a wide range, a mix of platforms is often required. Among the regions considered in this report are high latitudes in both the Arctic (Timmermans et al.) and Antarctic (Purkey and Dutrieux). Shallow coastal areas are energetic and biologically active, with many ALPS technologies finding application (Nidzieko et al.). The western boundary currents that drive oceanic heat transport and eastern boundary regions where the effects of global climate variability are felt by society are targets for ALPS networks (Todd et al.). Targeted deployments of ALPS are an active component of observations for studies of hurricanes (Goni et al.).

The specific observational requirements of regions prompt the use of certain ALPS approaches. Fast, propeller-driven AUVs are ideal for the short time and space scales near coasts. Underwater gliders find special application in boundary currents, and to connect the coast and open ocean. Surface drifters are especially useful to identify circulation patterns and to quantify dispersion. Profiling floats excel at broad coverage, for example, in the equatorial region. Instrumented animals are perfect for high-density observations where the animals live. Ice-based systems are essential for collecting collocated measurements of the upper ocean, ice, and atmosphere at high latitudes.

Special challenges in regional settings revolve around the merging of data and strengths of different platforms. In this respect, data services are key to successful regional observing systems. Assimilative modeling and state estimation yield optimized fields and forecasts for research and decision-making, and assessments of network design. Local logistical issues including Exclusive Economic Zones must be respected in regional studies.

Infrastructure

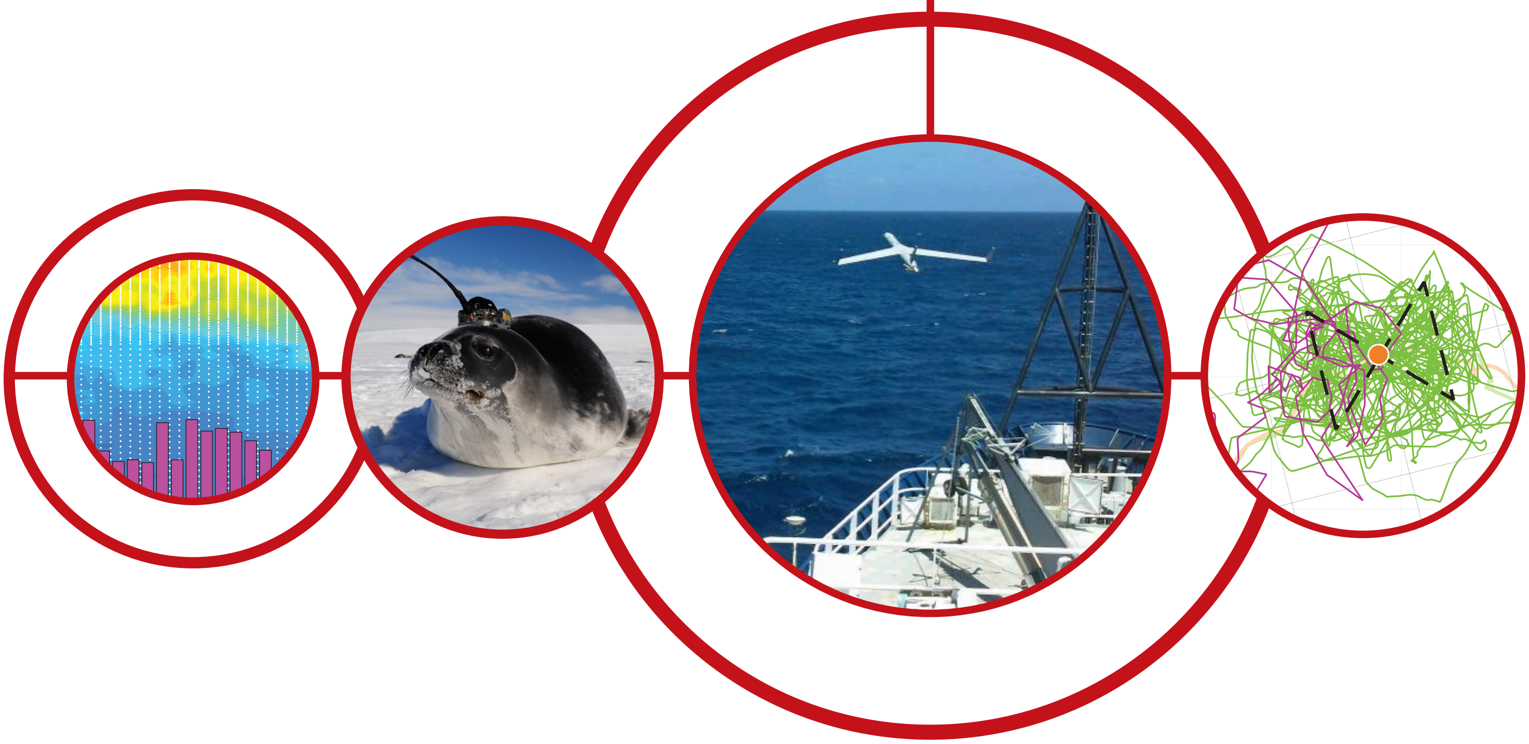
With the growth of ALPS over the last decade and a half, there are new requirements for infrastructure for support. Indeed, ALPS systems should begin to be appreciated as infrastructure as much as ships have been during the last several decades. Wynne and White present an approach to providing ALPS services as infrastructure in the UK. The massive amounts of data created by thousands of ALPS presents challenges and opportunities for data services (Zykov and Miller).

ALPS may improve observational capability in environments where resources are constrained, presenting an opportunity as well as a challenge. A key to moving forward is to broaden the user base by lowering barriers of expertise. At the same time, existing expertise must be maintained to continue progress. Improved data services would increase the use of ALPS data, creating additional justification for technological development.

Opportunities exist for educational efforts in platform and sensor use at sea, and in data analysis on land. Communities of practice must be built and supported. This is an area where cooperation between agencies may help to identify viable models and to craft pilot efforts.

With robotics a growing field, ALPS may especially benefit from focusing on partnerships between academia, government, and the private sector. With a number of private foundations focusing on the ocean and climate, new ideas for support may arise in the coming years. A future network of connected ALPS covering the global ocean and extending into societally important regions is and exciting possibility.

Technologies



Lagrangian Ocean Observing

Eric A. D'Asaro

A "Lagrangian" measurement platform moves with the surrounding water and, ideally, measures the changing properties of the same water over time. In contrast, an ideal "Eulerian" measurement platform stays at one location and measures the velocity and varying properties of different water masses as they move past. Neither is perfect; Lagrangian platforms cannot exactly follow water molecules, particularly their vertical motion, while Eulerian platforms always move, particularly in strong currents, due to surface waves. The advantages and problems of the Lagrangian approach are discussed here.

The ocean is complicated. Resolving this complexity is only possible with a large number of measurements. Even in physical oceanography with only a few basic variables, sampling the vast range of spatial and temporal scales, millimeters to megameters and seconds to decades or longer, presents a difficult challenge. For chemistry and biology, with an equal degree of variability, but many more things to measure, the challenge is greater. Many of the great successes of oceanography, for example, real-time, eddy-resolving models (Bell et al., 2015) and accurate decadal monitoring of the ocean heat content (Riser et al., 2016), rely on large and continuous data streams, satellite altimetry, and the Argo float array, respectively. Future progress is likely to require lots of measurements in lots of places.

Lagrangian instruments are well suited to deployment in large numbers. They move with the flow by having a high drag and a density close to that of the water, either being slightly buoyant (a "surface drifter"; Lumpkin et al., 2017) or accurately matching their density to that of the water so as to float at a subsurface depth (a "float"; Rossby, 2007). The minimal instrumentation is a measurement of their position, which usually requires small electronics and little power (Rossby et al., 1986). Small size and lightweight construction are easily possible and an advantage, increasing the drag and making near-neutral buoyancy easier. Lagrangian instruments thus tend to be inexpensive so that deploying large numbers is feasible. Thus, the Global Drifter Program (Lumpkin and Pazos, 2007) maintains a global array of about 1500 drifters. The average of velocities computed from these drifters measure the average and variability of ocean surface currents both globally (Figure 1) and regionally. Similarly, hundreds of subsurface floats measured the circulation of the North Atlantic (Bower et al., 2002) and Brazil Basin (Hogg and Owens, 1999). Hundreds of drifters have been deployed in dense local arrays (Poje et al., 2014) to study smaller-scale eddy properties.

Accurate Lagrangian measurements, like all oceanographic measurements, require attention to instrumental details. For surface drifters, minimizing the effects of wind and waves requires a sufficiently large underwater drogue area (Lumpkin and Pazos, 2007) relative to the surface expression, or a clever design backed by laboratory and field evidence (Novelli et al.,

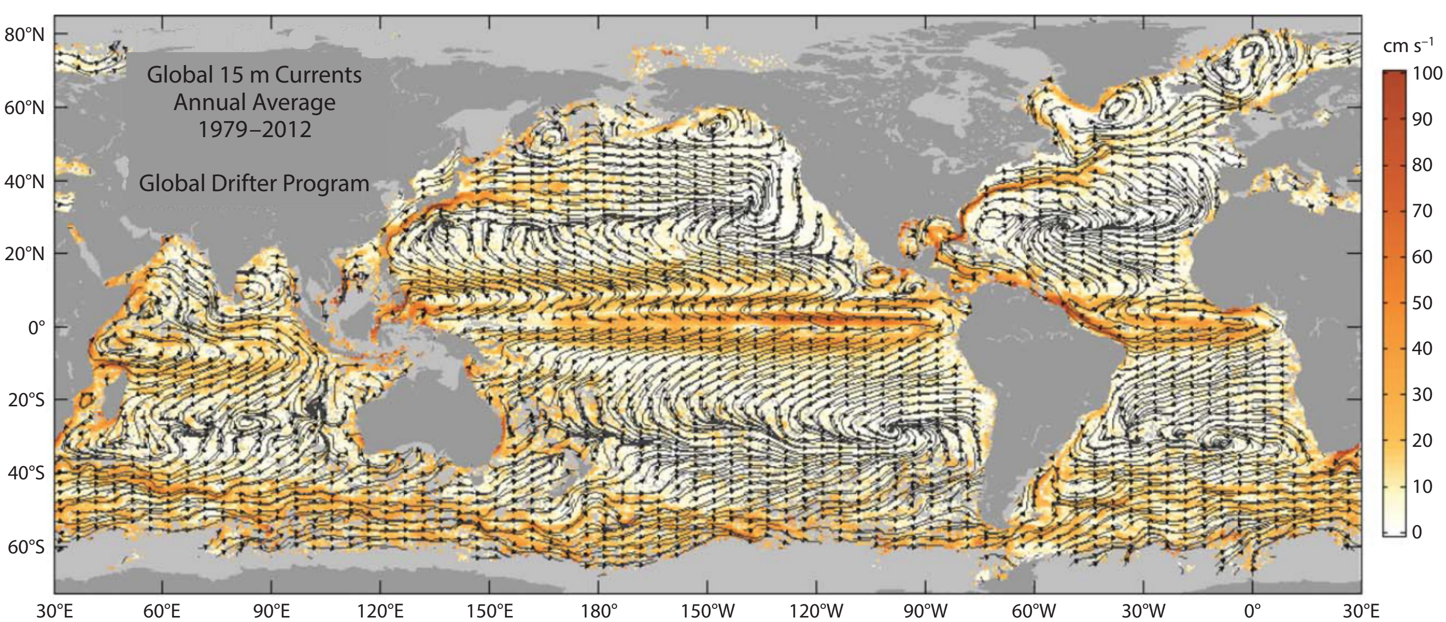


Figure 1. Mean current speeds (colors) from Global Drifter Program trajectories with streamlines (black lines). *Adapted from Lumpkin and Johnson (2013)*

2017). Subsurface floats require careful ballasting and attention to the compressibility and thermal expansion coefficients of the instrument relative to seawater (Rossby, 2007). Measuring the three-dimensional trajectories, including the vertical as well as horizontal components, is possible with care (Rossby et al., 1985; D'Asaro, 2003). However, most so-called "Lagrangian" measurements, including surface drifters and Argo floats, only measure the horizontal component of the trajectory.

With appropriate instruments, Lagrangian sampling allows measurement of unique flow characteristics. The average of many Eulerian velocity measurements in a region can define the average and variability of the currents. However, only Lagrangian methods directly measure where the water goes and how it spreads. For example, a week of measurements at the mouth of a river may indicate that the water is moving south at 0.5 ± 0.3 m s^{-1}, but give little information as to where that water, and any pollutants that it carries, will be in a week. The positions of an array of Lagrangian sensors deployed at the river mouth directly measure both this and the area over which the river water has spread. A large literature tackles the details of such "dispersion" statistics (LaCasce, 2008) and has developed a number of sophisticated Lagrangian diagnostics (Samelson, 2013), including methods to detect "coherent structures" that trap and transport water masses. The relationship between these Lagrangian properties and Eulerian statistics and dynamical understanding is an important, but difficult problem.

Lagrangian measurements of scalar properties, for example, temperature, salinity, and oxygen, can yield additional insights. The equation for variation in the concentration of ascalar C, advected by currents, mixed by a diffusivity and with a growth/decay rate S is

$$\frac{\partial C}{\partial t} + \vec{u} \cdot \vec{\nabla} C = \frac{DC}{Dt} = \vec{\nabla} \cdot \kappa \vec{\nabla} C + S. \tag{1}$$

Often, we want to estimate the left-hand terms in order to measure S or κ. Using Eulerian measurements, three quantities in the left-hand terms must be measured: the rate of change of C, the velocity and the gradient. Using Lagrangian measurements, only the center term, the Lagrangian rate of change of C, is necessary. For a conserved quantity ($S = 0$), the rate of change of C following a Lagrangian trajectory (DC/Dt) directly measures the effect of mixing.

For example, temperature changes measured along a three-dimensional Lagrangian trajectory during deep convection in the Labrador Sea (Figure 2) shows the cycle of surface cooling, downward transport of cold, heavy water, warming by entrainment at the bottom of the convective layer, and finally transport upward to the surface. This cycle is implicit in the traditional Eulerian formulations of convective heat flux, but is explicitly demonstrated by Lagrangian measurements. Such Lagrangian data have been used to compute the value of κ in a stratified fluid (D'Asaro, 2008) and heat, salt, and oxygen flux profiles within a boundary layer (D'Asaro 2004; D'Asaro and McNeil, 2007). Biogeochemical rates (S) can similarly be computed by measuring quantities following a Lagrangian instrument. For example, Landry et al. (2009) measured changes in phytoplankton and zooplankton biomass along Lagrangian trajectories in the California upwelling system and compared them with incubation-based growth and grazing rates to close budgets for the biomass.

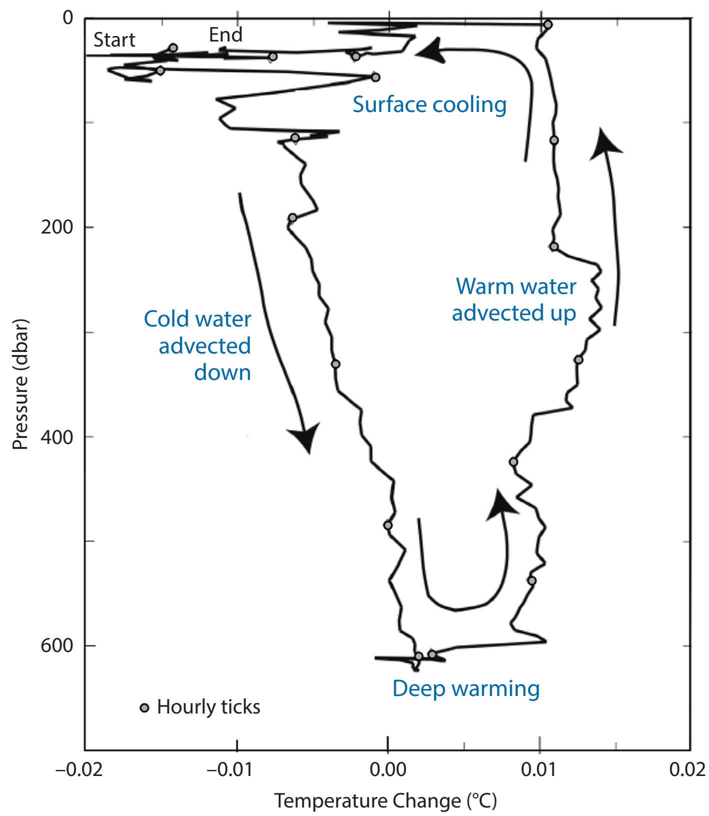


Figure 2. Variation of temperature and depth along a three-dimensional trajectory of a Lagrangian float during deep convection in the Labrador Sea (Steffen and D'Asaro, 2002) illustrate the cycle of warming and cooling that drives the convection. Water parcels cool and become heavier at the surface and thus sink, carrying cold water downward and warming slightly by mixing with the surrounding water. At about 600 m depth, they encounter warmer, saltier water at the bottom of the convective layer, and warm by mixing with this water. They then move upward, carrying warmer water, until they reach the surface to repeat the cycle.

Lagrangian instruments are often said to follow a "parcel" of water. However, the mass of water initially near a Lagrangian instrument usually does not remain localized, but spreads over a wide region, with its molecules eventually becoming distributed over the entire ocean and beyond. A single Lagrangian instrument can at best follow only one of many trajectories originating in its vicinity and provides no information on the surrounding water. Arrays of Lagrangian instruments (Poje et al., 2014) address this issue, but alone often do not provide sufficient measurements of the right type in the right places.

The combination of an Eulerian survey conducted around a Lagrangian instrument effectively combines the advantages of both approaches. The advective effects are minimized by moving with water, so that Equation (1) can be used, while the surrounding surveys provide a context for these measurements and allow corrections due to lateral and vertical shear. For example, during the 2008 North Atlantic Bloom Experiment (Alkire et al., 2012), four gliders surveyed around a mixed layer float for 60 days supplemented by several ship surveys. Variants of Equation (1) were used to diagnose the bloom's evolution (Bagniewski et al., 2011) along the float trajectory, while the surveys revealed the importance of submesoscale eddies in its dynamics (Mahadevan et al., 2012). Associated chemical and biological measurements made from a ship were critical to these interpretations. Similar approaches have proved successful even in the extreme currents and shears of the Gulf Stream (Thomas et al., 2016). Combinations of Lagrangian instruments, dye, and ship surveys can also be very powerful (Boyd et al., 2007).

The broader lesson is that a variety of sampling approaches—Lagrangian, Eulerian, or other—are necessary to address the variety of sampling problems faced in measuring the complicated ocean. Autonomous technologies have given us many new and powerful measurement tools; many more will become available. Each of these tools has strengths and weaknesses, and the best combination to address any particular problem will depend on the problem. My experience has been that combinations of these tools are often the most effective approach (Figure 3).

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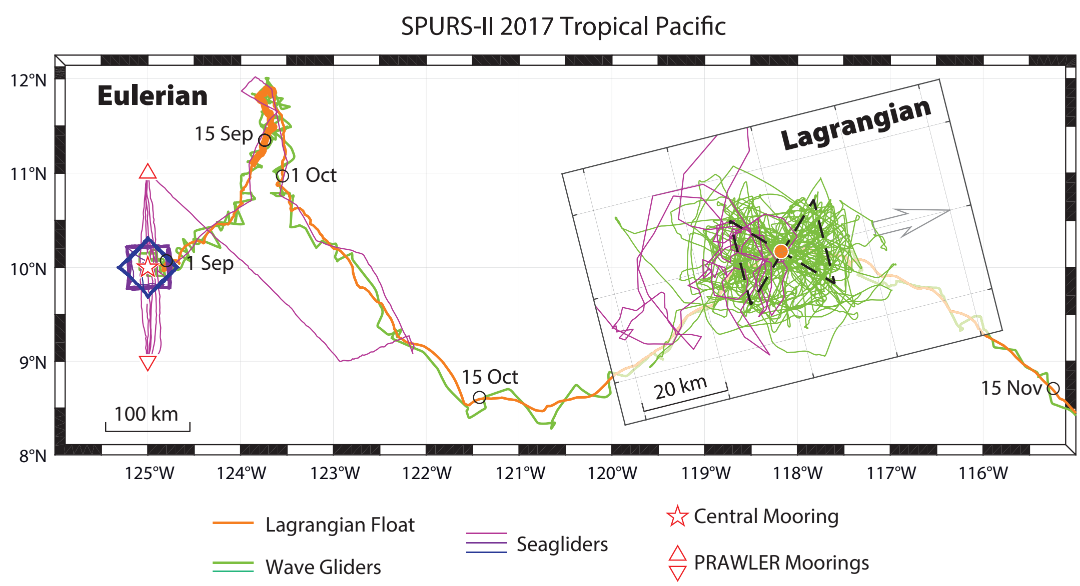

Figure 3. Experimental design for the autonomous components of the SPURS-II program shows a combination of Eulerian and Lagrangian components (from Lindstrom et al., 2017). A central mooring (star) provides intensive Eulerian measurements; Seagliders and Wave Gliders survey around it. A Lagrangian float (orange), launched at the mooring, is advected eastward in the strong currents and provides a reference point for a Seaglider (purple) and Wave Glider (green) surveying around it. The inset figure, rotated to align to the direction of the float drift, shows the Seaglider and Wave Glider trajectories relative to the float. A region approximately 20 km around the float is surveyed every few days. This design addresses the central goal of SPURS-II, which is understanding the salinity dynamics in this region by measuring both Eulerian and nearly Lagrangian time series and the spatial context of both.

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Author

Eric A. D'Asaro, Applied Physics Laboratory, University of Washington, Seattle, WA, USA, dasaro@apl.washington.edu

Observing the Biological Carbon Pump with Optical and Imaging Sensors

Meg L. Estapa and Emmanuel Boss

Background

The biological carbon pump starts with the fixation of CO_2 into organic matter by phytoplankton in the surface ocean (Volk and Hoeffert, 1985). Most of this material is cycled through the food web and respired back to CO_2, but a portion is transferred into deep water, resulting in a net flux of carbon from the atmosphere into the deep ocean that is globally estimated at 5 to >12 PgC per year (Boyd and Trull, 2007; Henson et al., 2011; Siegel et al., 2014). The estimate has a large uncertainty because observations of the vertical, biological carbon flux in the global ocean are scarce, particularly in the upper 1,000 m where rapid flux attenuation occurs. Processes that contribute to the biological carbon pump include the direct sinking of phytoplankton cells, aggregates, and zooplankton fecal matter; the subduction of suspended particulate organic carbon (POC) and dissolved organic carbon (DOC), and active transport by vertically migrating zooplankton (Ducklow et al., 2001; Siegel et al., 2014). Open questions include identification of specific biological mechanisms that drive carbon export and how these vary spatially and temporally; the interaction between physical processes and export of biologically derived carbon; the importance of particle size and density (including content of ballast minerals such as biogenic silica and particulate inorganic carbon) to export efficiency; and the development of process-based rather than statistical models that will enable us to predict future behavior of the biological pump under changing climate conditions.

Observational Techniques

Biological carbon fluxes can change on time scales of days to weeks, and can be spatially patchy on scales smaller than 10 km (Estapa et al., 2015). Measurements made in a Lagrangian frame aboard autonomous platforms have therefore featured heavily in key studies since the last ALPS workshop in 2003 (Rudnick and Perry, 2003). A review chapter by Stemmann et al. (2012) broadly summarizes developments in biogeochemical sensors on autonomous platforms; here we focus specifically on progress in measurements of the biological pump.

Measurement of sinking or subducting particle fluxes requires a sensor-platform combination that can detect the small flux of sinking particles against the much larger background stock of suspended particles. Typically, particle detection is carried out with bulk bio-optical sensors (e.g., backscatter, turbidity, fluorescence, beam attenuation) or imaging sensors (e.g., cameras, Laser Optical Particle Counter [LOPC], P-Cam). The more mature, bulk bio-optical sensors are easily integrated onto standard profiling float and glider platforms, have low power requirements and data volumes, but are not always specific to the sinking fraction of particles; imaging sensors are still maturing and have higher power and data requirements but provide information on particle size and transparency and can better elucidate specific mechanisms of the biological pump. However, while particles carrying carbon into the deep ocean have been observed to range from 10 μm (Durkin et al., 2015) all the way up to several centimeters (e.g., Bochdansky et al., 2016), no single imaging or particle counting sensor covers this entire size range. Another issue is that most sensor optical sampling volumes are too small to capture some of the largest, rarest particles. Finally, the present lack of a sensor for DOC that is suitable for deployment on autonomous platforms restricts carbon flux measurements to the particle-mediated export pathways listed above.

Sensor-platform combinations for measuring sinking particle flux have tended to fall into two categories: (1) those that physically collect sinking particles, either temporarily for imaging, or for sample return to a ship, and (2) those that repeatedly collect optical or image profiles of large (assumed sinking) particles in the water column and then use a deduced or assumed particle sinking rate to derive fluxes. Both approaches have advantages and drawbacks that are detailed in the following section, which covers significant developments since 2003.

Advances Since 2003

DIRECT PARTICLE INTERCEPTION TECHNIQUES

Semi-Autonomous Sediment Traps. The collection of sinking, upper-ocean particle samples from an untethered, quasi-Lagrangian platform is advantageous even disregarding the other benefits of platform autonomy, because of biases from hydrodynamic effects associated with surface tethered sediment traps (Buesseler et al., 2007). Standard profiling floats have been modified independently by two groups to carry sediment traps for ship-supported sample collection. Both designs—the Neutrally-Buoyant Sediment Trap (NBST; based around a SOLO float and designed at Woods Hole Oceanographic Institution; Valdes and Price, 2000) and PELAGRA (based around an APEX float and designed at the National Oceanography Centre, Southampton; Lampitt et al., 2008), have featured prominently in recent biological carbon pump process studies. Both platforms have more recently been modified to carry bulk optical sensors and camera systems, which are described separately in sections below. In this respect they serve as an important intercalibration link between completely autonomous, sensor-based approaches and traditional sediment trap and ^{234}Th tracer-based observations that are still the primary tools of the longest-running time-series programs (Estapa et al., 2017).

Transmissometer as "Optical Sediment Trap". The first truly autonomous measurements of sinking carbon flux were made by using a vertically mounted transmissometer aboard a profiling float to physically collect sinking particles on the upward-looking optical window during the drift phase of the float's mission cycle (Bishop et al., 2004; Bishop and Wood, 2009; Estapa et al., 2013, 2017; Figure 1). This method has the advantages of not requiring a particle sinking-rate assumption to be made, and utilizing commercially available, mature sensor technology with relatively low power and data transmission requirements. It is best suited to use in areas where calibration samples (for instance, versus a neutrally buoyant sediment trap) can be collected, and in the upper few hundred meters of the water column where ambient turbulence is sufficient to carry sinking particles into the transmissometer sensing volume (Estapa et al., 2017).

Imaging Sediment Traps. Building further upon the concept of optical detection of physically intercepted, sinking particles is a class of new devices that are best described as imaging sediment traps. Observations from one such device, the Carbon Flux Explorer (CFE), are presented by Bishop and Wood (2009) and Bishop et al. (2016), and illustrate the wealth of information about sinking particle size and origin that is gained through use of imaging sensors. The CFE consists of an imaging trap mounted aboard a profiling SOLO float; power and data are self-contained but at the time of this writing, physical platform collection is required to retrieve data post-deployment.

INDIRECT TECHNIQUES REQUIRING ESTIMATES OF SETTLING VELOCITY

Optical Spike Flux. Profiles of bulk optical properties collected at a fast sampling rate often contain many spikes, which have for some time been interpreted as arising from large particles passing through the optical detection volume (Bishop, 1999; Gardner, 2000; Bishop and Wood, 2008). By filtering optical profiles of fluorescence and backscattering to separate the baseline signal from this "spike" signal, Briggs et al. (2011, 2013) were able to estimate the relative vertical distribution of large particles from autonomous float and glider observations during the 2008 North Atlantic Bloom Experiment. In that study, the export flux of large aggregates occurred as distinct pulses during the study period and so the increasing penetration depth of the large particle spikes was used to deduce the particle sinking rate and estimate the particulate carbon flux. This method also has the advantage of using only low power, commercially mature sensors, although some means of estimating the particle sinking rate and converting the bulk optical properties to carbon are required. The profile repeat interval and the sensor sampling rate must also be relatively fast in order to implement this method.

Fluxes Derived from Changes in the Vertical Distribution of Particles Over Time. Optical or imaging sensors aboard autonomous profiling platforms can be used to estimate the change in the vertical distribution of particles over time down to some reference depth, and therefore derive a flux estimate. In this method, the particle sinking speed must again be derived

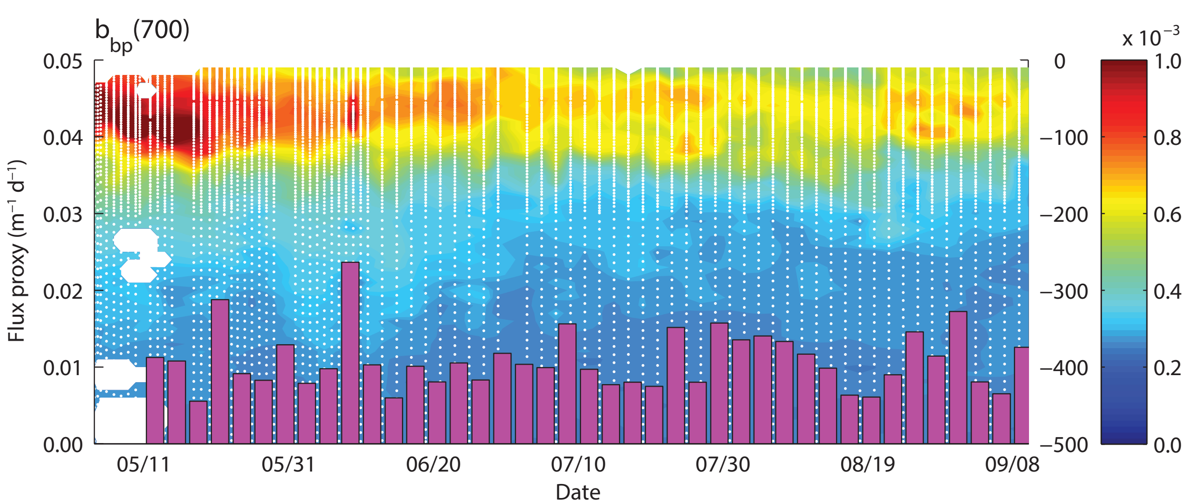

Figure 1. Upper water column optical backscatter (color contours) and particle flux measured at 1,000 m between bio-optical float profiles using an optical sediment trap (magenta bars). Right-hand y-axis denotes depth in meters. Data were collected in 2012 in the western Sargasso Sea. *From Estapa et al. (2013)*

from observations, and the water column must not experience appreciable shear during the measurement period. The optical or imaging sensor properties determine the type(s) of sinking particles that can be observed. Recent papers illustrate different applications of the method. Dall'Olmo and Mork (2014) and Dall'Olmo et al. (2016) utilized bulk optical backscattering sensors to show how the spring/summer shoaling of the mixed layer in part drives the seasonal export cycle (the "mixed layer pump" described by Gardner et al.,1995). As optical backscattering is mainly sensitive to particles <20 µm, the authors surmised that the observed flux signal was due to small, sinking particles or to large particles disintegrating at depth. Jackson et al. (2015) used the SOLOPC sensor/platform combination in a similar manner to derive sinking rates of larger particles sensed by the LOPC, which counts particles in the water column using a sheet of adjacent laser beams and allows discrimination of particle sizes ranging from 90 µm to 3,500 µm.

Fluxes Derived from Particle Size Distributions and Modeled Settling Velocities. Imaging and particle sizing sensors capable of resolving water column particle size distributions can be used to estimate carbon fluxes if an accurate, modeled particle settling velocity spectrum is available. Most examples in the literature that estimate particulate carbon fluxes using this type of technique rely on ship-based image profiles of a device such as the Underwater Video Profiler (e.g., Guidi et al., 2007, 2016; McDonnell and Buesseler, 2010, 2012) or holographic sensors (such as Sequoia Scientific's LISST-HOLO or the 4Deep holographic microscope). One of the first applications used particle size distributions from SOLOPC profiles and settling velocities predicted via Stokes' Law to estimate carbon fluxes due to particles >90 µm in diameter (Jackson and Checkley, 2011). Ongoing efforts to adapt and integrate imaging sensors onto profiling floats also include onboard image processing to allow fully autonomous operations. These include the GUARD1 system (Corgnati et al., 2016) and the Octopus sensor (a miniaturized, low-power version of the Underwater Vision Profiler), which is being integrated into the NKE float platform (Mar Picheral, *pers. comm.*). The main drawbacks of these particle imaging methods are the requirement for an accurate estimate of the particle settling velocity size spectrum, and the current lack of an imaging sensor capable of resolving the entire, relevant particle size range (from 10 µm up to tens of millimeters).

Future Challenges

The benefits of making particle flux measurements from autonomous platforms will include broader spatiotemporal coverage, better links to satellite remote-sensing observations, and higher-resolution measurements of a patchy set of processes. However, such measurements are not yet widespread. One of the main challenges is that bulk optical properties and particle imagery must be translated into geochemical (usually carbon) flux units, and the accuracy of flux estimates is only as good as the calibration. Sinking particles range through six orders of magnitude in size, which currently requires a multi-sensor approach; particles responsible for carbon export also have a broad range in composition, fractal dimension, and pigmentation. These factors will continue to make the site-specific calibration of particulate flux sensors a requirement in studies going forward. Further complicating the need for calibration is the lack of a standard method for direct measurements of carbon flux given the issues with many types of sediment traps (Buesseler et al., 2007), and the three-dimensional, time-dependent nature of ^{234}Th derived measurements of flux (e.g., Buesseler et al., 2009).

Sensor developments that would improve autonomous observations of biological pump processes include a sensor for dissolved organic carbon, and a particle imaging sensor with a large sensing volume (to detect rare, large particles) and that is capable of resolving the full size range of sinking particles. In general, imaging sensors will require greater capabilities for built-in, onboard data reduction so that parameterized observations can be transmitted via satellite, minimizing the risk of data loss in the event a platform cannot be recovered.

The incorporation of all but the simplest particle flux observational techniques into large-scale autonomous sample programs such as Bio-Argo is currently precluded by the available power and communications budgets of float platforms. At present, the only method described above that could be easily managed within the proposed US Biogeochemical Argo framework is the derivation of flux from changes in the vertical distribution of particles with time, assuming particle distribution is measured with a low power, commercially available sensor such as a backscattering sensor. Binned profiles every one to two days to 1,000 m would be sufficient for this technique. Utilization of the "optical spike flux" method would require sampling at very high vertical resolution, and implementation of the "optical sediment trap" technique would require measurements to be made during the "drift" phase at a depth shallower than 1,000 m. Both of these methods could be implemented on a large scale (perhaps on a subset of floats in a globally distributed program) using currently available platforms and technology. All of the other methods described above require the collection and transmission of large amounts of image data using sensors with high power requirements and are thus better suited at present to medium-length deployments or ship-supported process studies.

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Authors

Meg L. Estapa, Skidmore College, Saratoga Springs, NY, USA, mestapa@skidmore.edu

Emmanuel Boss, University of Maine, Orono, ME, USA, emmanuel.boss@maine.edu

On the Use of Animal-Borne Instruments to Monitor the Ocean

Fabien Roquet and Lars Boehme

Abstract

In addition to collecting information on the behavior of diving animals, miniaturized data loggers can now record physical and biogeochemical data to improve ocean-observing capabilities. Marine mammals in particular help gather oceanographic information on some of the harshest environments on the planet. Study species such as the elephant seals travel thousands of kilometers and continuously dive to great depths (up to 2,500 m). The past decade of animal tagging has demonstrated the feasibility and high value of this approach for ocean observation. At the core of this success has been collaboration between biologists and physical oceanographers, an example of a truly multidisciplinary approach that has yielded great results for both communities. The use of animal-borne instruments has been particularly successful in polar and coastal areas, and new opportunities are emerging as miniaturization and telemetry progress and new sensors and techniques are developed.

Figure 1. Weddell seal carrying an CTD-SRDL instrument that collects temperature and salinity profiles while the animal is diving at sea. *Photo credit: D. Costa*

Background

Sustained ocean observations are crucial for monitoring and understanding the marine environment and its variability within the Earth system. A range of ocean-observing systems have come a long way in balancing the sustained monitoring requirements with the need for research. The polar oceans are important marine environments that respond to environmental change and influence our planet, but are still undersampled. The harsh climate and remoteness of the polar regions, as well as the large-scale offshore pelagic environments, make them extremely difficult to observe. Achieving a comprehensive network of instruments delivering precise oceanographic measurements is a particular goal. For the last decade, diving marine animals equipped with sensors have been contributing to the observing systems and increasingly filling existing gaps, especially in the polar oceans.

Animals tagged with oceanographic sensors (Figure 1) have now become essential sources of temperature and salinity (TS) profiles, especially for high-latitude oceans (Charrassin et al., 2008; Boehme et al., 2010; Costa et al., 2010; Fedak, 2013; Roquet et al., 2014; Hussey et al., 2015). For example, data from elephant seals and Weddell seals represent 98% of the existing TS profiles within Southern Ocean pack ice. The instruments are non-invasive (attached to the animal's fur and naturally falling off during the animal's next molt) and they also record the animal's behavior in the context of its environment. Since 2002, several hundreds diving marine animals, mainly Antarctic and Arctic seals, have been fitted with instruments delivering data to the ocean-observing system.

The international consortium MEOP (Marine mammals Exploring the Ocean Pole-to-pole, see Treasure et al., 2017, for a review), originally formed during the International Polar Year in 2008–2009, aims to coordinate animal tag deployments, and oceanographic data processing and data distribution globally. The data are made available to the global scientific community through http://www.meop.net (Figure 2). The value of the hydrographic data produced by MEOP within the existing Southern Ocean Observing System was demonstrated using seal-collected data. These data improved mixed-layer properties, circulation patterns, and sea-ice concentrations in model simulations (Roquet et al., 2013). The data collected within MEOP have already contributed to important oceanographic findings (e.g., Pellichero et al., 2016; Williams et al., 2016; Zhang et al. 2016) and insights into marine ecology through the availability of concurrent information about the animal's behavior (e.g., Hindell et al., 2016).

Animal-Borne Instruments

A range of instruments are available that can be attached to marine animals, but only a few can deliver the data at the necessary quality to warrant inclusion in observing systems. One instrument meeting such specifications is the SPLASH tag manufactured by Wildlife Computers Inc. (USA). It generally incorporates a FastLoc GPS antenna for geolocation and an ARGOS antenna for telemetry, combined with pressure and temperature sensors with accuracies of ±5 dbar and 0.1°C, respectively. Owing to its small size, it can be used on most diving birds and marine mammal species, yielding thousands of profiles especially in various coastal and continental shelf areas.

The CTD Satellite Relay Data Logger (CTD-SRDL) built at the Sea Mammal Research Unit (SMRU, University of St Andrews, UK) is currently the only existing tag that includes a miniaturized CTD unit (Figure 3). CTD-SRDLs record temperature and conductivity during the ascent part of an animal's dive (Boehme et al., 2009; Roquet et al., 2011). These CTD profiles are then telemetered in a compressed form (between 10 and 25 depth levels per profile depending on the configuration) using radio telemetry (ARGOS, GSM, UHF). More detailed descriptions of the instruments can be found in Fedak et al. (2002), Cronin and McConnell (2008), Boehme et al. (2009) and Photopoulou et al. (2015). CTD-SRDLs are calibrated by the manufacturer, and the delayed-mode data quality is estimated to be ±0.03°C in temperature and ±0.05 psu or better in salinity (Roquet et al., 2011).

Most loggers also archive data at the maximum sampling frequency in an internal memory. The complete data set can then be downloaded if the instrument can be retrieved in the field. Recovery is often not possible due to the nature of tagging animals in remote places, but has been done in some areas. For example, instruments deployed on elephant seals on the Kerguelen Islands (Southern Ocean), Marion Island (Southern Ocean), and at Año Nuevo (California, USA) were often recovered, providing data sets with exceptional spatio-temporal resolution—typically 60+ TS profiles per day for two to four month periods—in critical areas of the ocean.

Manufacturers are integrating sensor capabilities beyond measuring basic physical ocean variables. Instruments can now include sensors to measure light levels, fluorescence, or oxygen (e.g., Guinet et al., 2013; Bailleul et al., 2015). This step is important and will lead to a better understanding of the link between physical and biogeochemical processes. A recent pilot study showed that accelerometers on tags can be used to monitor wave conditions when animals are near the surface (Cazau et al., 2017b), while other logger types that record the underwater acoustic signal could be used to estimate the surface wind speed with an accuracy of 2 m s^{-1} (Cazau et al., 2017a). This opens the possibility of using bio-logged animals as weather buoys of opportunity.

Integration into the Global Ocean Observing System

Animal-borne instruments provide several thousand oceanographic profiles per year, closing gaps in our understanding of the climate system and complementing other observing platforms such as Argo floats. They also deliver data from shallow and highly dynamic coastal areas in which other autonomous platforms have difficulty operating. The concurrent behavioral information also makes the data useful, for example, for understanding the foraging behavior and ecological vulnerability of the tagged species, which in turn can improve our understanding of ocean health. The successful and useful integration of data from animal-borne instruments into ocean-observing systems depends on three key requirements: sufficient quality, data standardization, and robust data delivery.

While animal-borne instruments have been recording oceanographic variables for a long time, accuracies needed

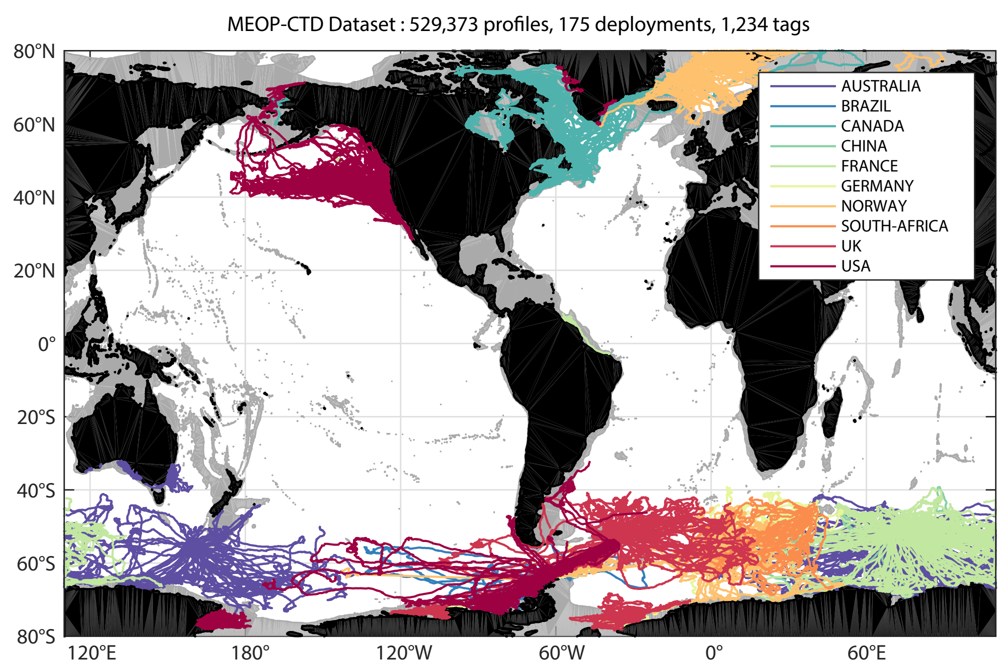

Figure 2. World map showing the 1,200 tracks currently available in the MEOP-CTD database, representing 530,000 hydrographic profiles (July 2016 version). See http://meop.net for more information on the data portal.

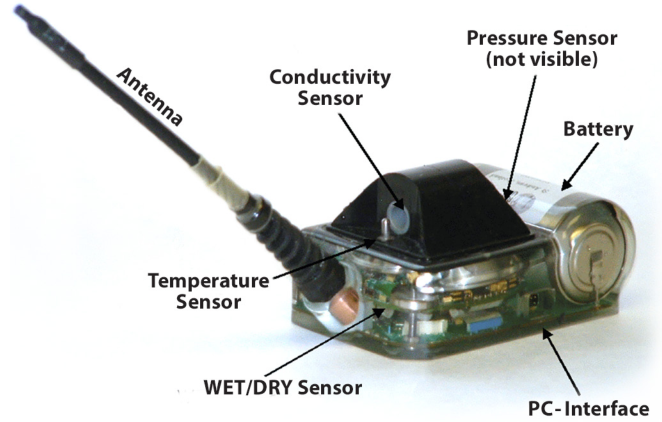

Figure 3. Photograph of a CTD-SRDL, with visible hardware components labeled (photograph by Lars Boehme, SMRU). The tag is potted in epoxy rated to 2000 m depth. Standard sensors include a CTD unit manufactured by Valeport Ltd (Devon, UK). The tag has a PC interface, is powered by a primary cell (battery) and has a telemetry option (ARGOS, GSM, UHF). *From Photopoulou et al. (2015)*

for tracking oceanographic changes were only achieved recently. The CTD-SRDL was the first to provide calibrated sensors with oceanographic applications in mind, but other instruments are emerging that are able to provide, for example, temperature measurements with an accuracy of better than 0.1°C. Manufacturers are now aiming to integrate sensors that can deliver data that are better by one order of magnitude. Improved calibration methods and delayed-mode quality procedures appear as crucial as the quality of sensor technology in achieving the best data accuracy.

Timely data delivery is important for ocean-observing systems. Data from animal-borne instruments are often provided to the observing systems after considerable quality control. Many of the quality-control processes have been adapted from proven systems supporting, for example, the Argo float community. Data can also be transmitted in near-real time using the ARGOS or GSM networks. Such data, especially from remote locations or from the sea-ice zones, are particularly important to the real-time services supported by the observing systems. Large efforts are ongoing to provide a unified real-time data flow for such operational applications.

Regional communities and initiatives are coming together to promote integration of this multidisciplinary tool into the observing system, including the US Animal Telemetry Network (ATN, Block et al., 2016), the EuroGOOS Animal-Borne Instrument (ABI) Task Team in Europe, the Australian Integrated Marine Observing System (IMOS), and the Canadian Ocean Tracking Network (OTN). Better coordination with other marine observing capabilities is supported within the framework provided by the Observations Coordination Group of the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM-OCG). Ultimately, the objective is to have the animal tagging approach become an integral component of the Global Ocean Observing System, making a sustained contribution to climate and marine life monitoring.

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Authors

Fabien Roquet, Department of Meteorology (MISU), Stockholm University, Stockholm, Sweden, roquet@misu.su.se

Lars Boehme, Scottish Oceans Institute, University of St Andrews, UK, lb284@st-andrews.ac.uk

Measuring the Ocean and Air-Sea Interactions with Unmanned Aerial Vehicles

Benjamin D. Reineman

At the time of the first ALPS meeting in 2003, unmanned aerial vehicles (UAVs),[1] though already a staple for military surveillance, were out of reach for much of the oceanographic community. Lower costs and improved positioning, control, and ease of use have since opened doors for scientists with less flight expertise and a more modest budget. Technology has improved such that aircraft can launch and recover from a modestly sized research vessel, either by net or catch lines, or, in the case of a small multi-rotor craft, even in the palm of the hand.

Unmanned aircraft for ocean-related science is a growing and multi-faceted field, with platforms and field campaigns ranging in scales from week-long missions with NASA-operated 130-ft wingspan GlobalHawks outfitted with weather radar and dozens of dropsondes, down to missions of tens of minutes with commercial off-the-shelf multi-rotor craft and a camera. This report is an attempt to brief the oceanographic community on the current state of the art in oceanographic science enabled by unmanned aircraft and comment on their potential future in the field. Figure 1 presents a sampling of various UAVs used in oceanographic research.

With the exception of a number of high-altitude, solar-powered prototype crafts (notably "pseudo-satellite" efforts by NASA, Facebook, Google, and others as high-altitude communication nodes), petroleum-based fuels are still the preferred energy source for endurance-focused UAVs. As with many instruments in oceanography, a major advance in battery technology will open up many new opportunities. At present, we are often still bound to gasoline, which has 50 to 100 times

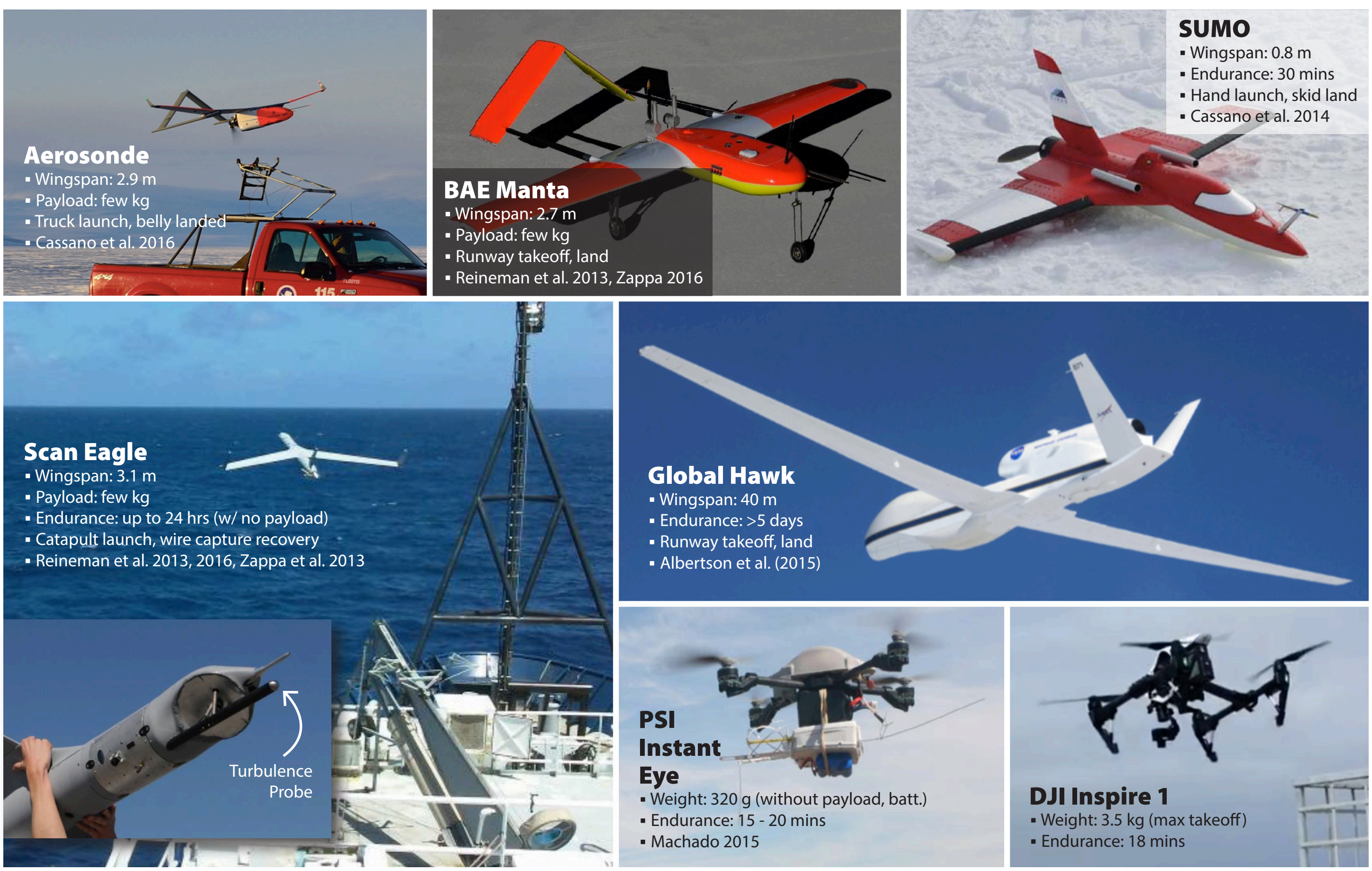

Figure 1. Examples of unmanned aerial vehicles presently used for oceanographic or atmospheric research, with sample studies referenced.

[1] I give preference here to the term UAV rather than UAS (unmanned aerial system; though neither really ought to be gender-specific), which refers to the platform along with the ground station and any associated infrastructure. The term "drone" is avoided as it has a military connotation, and can refer to missiles as well

the specific energy density of commercially available lithium ion cells.[2] For mid-size (20 kg) fixed-wing craft, electric planes can typically stay aloft for a few hours, while gasoline-powered planes can perform missions up to 24 hours (with a trade-off of payload and additional fuel).

Small multi-rotor craft have seen incredible commercial popularity growth in the last five years, driven by amateur and professional videographer demand. Given their small size, relatively low price, and pinpoint maneuverability and stability, they are an attractive alternative to fixed-wing UAVs, when limited endurance and range are not restricting factors. They are usually a few kilograms or less, with payload capacities of a few hundred grams, and endurances of 20 to 30 minutes (powered by rechargeable lithium batteries). For fine-scale atmospheric measurements, the propeller wash is a potential issue, though some studies have investigated multi-rotor craft for atmospheric sampling (e.g., Machado, 2015).

Land-based Earth and atmospheric research with UAVs is more well established than that over the ocean, given more straightforward access to runways for launch and recovery (typically required by medium and large fixed-wing craft). Aviation restrictions have historically hindered ocean and marine atmospheric boundary layer studies from land-launched UAVs, as these missions required approved corridors to sanctioned ocean airspace, but recently updated aviation regulations have opened up more airspace. Additionally, in recent years, fixed-wing craft have pursued innovative launch and capture techniques, or VTOL (vertical take-off and landing), which have and will enable expanded oceanographic, air-sea interaction, and marine atmospheric boundary layer research.

To date, a large portion of the science conducted with unmanned vehicles has been imagery-based, using small commercially available platforms. For under $1000, a quadcopter capable of carrying a high-definition camera that can stream imagery back to the ground control station, which in some cases is just a smartphone or tablet, can be acquired. Marine surveillance and situational awareness have been strong drivers of maritime UAV use. A recent chapter in the *Handbook of Unmanned Aerial Vehicles* by de Sousa et al. (2014) reviews thoroughly the state of UAVs for maritime operations, including search and rescue, ice operations, and coastal and shipping security. In the scientific community, early adopters of UAV imaging have been marine mammal surveyors (Durban et al., 2015), where cost-effective cetacean and pinniped surveys can be performed with minimal behavioral disturbance.

Infrared imaging from UAVs has permitted small- to mesoscale observations of surface temperature structure. Using thermal imaging aboard ScanEagles, Zappa et al. (2013) and Maslanik (2016) examined surface meltwater from sea ice, and Reineman et al. (2013) examined Langmuir-type circulations aligned with the wind (Figure 2a). Upcoming experiments using smaller multi-rotor craft with thermal imaging hope to examine fine- and mesoscale surface temperature structure (Figure 2b), crucial to understanding and modeling air-sea interaction.

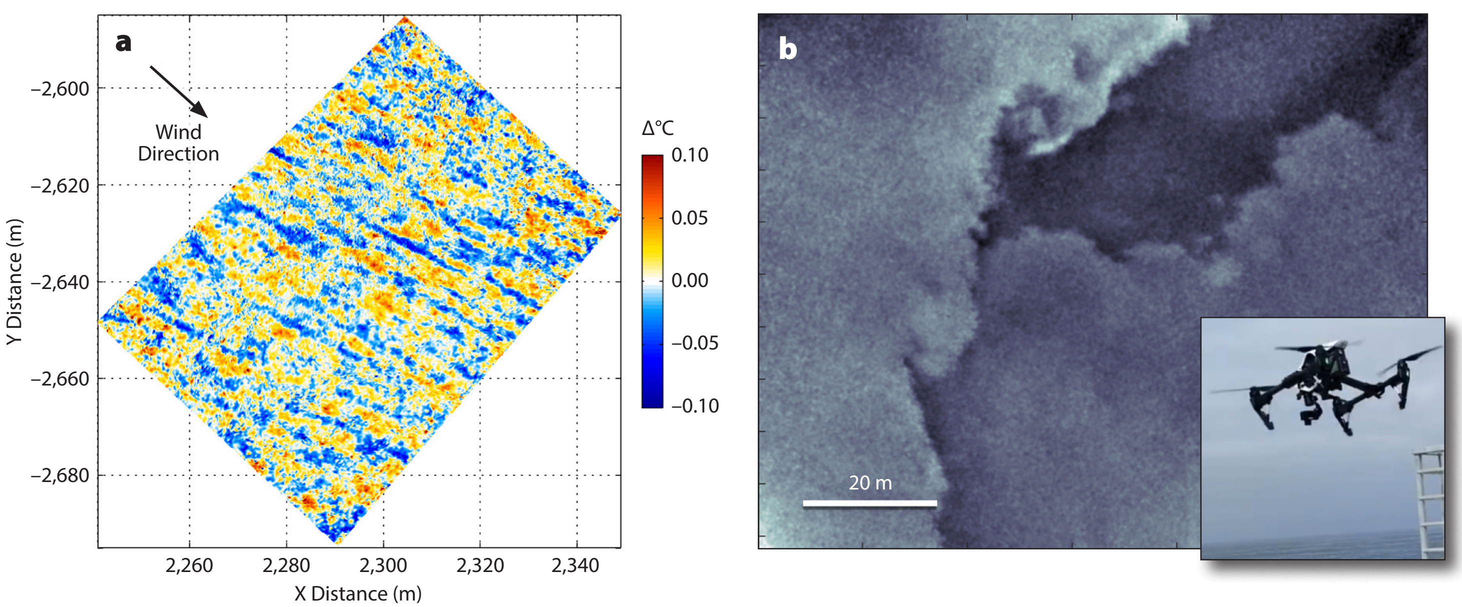

Figure 2. (a) Sample infrared imagery from a FLIR A325 aboard a ScanEagle (adapted from Reineman et al., 2013) showing Langmuir-like surface signatures aligned with the wind. (b) Uncalibrated test image from a FLIR-DJI ZenmuseXT aboard a small DJI Inspire 1 quadcopter (inset) showing a temperature front (A.F. Waterhouse, E. Lo, and D. Rissolo, *pers. comm.*).

[2] If we consider drivetrain efficiency of electric systems to be much more efficient than internal combustion (lighter comparable engines and much more efficient energy conversion), the available power output per kg storage medium for a complete gasoline system is closer to 5 to 20 times that for an electric system, but there are still many trade-offs to consider.

High-resolution wavefield measurements are important for air-sea interaction research and wave modeling, and are intriguing for satellite altimetry calibration and validation of "sea-state bias" (Melville et al., 2016). From a ScanEagle, single-point lidar for along-track surface elevation measurements was demonstrated for surface wave measurements (Reineman et al., 2013) as well as for surface signatures of internal waves (Reineman et al., 2016). While state-of-the-art complete scanning lidar acquisition and imaging packages are in the 20–50 kg range, smaller packages may facilitate this technology to transition to the unmanned aircraft realm. RIEGL (Austria; http://www.rieglusa.com) now has a commercially available, fully outfitted multi-rotor craft with scanning lidar (RiCOPTER), a 25 kg electric craft with endurance up to 30 minutes. Technology such as this will greatly expand the sampling capability of ocean surface waves, and if deployed from a research vessel, will provide accurate surface wave measurements over any ocean region.

UAVs used for standard atmospheric soundings have been employed for over a decade in the marine atmospheric boundary layer. Mean winds can be inferred by comparing airspeed and heading to GPS-derived ground speed and course over ground. Combined wind, temperature, and humidity measurements over a spatial distribution can be used to quantify bulk heat fluxes. Since 2009, Knuth and Cassano (2014) and Cassano et al. (2016) have been flying routinely in the Antarctic, measuring, among other things, the polynyas coming down the West Antarctic Ice Sheet. Bradley et al. (2015) and Zappa (2016) are experimenting with UAV-launched, air-deployed microbuoys for atmospheric soundings and also Lagrangian surface-layer temperature measurements. UAV atmospheric data have also been assimilated into real-time coupled ocean-atmosphere models in a manner similar to balloon-sonde data (Doyle et al., 2016; Reineman et al., 2016). The advantages of UAV atmospheric profiles over balloon profiles include reusability, directed and reproducible tracks, and sampling of horizontal gradients.

For three-dimensional, high-resolution turbulent wind measurements, which are necessary for directly measuring turbulent air-sea heat and momentum fluxes (using eddy-covariance techniques), multi-port pressure probes have been developed and combined with high-accuracy inertial and GPS units. Such a sensor has been implemented on a ship-launched Boeing-Insitu ScanEagle, measuring momentum flux, and latent and sensible heat fluxes in the marine atmospheric boundary layer during several field campaigns (Reineman et al., 2016). Figure 3 presents vertical profiles of momentum flux as measured during cross- and along-wind segments, where the differences in fluxes between cross- and along-wind are attributed to the presence of planetary boundary rolls. The low altitude required for accurate air-sea fluxes (typically 30 m) is below the typical limit for safe manned aircraft operation.

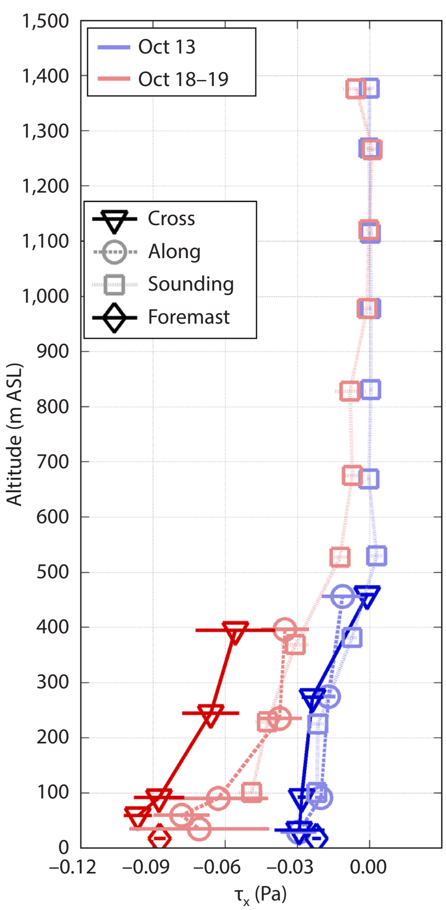

Figure 3. Vertical profiles of momentum flux in the marine atmospheric boundary layer, as measured by a turbulence probe on a ScanEagle. *From Reineman et al. (2016)*

The Federal Aviation Administration (FAA) is also embracing UAV technology. With new regulations issued in July 2016, flights in general airspace are permitted for UAVs below 55 pounds, following some basic rules, including but not limited to: staying below 400 ft, staying away from populated areas, and maintaining visual line-of-sight. Easements of these rules and others can be obtained through a straightforward process. The pilot-in-command must have passed an online certification course.[3] These new regulations will surely permit increased access to oceanographic studies with UAVs in coming years.

Unmanned aircraft are primed to bring the next wave of oceanographic, marine atmospheric boundary layer, and air-sea interaction measurements to scientists' desks. They have the ability to fly dangerous missions at little risk to human operators, or to fly long-endurance or tedious missions, giving novel measurements of the atmosphere or ocean surface. The immense range of scales in sensor and platform cost and complexity results in a wide range of scales of physical processes that can be measured and questions that can be answered. When combined with shipboard sampling, unique space and time data sets from the subsurface up into the atmosphere can be generated, and point measurements from the ship can be placed in a larger atmospheric and oceanographic context.

[3] For the full text, see https://www.faa.gov/uas/media/RIN_2120-AJ60_Clean_Signed.pdf (or search "FAA Part 107").

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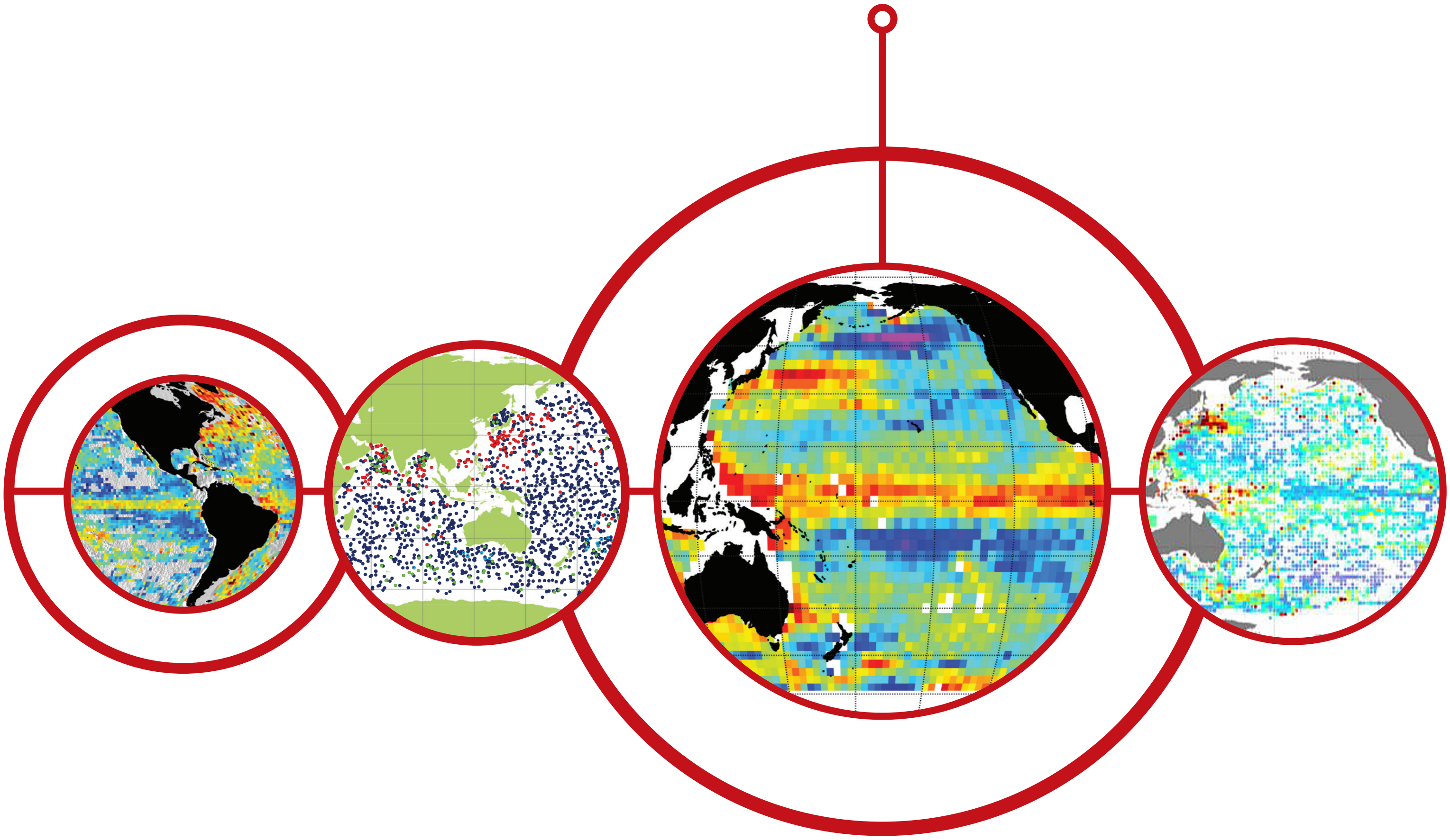
Authors

Benjamin D. Reineman, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA, reineman@ucsd.edu

Global



Observing the Global Ocean with the Argo Array

Alison R. Gray

Understanding the ocean's role in the climate system, one of the central problems of oceanography, requires global observations of ocean state. The Argo array, which was in its infancy 15 years ago, represents one of the most substantial advances in our ability to observe the world ocean and today forms a central component of the Global Ocean Observing System (Riser et al., 2016). The autonomous profiling floats that comprise this array evolved from the floats developed in the World Ocean Circulation Experiment of the 1990s (Davis et al., 1992, 2001). Current generation Argo floats measure temperature and salinity in the upper 2,000 m of the global ocean every 10 days and drift at a depth of 1,000 m between profiles. At the surface, the profile data, together with position information, are transmitted to shore via satellite. Floats typically complete more than 200 profiles over five or more years in a cost-effective manner. The array reached its target size of approximately 3,000 floats in 2007 and presently consists of over 3,800 floats, with more than 30 nations making contributions. All data are made freely available in near-real time for use in operational forecasting; the data are also subject to further examination, resulting in a high-quality data set for scientific purposes. The improvements in the spatial and temporal coverage of subsurface ocean observations is remarkable (Figure 1).

Over the past decade, the data collected by the Argo array have revolutionized large-scale physical oceanography and advanced our understanding of the ocean's role in the climate system. Numerous studies have used Argo data to address one of the primary scientific objectives of the array, namely to quantify upper-ocean climate variability, including heat and freshwater storage and transport. For example, the unprecedented

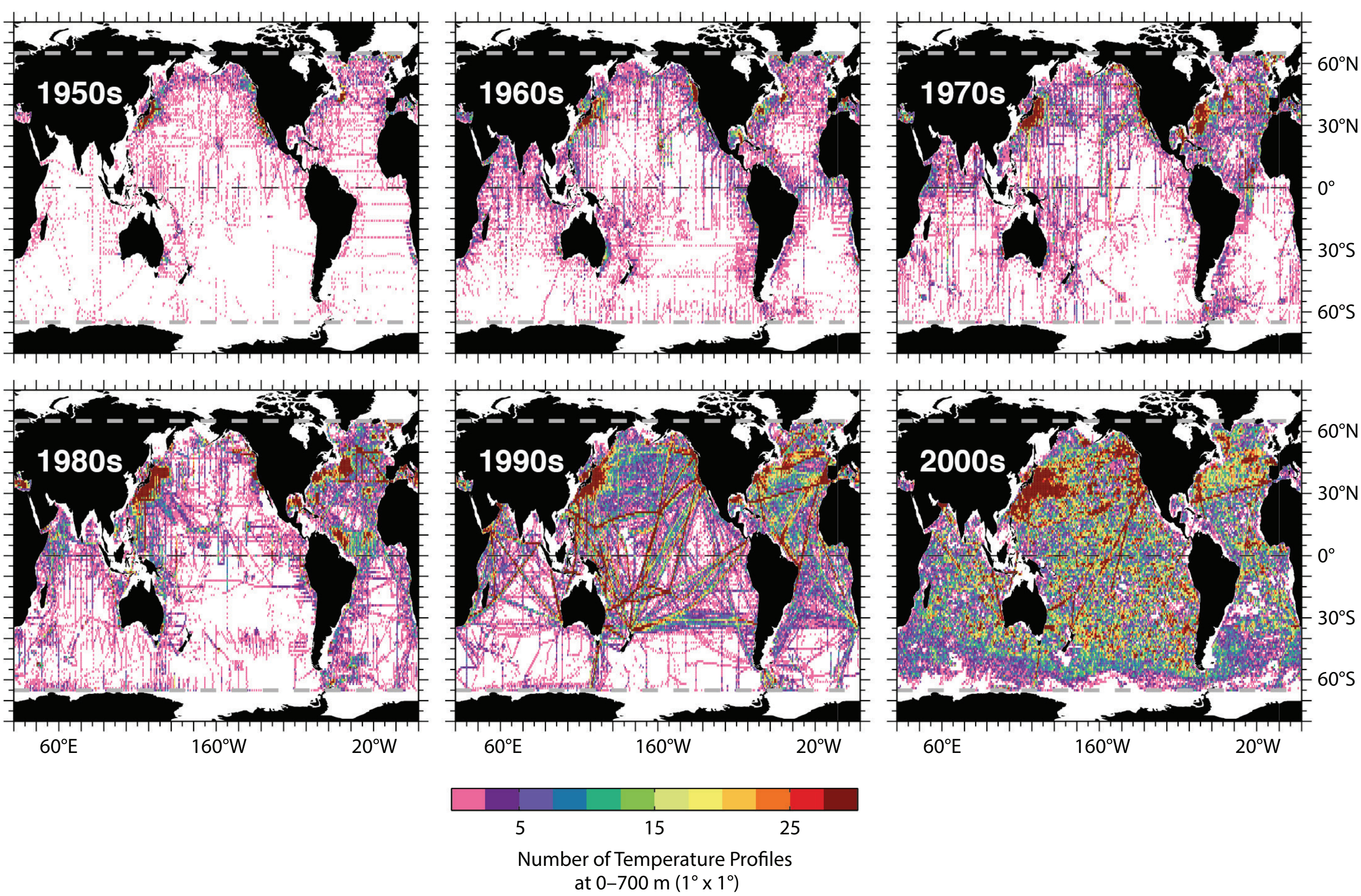


Figure 1. Historical coverage of upper-ocean temperature profiles in each decade since the 1950s. The drastic changes in the 2000s, especially in the Southern Hemisphere, are due to the advent of the Argo array of autonomous profiling floats. *From Rhein et al. (2013)*

spatial coverage of the data allowed for a detailed analysis of the patterns of upper-ocean heat gain since 2006 (Roemmich et al., 2015). Combining Argo temperature measurements with historical data demonstrated that the ocean has been warming for at least a century (Roemmich et al., 2012). The Argo array has dramatically increased the amount of high-quality salinity measurements in the open ocean, allowing for the first time a comprehensive examination of the salinity structure of the ocean surface and interior. In one such study, changes in surface salinity fields detected with Argo data were shown to indicate substantial intensification of the global hydrological cycle (Durack et al., 2012).

Considerable progress has also been made toward achieving the other scientific goals of the Argo array. The trajectory information provided by the floats has been used to quantify the large-scale circulation of the global ocean (Ollitrault and Colin de Verdiere, 2014; Gray and Riser, 2014) in ways that were previously impossible. Argo data have also been combined with satellite altimetry to determine, for example, the Atlantic meridional overturning circulation (Willis, 2010). Substantial improvements in ocean analysis and forecasting systems have been realized due to the Argo array, and most climate models now depend on these data for initialization and validation.

In addition to proving essential for addressing key questions concerning climate variability in the ocean, Argo data have also been used in an incredibly wide range of applications, many of which were unrecognized at the onset of the program. Indeed, over 2,800 scientific studies using Argo data have been published to date, an accomplishment only made possible by the high-quality and publicly available nature of the data. Some examples include investigations of the spatial variability of mixed layer depths (Holte and Talley, 2009), ocean mixing (Whalen et al., 2012), the internal gravity wave field (Hennon et al., 2014), and horizontal diffusivities (Cole et al., 2015).

The significant scientific achievements of Argo have been enabled by the many engineering and technological innovations contributed by numerous research groups in partnership with float and sensor manufacturers (Riser et al., 2016). For instance, the continuing shift to Iridium satellite communications, which is bi-directional, has resulted in less time at the surface, greater data return, and the ability to alter float missions after deployment. Software algorithms have been developed that allow floats to spend winter under sea ice, greatly expanding our observations of the high-latitude seasonally ice-covered ocean. The design of air-deployable floats has also increased applications in studies of polar sea ice regions, as well as tropical cyclones. The Argo program has also benefited from open communication among participants and strong international collaboration, which have facilitated the development and implementation of improvements and best practices. Capable data management and thorough quality control have been key factors in assuring the scientific successes of the program. The commitment of national and international agencies has been crucial as well.

Argo data continue to be an invaluable asset for scientific studies of large-scale physical oceanography, and sustaining the core array will enable more and more detailed investigations of the ocean's role in the climate system in the future. Building on more than 15 years of measurements currently available, data from the Argo array will soon be able to address questions of trends and variability in upper-ocean heat and freshwater transport and storage over interannual to decadal time scales. In addition, the trajectory information provided by the floats is becoming more useful due to recent changes to the management of these data, which will lead to better estimates of ocean circulation on global and regional scales. As long as the quality and coverage of the data are ensured, new and creative applications of Argo data will continue to be conceived.

Given the successes of Argo, there is considerable interest in enhancing and expanding the array. Western boundary current regions play a central role in ocean-atmosphere interactions and the transport of heat and other quantities. However, because of the intense turbulence and variability found there, accurately assessing the ocean state in these areas requires greater data density than the current float distribution provides. Similarly, the near-equatorial bands of the world ocean exert a powerful influence in the coupled climate system, so that increased sampling density there will improve predictions of phenomena such as the El Niño-Southern Oscillation that have an enormous impact on societies around the globe. The ice-covered Southern Ocean, although not originally part of the Argo array design, is now accessible due to advances in float technology. Enhancing the array in this region will provide invaluable observations in areas historically undersampled. The marginal seas were likewise excluded from the initial program, but deployments in these areas, which are often vitally important for the surrounding nations, have been increasing. The Argo Steering Team has endorsed these enhancements to the array, and work has begun in each of these regions.

In addition to augmenting the Argo array in these crucial areas, two major expansions are presently being implemented (Figure 2). The ocean's role in the climate system is not limited to heat and freshwater but encompasses global cycles of carbon, oxygen, nutrients, and productivity. To address questions on these fundamental topics, Biogeochemical Argo seeks to add new sensors to profiling floats to measure additional variables including dissolved oxygen, nitrate, pH, irradiance, and bio-optical properties of seawater. Plans to build a global array of biogeochemical floats have been established (Johnson and Claustre, 2016), and pilot arrays in the Southern Ocean and North Atlantic are being deployed. Just as the core Argo array transformed large-scale physical oceanography, building

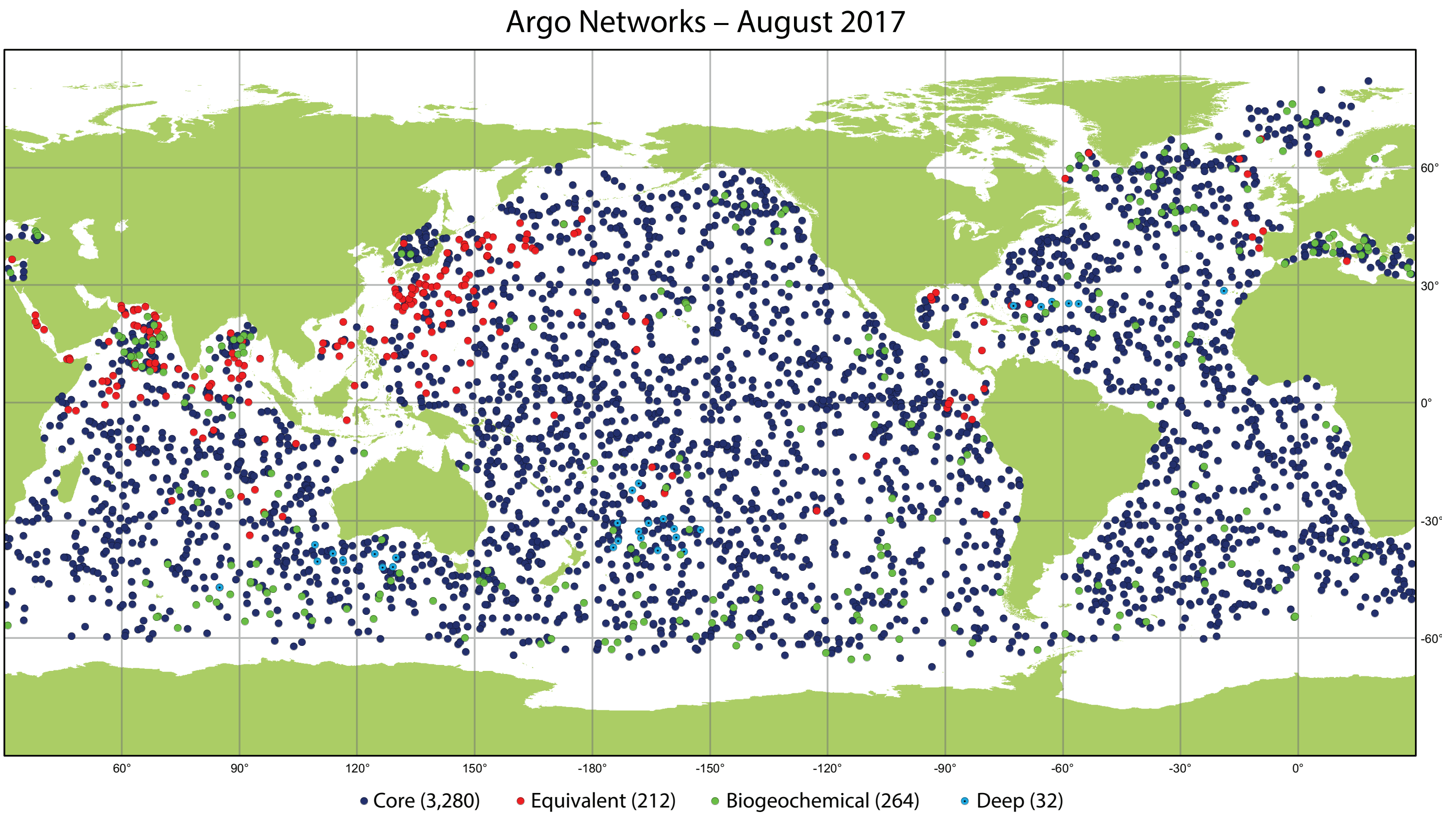


Figure 2. Argo float distribution for August 2017. Core floats and Argo-equivalent floats, which measure temperature and salinity in the upper 2,000 m, comprise the bulk of the array, but deployments of Biogeochemical Argo floats and Deep Argo floats are increasing. *From http://www.jcommops.org*

a global array of biogeochemical floats will likely revolutionize biological and chemical oceanography.

Deep Argo, the second significant expansion of the array, aims to deploy floats that profile the full depth of the ocean, allowing for computation of closed budgets of heat, freshwater, and sea level and investigation of the circulation of the deep ocean. Two different deep floats designs have been developed and are rated for depths up to 4,000 and 6,000 m. Early deployments of deep floats have been successfully carried out, and a design for a global array has been developed (Johnson et al., 2015). The success of both of these expansions will depend on having reliable and cost-effective platforms (in the case of Deep Argo) and sensors (in the case of Biogeochemical Argo).

As we move toward 20 years of ocean observations from the Argo array, sustaining the quality and coverage of the data remains imperative because of the numerous scientific and operational benefits of this component of the Global Ocean Observing System. Continuing to advance basic float technology should be an essential part of the strategy moving forward, as such efforts will lead to increased quality and efficiency. The planned enhancements and expansions of the Argo Program each come with their own set of engineering challenges and opportunities, which will necessitate basic research and experimentation. Many of the lessons learned during the development of the Argo array will be valuable, not just to those working to expand Argo to more regions of the global ocean, to new types of data, and to the deep ocean, but to users of many different types of ALPS. Additionally, efforts to strengthen the integration of Argo data with observations from other ALPS and other parts of the Global Ocean Observing System will improve our ability to understand and predict the ocean and its role in the climate system.

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Author

Alison R. Gray, University of Washington, Seattle, WA, USA, argray@uw.edu

Investigating Small-Scale Processes from an Abundance of Autonomous Observations

Sylvia T. Cole

Abstract

Small-scale processes, those with spatial and/or temporal scales less than a few hundred kilometers and a few weeks, vary on global and decadal scales. Such large-scale variations in small-scale processes have been difficult to observe. Within the last decade, global and regional-scale autonomous observations have begun to fill this observational gap. The specific processes that can be investigated from autonomous platforms are determined by the minimum scale in space and time sampled by each platform. Recent examples are highlighted, and the future potential is discussed.

Introduction

Autonomous platforms sample a range of horizontal and temporal scales regardless of whether they are utilized for short-term localized studies, regional studies, or decadal-scale global studies. Spatially, observations span the submesoscale or mesoscale in the horizontal to regional or global scales of interest. Temporally, observations span hours to weeks at a minimum, to several months or, increasingly, more than a decade at a maximum. Data collection is often motivated by larger-scale phenomena, whether regional or global in nature, and the smaller-scale phenomena that are also observed are frequently removed or smoothed. Increasingly, smaller spatial or temporal scale phenomena are being investigated, and the potential to investigate such processes on the regional to global scale or seasonal to decadal scale should not be overlooked in the future.

Investigating global- or decadal-scale variations in smaller-scale processes requires a large amount of data. Global-scale programs have collected enough data through operations over multiple years (e.g., surface drifters, Argo floats). Such data sets are appealing for this purpose, as data coverage is somewhat uniform in space and time. Regional-scale programs will continue to build up sufficient data through the combined data set of a particular platform (e.g., all glider or autonomous underwater vehicle data). While coverage is certainly not uniform in space or time, and is often biased toward dynamically interesting regions, investigating dependence on parameters of interest (e.g., latitude, background stratification) is feasible.

Mining Small-Scale Processes

The specific small-scale processes that can be investigated are determined by the minimum scale at which platforms sample. This minimum scale varies by platform, for example, one hour for drifters (Lumpkin and Pazos, 2007), a few hours and a few kilometers for gliders (Rudnick et al., 2004; Rudnick 2016) and Ice-Tethered Profilers (Toole et al., 2011); 10 days and typically tens of kilometers for Argo floats (Roemmich et al., 2009). The minimum scale is often variable, with higher temporal or spatial resolution for some deployments compared with their standard operation. With profiling platforms, the vertical resolution can also be a determining factor, with minimum vertical resolutions ranging from 0.25 m for Ice-Tethered Profilers to 10 m or more for the standard operation of Argo floats.

On the global scale, the Argo and drifter data sets have been utilized to investigate several small-scale processes. Near-inertial and tidal surface currents have been quantified from the global drifter data set (Poulain and Centurioni, 2015; Elipot et al., 2016). Internal wave energy and parameterizations of vertical diffusivity have been investigated from Argo floats utilizing vertical strain of the density field (Whalen et al., 2012; Figure 1a,b). Mesoscale processes have also been studied using Argo float profiles or drifter data, resulting in parameterizations of horizontal diffusivity with global coverage (Zhurbas et al., 2014; Cole et al., 2015; Figure 1c,d). Such studies have shown significant variability with depth and geographic location of for example, horizontal and vertical diffusivity (Figure 1). This variability is not captured by other platforms with global coverage, as such platforms are limited in either depth resolution (satellites) or spatial and temporal resolution (e.g., ship-based hydrographic surveys). Autonomous platforms have advanced our knowledge about the larger-scale variations of such small-scale processes.

At the regional scale, the use of autonomous platforms to gather multiyear data sets is of interest here (e.g., Toole et al., 2011; Rudnick et al., 2017), as opposed to short-lived process studies that are designed specifically to capture smaller-scale features (e.g., Martin et al., 2009). Similar themes to the global scale emerge, with investigations of submesoscale and mesoscale dynamics and vertical mixing and diffusivity. Glider data have been used to investigate internal wave

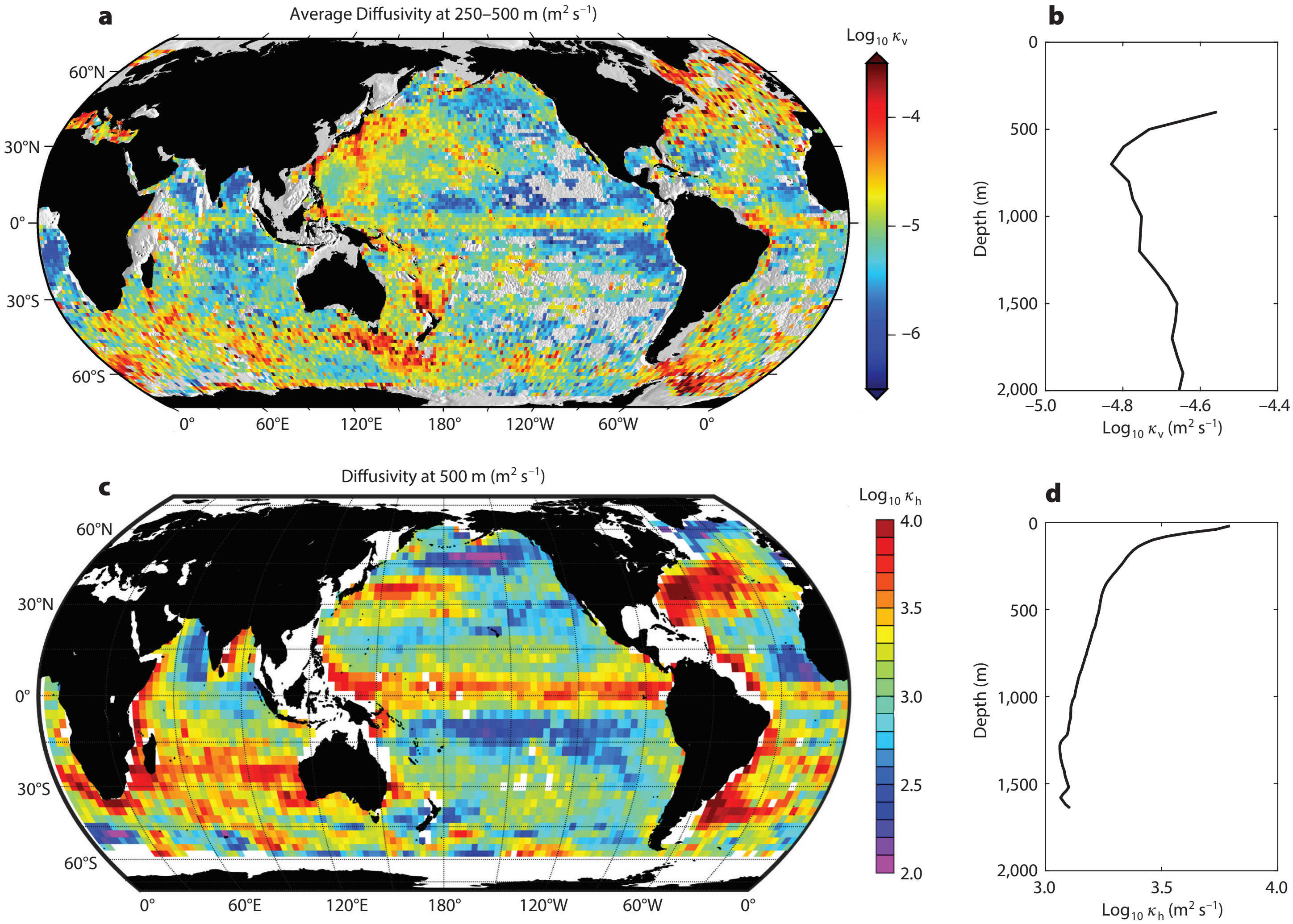

Figure 1. (a) Map, and (b) globally averaged profile of vertical diffusivity from Argo float temperature and salinity profiles (adapted from Whalen et al., 2012, with data updated through June 2016). (c) Map at 500 m depth, and (d) globally averaged profile of horizontal eddy diffusivity derived from Argo float temperature and salinity profiles and ECCO-2 eddy kinetic energy (adapted from Cole et al., 2015, with data updated to cover 2005–2015). Global averages are shown at depths with sufficient data.

energy at a regional scales, illustrating its enhancement near topography (e.g., Johnston et al. 2013; Johnston and Rudnick, 2015). Ice-Tethered Profiler data have demonstrated decadal and latitudinal trends within the Arctic Ocean (Dosser and Rainville, 2016). Ice-Tethered Profiler data have also been used to quantify spatial modulations in double-diffusive staircases at the shortest vertical scales (Shibley et al., 2017). Mesoscale and submesoscale processes are also routinely investigated in regional data sets (e.g., Cole and Rudnick, 2012; Pelland et al., 2013; Zhao et al., 2016). While investigations of such processes are not exclusive to autonomous platforms, they are growing increasingly common and feasible. Even at the regional scale, autonomous platforms show larger spatial- or temporal-scale modulations in smaller-scale processes then are practical from other platforms (e.g., ship-based observations or moorings).

Regional platforms also often permit a more thorough investigation of processes of interest, such as the internal wave energy flux and energy density (that requires velocity measurements; Johnston et al., 2013) and not simply the parameterized vertical diffusivity (via Argo float density profiles; Whalen et al., 2012). Global analysis of regional-scale observations will provide key advances in the future.

Future Potential

Several factors influence the future potential of autonomous platforms to advance our knowledge of small-scale processes on regional to global scales. The amount, resolution, and types of data collected are the main factors, though availability of the data sets is also important. Regardless of what specific advances are made, many different studies have already advanced our knowledge of smaller-scale processes by combining multiple years of autonomous observations, and that will continue into the future.

Increasing amounts, resolution, and types of data collected will permit more detailed investigations of many processes. Improvements in technology will allow for finer temporal, horizontal, or vertical resolution via cheaper platforms that increase the number of platforms deployed, increase battery life, and/or increased ease or decrease cost of data telemetry. Additional sensors on autonomous platforms will also expand and enhance the study of smaller-scale phenomena. For example, as biogeochemical observations become more routine, they permit studies of biogeochemical-specific processes, as well as physical processes for which such observations serve as a maker (e.g., eddy stirring). Turbulent-scale processes are already directly observed from autonomous platforms (e.g., gliders, autonomous underwater vehicles, Wave Gliders), and the growing collection will lead to its study on larger spatial and temporal scales. The range of temporal scales will also expand beyond decadal, providing a more detailed look at interannual variability of small-scale phenomena. Access to autonomous observations is a key component of such future studies, especially for those platforms that are used in numerous regional studies throughout the global ocean.

Autonomous platforms provide a tool for studying the ocean as a system, and the interactions between processes at different scales. The geography and seasonal to decadal variations in such processes are still being explored. The next decade of autonomous observations will significantly improve our ability to understand the link between smaller-scale processes and larger-scale or longer-time dynamics within the ocean.

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Author

Sylvia T. Cole, Woods Hole Oceanographic Institution, Woods Hole, MA, USA, scole@whoi.edu

Air-Sea Observations from ALPS

Jim Thomson, Sophia Merrifield, James Girton, Sebastiaan Swart, Chris Meinig, and Luc Lenain

Introduction

Air-sea interactions are essential processes in forecast and climate models, yet observations of these processes remain sparse. Despite significant progress over the last 50 years, the air-sea interaction community is still actively working on developing better understanding of the fundamental processes occurring in the coupling between the ocean and the atmosphere, such as the kinematics and dynamics of momentum, heat, moisture, and gas (carbon dioxide in particular) exchange (i.e., flux) between the atmosphere and ocean, as well as the structure of turbulence in the ocean boundary layer. Traditional methods observe these fluxes from research platforms (e.g., Grare et al., 2013), ships (e.g., Edson et al., 1998), and moored surface buoys (e.g., Edson et al., 2013). These approaches have driven considerable progress in air-sea flux estimation, including the TOGA-COARE routines for bulk estimates (Fairall et al., 2003). However, shipboard measurements often suffer from flow contamination and interference associated with the ship superstructure. Attempts have been made to account for those effects (Landwehr et al., 2015), but it remains a major source of error. Additionally, both ships and moorings can have significant operational costs and deployment restrictions. Alternative approaches using autonomous and Lagrangian platforms have emerged in recent years, with considerable progress made in the last decade. As the level of autonomy has improved, including capabilities such as AIS ship traffic avoidance, users and developers are pressing forward with more comprehensive suites of air-sea observations.

Figure 1. A Saildrone deployed off the coast of Alaska, with a three-axis sonic anemometer at the top of the sail, along with temperature, humidity, and radiation on a forward probe. *Image credit: Saildrone Inc.*

Autonomous surface platforms have their own challenges. While the small size of these platforms can be an advantage in making a minimal disturbance within the signal of interest (e.g., near-surface stratification, atmospheric turbulence), the platforms often experience significant motion contamination and limitations in sensor heights/depths. One example is in wind measurements, which are typically made above the wave-influenced layer (e.g., Hara and Sullivan, 2015) and corrected to a 10 m reference height. Small platforms often can only support short masts (1 m is common), and there may be significant wave sheltering effects in measuring winds at these heights. These effects are small for moderate wind speeds, and then become increasingly significant above 20 m s^{-1} (Donelan et al., 2012). Work is ongoing to improve interpretations of wind speed and wind stress (i.e., momentum flux) measured at low heights.

Another challenge for autonomous surface platforms is biofouling, because surface platforms are constantly in a productive zone (by definition). This is particularly relevant to heat flux estimates, because incoming short- and long-wave radiation often dominate the ocean's surface heat budget. Downwelling radiometer measurements are thus essential, but these instruments perform best when routinely cleaned (which is difficult to achieve on autonomous platforms). These and other measurement challenges are being pursued by a broad community of developers and users. Many of these systems are well beyond demonstration phase and are in operational use for research and monitoring. The following is a brief survey of various recent developments in using ALPS for air- sea measurements. This list covers water platforms only, though there has been notable activity in making similar air-sea measurements from aerial platforms (e.g., Reineman et al., 2016).

Recent Developments and Examples of Air-Sea Fluxes from ALPS

WIND-DRIVEN AUTONOMOUS SURFACE VEHICLES

Wind-driven autonomous surface vehicles, such as the Saildrone (Saildrone Inc.), the Datamaran (Autonomous Marine Systems Inc.), and the Sailbuoy (Offshore Sensing AS), have demonstrated the ability to survey large areas of open ocean while collecting air-sea data. The Pacific Marine Environmental Laboratory at the National Oceanic and Atmospheric Administration (PMEL-NOAA) has been using Saildrones for multi-month research surveys in the Bering Sea (Meinig et al., 2015). Figure 1 shows the Saildrone and associated instrumentation.

The Saildrone has a particular advantage of mast height for atmospheric measurements above the wave-affected layer. Figure 1 shows a three-axis sonic anemometer many meters above the surface, which is much higher than many of the other autonomous surface vehicles can support.

WAVE-DRIVEN AUTONOMOUS SURFACE VEHICLES

Wave-driven autonomous surface vehicles, such as the Liquid Robotics Wave Glider or the Autonaut, have become common platforms for air-sea observations. For example, Lenain and Melville (2014) used a Wave Glider to measure waves heights up to 10 m and winds up to 37 m s^{-1} in Tropical Cyclone Freda. Using the motion of the surface flotation for wave measurements, they measured and analyzed the evolution of the directional wave field as the storm passed near the wave glider. The Langmuir turbulence number, the Stokes depth scale, and the Stokes drift computed from measurements of these directional wave spectrum across the track of TC Freda showed remarkable agreement with hurricane marine boundary layer studies that include numerical wind-wave model predictions as input to the Large Eddy Simulation (LES) model of the marine boundary layer (Sullivan et al., 2012).

Following on this success, Mitarai and McWilliams (2016) used a Wave Glider to measure winds up to 32 m s^{-1} during Typhoon Danas. More recently, Schmidt et al. (2017) used a Wave Glider to measure winds and evaluate global satellite and reanalysis wind products. Very recently, Thomson and Girton (2017) used a Wave Glider to observe air-sea interactions across the fronts of the Antarctic Circumpolar Current (ACC) in a mission that lasted four months and spanned wave heights up to 6 m and winds up to 18 m s^{-1}. As shown in Figure 2, their sensor payload included many of the same sensors that NOAA-PMEL has integrated on the Saildrone, such as a three-axis sonic anemometer.

Wave Gliders have also been used to estimate air-sea gas exchange, notably of CO_2 (Monteiro et al., 2015), which has provided insight into the scale of variability of bio-physical exchange at the sea surface. The gas exchange application has progressed rapidly in recent years, with autonomy dramatically increasing the amount of data collected (e.g., Sutton et al., 2014).

FUEL/ELECTRIC AUTONOMOUS SURFACE VEHICLES

In addition to wind- or wave-powered systems, there are many fuel/electric-powered autonomous surface crafts in use for data collection, such as the C-Enduro from ASV Global. Many of these systems are in use for air-sea measurements (e.g., Srinivasan et al., 2013). Codiga (2015) demonstrated coastal surveys with such a system. Hole et al. (2016) demonstrated directional wave estimation from such systems. These systems generally have less endurance than their wind- or wave-powered counterparts, but deployments exceeding a month and more have been successfully completed.

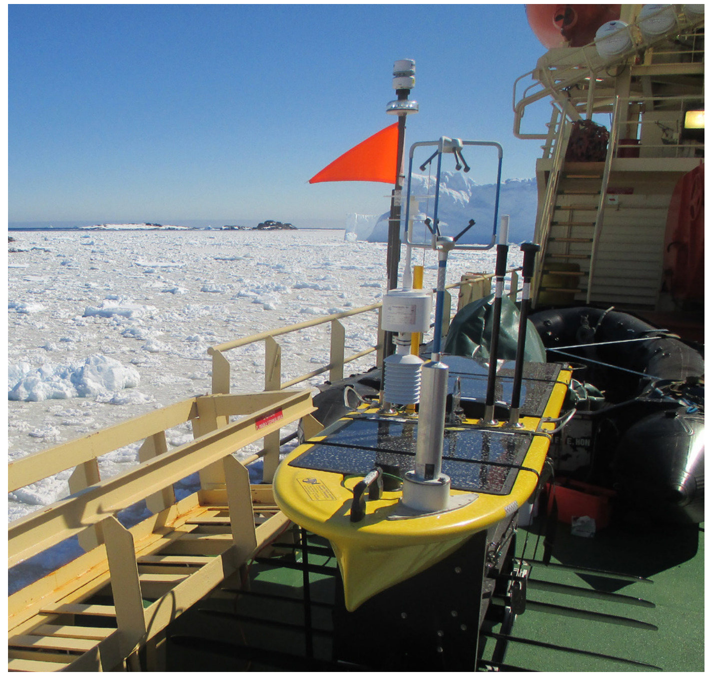

Figure 2. A Wave Glider before deployment off the Antarctic Peninsula, with a three-axis sonic anemometer at the bow, along with temperature, humidity, and pressure sensors on a mast. *Image credit: Avery Snyder (APL-UW)*

LAGRANGIAN SURFACE DRIFTERS

Although lacking the navigation capability of autonomous surface vehicles, Lagrangian surface drifters provide excellent air-sea observations. In many cases, the Lagrangian nature of the platform provides robust estimates of surface currents and waves (e.g., Herbers et al., 2012), as well as a reference frame with minimal contamination of turbulent signals (Thomson, 2012). Such platforms have included detailed measurements of the high-frequency tail of the wave spectrum (Graber et al., 2000) and evolution during high winds (Drennan et al., 2014). These platforms have also been used to measure the motions within breaking waves (Amador and Canals, 2016). As demonstrated by the Scripps minibuoys, deploying large numbers of drifting assets can supplement existing/conventional

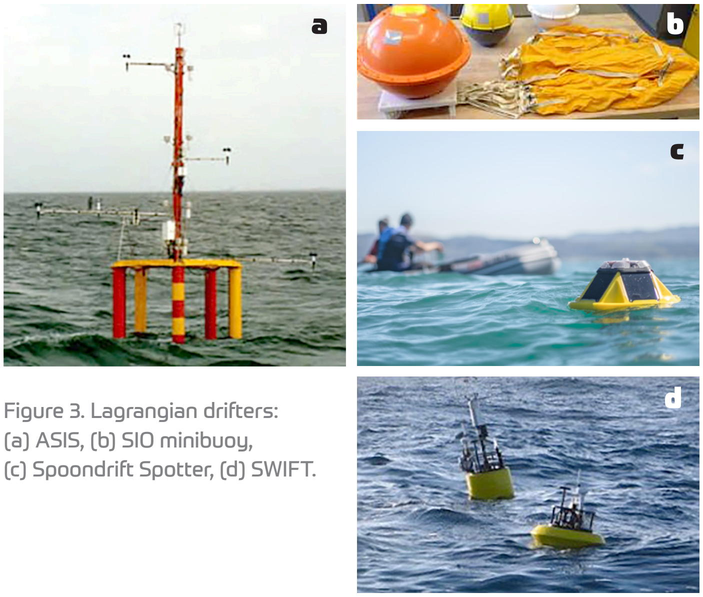

Figure 3. Lagrangian drifters: (a) ASIS, (b) SIO minibuoy, (c) Spoondrift Spotter, (d) SWIFT.

operational networks, such as the National Data Buoy Center (NDBC). Figure 3 shows a selection of drifters presently in use for research and operational data collection. Many other similar systems are available commercially, as well as produced by various academic research labs. In some cases, buoys that are traditionally moored, like the Woods Hole Oceanographic Institution's air-sea flux buoys, can be allowed to drift as Lagrangian platforms.

Future Work with ALPS

ALPS will undoubtedly continue to expand the quantity and quality of air-sea observations collected for both research and operational uses. Specific advances in the near future may include:

- Extended endurance of platforms, including engineering solutions to harness energy from waves, currents, or winds, as well as energy storage improvements.
- Improved motion correction of sensor data (via integrated/synchronous IMUs)
- Autonomous feature sampling (e.g., mapping fronts)
- Antifouling/cleaning for radiometers and other optical sensors
- Ocean profiles (via automated casting or towed chains)
- Lower atmosphere profiles (via partner/coordinated unmanned aerial systems)
- Development of novel biogeochemical and physical sensors
- Automated coordination between unmanned platforms (aerial, surface, and underwater vehicles)

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Authors

Jim Thomson, Applied Physics Laboratory, University of Washington, Seattle, WA, USA, jthomson@apl.washington.edu

Sophia Merrifield, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA, smerrifield@ucsd.edu

James Girton, Applied Physics Laboratory, University of Washington, Seattle, WA, USA, girton@apl.washington.edu

Sebastiaan Swart, University of Gothenburg, Gothenburg, Sweden, sebastiaan.swart@marine.gu.se

Chris Meinig, National Oceanic and Atmospheric Administration/Pacific Marine Environmental Laboratory, Seattle, WA, USA, christian.meinig@noaa.gov

Luc Lenain, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA, llenain@ucsd.edu

Current Usage of ALPS Data and Future Challenges for ALPS Network Design

Perspectives from Operational Data Assimilation and Climate State and Parameter Estimation

An T. Nguyen and Patrick Heimbach

ALPS in Data Assimilation and Estimation

Since the early 2000s, ALPS data have been an invaluable component of data assimilation (DA) in operational oceanography (e.g., Martin et al., 2015; Oke et al., 2015), and state and parameter estimation (SPE) for climate research (Wunsch and Heimbach, 2013; Edwards et al., 2015; Stammer et al., 2016). A quantitative assessment of how "useful" or "critical" any set of ALPS data is to DA and SPE systems depends on the system's scientific goal and application. Common to both systems, the aim is to obtain the time-evolving description of the ocean (and sea ice) over temporal scales ranging from days to many decades (Stammer et al., 2016). Functioning as a temporal and spatial interpolator, the underlying numerical and/or statistical models fill the gaps between sparse observations from ALPS and other diverse streams to produce an optimally "merged" product (Figure 1) to serve specific needs of the end users.

In operational forecasts and ocean reanalyses, data streams are typically assimilated within a specific time window whose length is governed by practical needs (e.g., availability and quality control of the data, and computing times to produce the analysis and forecast), and the system's "predictive" skill (black solid and dashed curves in Figure 1). Predictability refers to the time scale over which a model trajectory remains within a tolerable threshold defined by, for example, the ensemble standard deviation or the combined model-data errors (Robinson et al., 2002; Edwards et al., 2015; Oke et al., 2015). Examples of practical needs include the ability to predict the presence of sea ice to mitigate potential shipping hazards, paths of an oil spill to mitigate the potential environmental damage, or paths of warm currents to follow schools of fish to maximize potential catch.

The aim of state and parameter estimation is toward "understanding" of processes at multidecadal to longer time scales. These systems emphasize the underlying model dynamics and property conservation implied by the equations of motion. They utilize data to constrain the state estimate's overall trajectory, fitting the data to within data and model representation uncertainty, over the entire estimation period of up to a multidecadal time scale. In addition to being used to invert for optimal initial conditions as in operational DA, ALPS and other complementary data sets (e.g., from satellites, surface drifters, ship-based and moored instruments) are also used to estimate time-mean internal model parameters and time-varying adjustments to lateral/surface fluxes (Stammer, 2005; Moore et al., 2011a; Liu et al., 2012; Forget et al., 2015b).

Following the success of satellite altimetric data available since the early 1990s (Wunsch and Stammer, 1998) for constraining upper ocean circulation, since the mid-2000s Argo has become the single most important data source for constraining subsurface hydrographic mean

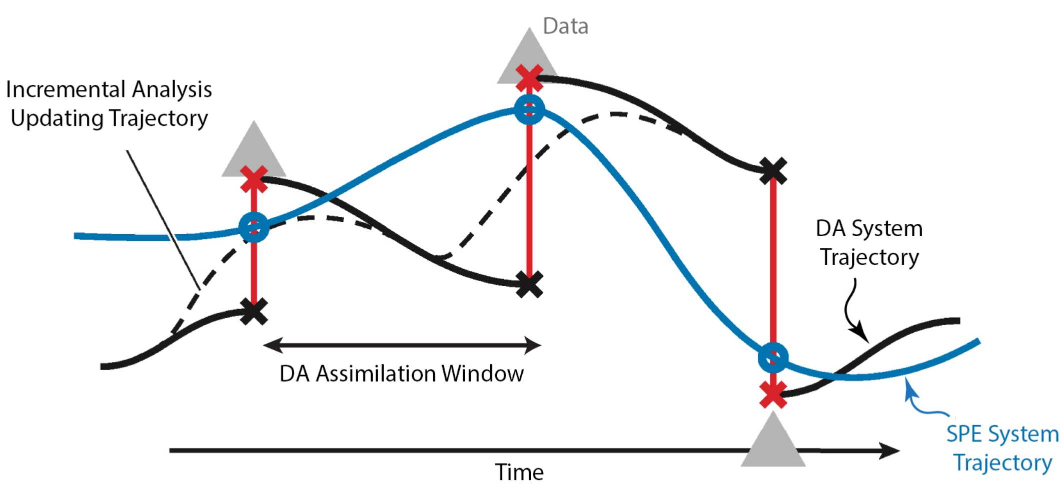

Figure 1. Schematic difference between data assimilation (DA) and state and parameter estimation (SPE) systems. Trajectories of DA and SPE systems are depicted with solid black and blue lines, respectively. In a DA system, at the end of each DA assimilation window, the model trajectory can lead to an ocean state (black cross) that diverges from observations (gray triangle), and a correction (re-initialization) can bring the model toward the observation (to within pre-defined criteria, red cross). Unphysical "discontinuities" can potentially be introduced in this correction step (red vertical lines) and can be mitigated through incremental adjustments (dashed black line), though the resultant smooth solution can remain dynamically unbalanced. SPE system trajectory (blue solid line) matches observations to within a pre-defined uncertainty range and guarantees conservation of heat, salt, and momentum over the entire estimation period. *Figure adapted from Stammer et al. (2016)*

state and variability (e.g., Wunsch et al., 2009; Forget et al., 2015a; Oke et al., 2015). In a review of several representative DA systems, Oke et al. (2015) concluded that the Argo data set is "unanimously" critical to all systems, in particular at depths and in constraining the global salinity. Similarly, Liu et al. (2012) and Forget et al. (2015b) showed that significant reduction of global temperature and salinity misfits was achieved through improved global estimates of ocean mixing parameters, with Argo, ship-based hydrography, and satellite altimetry being used as primary constraints. In coastal regions or where Argo data coverage is too sparse, dedicated ALPS data sets from gliders and Lagrangian ocean drifters have contributed significantly to improving representation of regional oceanography to serve specific needs, ranging from surface oil spill prediction to tracking fishery along the California coast (e.g., Todd et al., 2011; Poje et al., 2014; Edwards et al., 2015, and references therein).

Synergy Between DA/SPE Frameworks and ALPS to Address Scientific and Technological Challenges

The successful use of ALPS data, in particular, Argo observations, in DA/SPE systems is widely attributed to the accessibility of the data and the quasi-global coverage of independent subsurface observations that complement satellite observations in improving estimates of ocean state and its uncertainties. However, relevant to the discussion here, no single observation platform can address all the scientific questions and technical challenges of DA/SPE systems. Below is a list of some outstanding challenges that can be addressed with future synergy between DA/SPE systems/frameworks and potential new ALPS observation types or deployments, keeping in mind of the overall goal to improve the estimation of ocean state in ocean-sea ice models.

MODEL DRIFT. Oke et al. (2015) reported that when Argo data are not used to tightly constrain ocean DA systems, model trajectories diverge quickly from observations within a few months. In energetic regions, the degradation can occur within days (Janekovic et al., 2013). Model drift arises from various sources, including imperfect model physics, model representation errors, model structural uncertainty, and often sensitive yet highly unconstrained model parameters (Mignac et al., 2015; Oke et al., 2015; Stammer et al., 2016). Large model-data misfits persist in regions where mesoscale to submesoscale eddy activity dominates, for example, along energetic western boundary currents, in the Antarctic Circumpolar Current (Figure 2a; Forget et al., 2015a; Turpin et al., 2016; Sivareddy et al., 2017), or along coastal regions where temporal and spatial decorrelation length scale are short (Moore et al., 2011c; Janekovic et al., 2013). In the DA framework, model drift can often be mitigated by adjusting the assimilation window. This window length often depends on how long nonlinear processes will "overwrite" the initial condition and the model trajectory becomes unpredictable (Moore et al., 2011a; Janekovic et al., 2013). In these regions, increased ALPS spatial coverage and temporal sampling rate help improve the estimations of initial condition (primary task of most DA systems), representation errors, and the time-mean

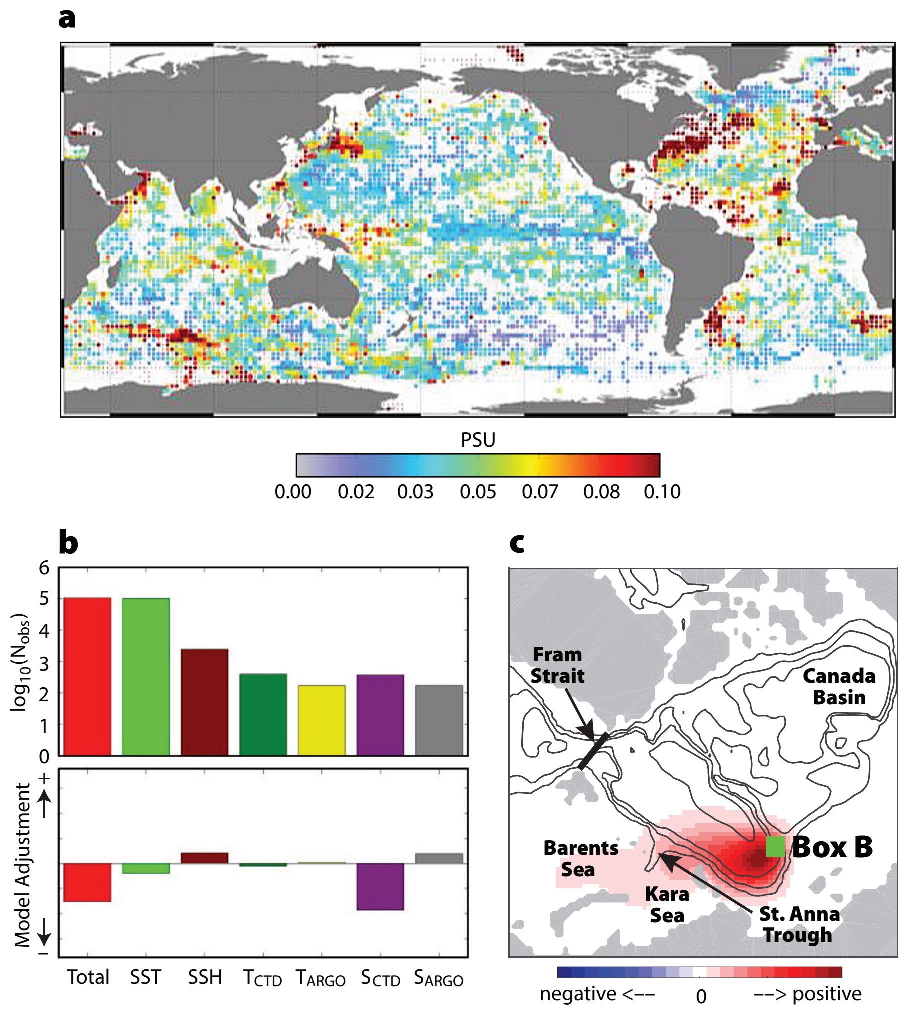

Figure 2. (a) Large misfits in salinity between a data constrained DA system and Argo float data over depth range 300–2000 m (subfigure adapted from Turpin et al. (2016)), (b) number of observations (upper) and impact of observations on the total adjustment (lower) during a 7-day assimilation in a California Current ocean data assimilation framework (subfigure adapted from Moore et al. (2011c)), (c) sensitivity of box B mean temperature at depth ~150 m to ocean salinity at depth 125 m up- and down-stream. *Figure adapted from Nguyen et al. (2017)*

and time-varying model internal parameters in SPE framework. The DA framework can also be used as a quantitative tool for assessing model error by understanding the causes of recurring analysis increments (e.g., Rodwell and Palmer, 2007).

MEASUREMENT REDUNDANCY. While some of the challenges of DA/SPE systems' ability to represent the realistic ocean state are computational in nature, for example, model resolution and associated representation errors, the majority can be traced back to lack of appropriate observations to constrain unknown parameters/processes and their error covariance (Moore et al., 2011b). The notion of having already "enough" data of "global" coverage should be critically assessed. The SPE framework can be used to address the issue of over- and undersampling and sampling redundancy. As an example, Moore et al. (2011c) showed that depending on the region and scientific objective, data sets with orders of magnitude more data and good spatial coverage can have up to 90% redundancy (i.e., the first few measurements or only measurements in independent "super sites" contribute to improving the state estimate while the rest did not provide additional information; Figure 2b). Their study also highlighted the importance of very few observations with independent information in inaccessible sites, for example, subsurface or coastal, that can significantly impact model's adjustments. Additional studies (e.g., Köhl and Stammer, 2004; Heimbach et al., 2011; Nguyen et al., 2017) show strategically positioned observations that take into account upstream and downstream ocean dynamics in delivering integrated information can be more effective than uniform coverage and a high quantity of observations at the site of interest (Figure 2c).

DATA TYPE. One of the primary goals of SPE is estimating model internal parameters, such as ocean mixing (Stammer et al., 2016). Such parameters are often not easily observed and must be indirectly inferred from observations. Indeed, model drift is found to be largely a consequence of variations in these unconstrained yet highly sensitive model parameters. Ocean mixing rates in the lower latitudes (±60°N) have recently been calculated from Argo float temperature/salinity (e.g., Whalen et al., 2012; Cole et al., 2015) and should be used to directly constrain model parameters. Observational challenges remain in the deep ocean, in vigorous currents and in ice-covered regions. Thus, extending ALPS measurements to the deep ocean below 2,000 m in the lower latitudes and throughout the water column at high latitudes will help constrain and improve these parameter estimates.

UNCERTAINTIES. Both DA and SPE systems require knowledge of model representation error. "Representation error" here refers to what processes the model is able to resolve (represent) given its horizontal and vertical resolution, compared to point-wise measurement taken by in situ systems. Rigorous quantification of this error requires dense coverage of observations that can capture the spatial and temporal variability of the targeted model tracer, velocity, or parameters, but is often out of reach in practice. At a nominal spacing of 3° x 3° global coverage, Argo floats capture variability at a resolution that is inadequate for regions where the first baroclinic Rossby radius of deformation is below the floats' spatial sampling (e.g., Figure 2a).

Summary

ALPS data have greatly advanced the quality of DA/SPE frameworks over the last decade. Challenges remain in model structural errors and representation errors. An increased sampling by and systematic use of ALPS data within DA/SPE frameworks may help improve understanding and better addressing such error sources in both operational forecasting and climate estimation. In DA frameworks that rely on statistical approaches and do not obey the underlying physics, spurious "signals" may arise due to over-constraining of/over-reliance on data (Sivareddy et al., 2017). In this framework, continuous observations in space and time would be valuable to mitigate and/or damp out propagations of these spurious signals.

In terms of sustained, quasi-global hydrographic sampling of the top 2,000 m of the water column, the Argo float network has become a primary ALPS platform. Its present coverage, at a minimum, is deemed critical to support short-term operational and long-term research-focused global DA and SPE systems. DA and SPE tools can be deployed for numerical observing system experiments (OSEs) and observing system simulation experiments (OSSEs) to assess or identify data sets and/or locations of data redundancy and those which have optimal impact on the system (Köhl and Stammer, 2004; Heimbach et al., 2011). ALPS data show promise to fill the gaps required by OSE/OSSEs. The shortcomings of ocean models to capture first order ocean dynamics in energetic regions and in polar regions (Ilicak et al., 2016) are likely systematic deficiencies. Studies such as Moore et al. (2011c), Köhl and Stammer (2004), and Nguyen et al. (2017) should be conducted, with targeted metrics, to methodologically address the potential impact current and future observations have to better understand and tackle model errors (Rodwell and Palmer, 2007; Moore et al., 2011c). In the same vain, tools available within DA/SPE frameworks should be used more widely to guide the deployment of new ALPS instruments at locations that can maximize their contributions to improved ocean-sea ice state and parameter estimation.

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Authors

An T. Nguyen, Institute for Computational Engineering and Sciences, University of Texas at Austin, TX, USA, atnguyen@ices.utexas.edu

Patrick Heimbach, Institute for Computational Engineering and Sciences, Institute for Geophysics, and Jackson School of Geosciences, University of Texas at Austin, TX, USA, heimbach@utexas.edu

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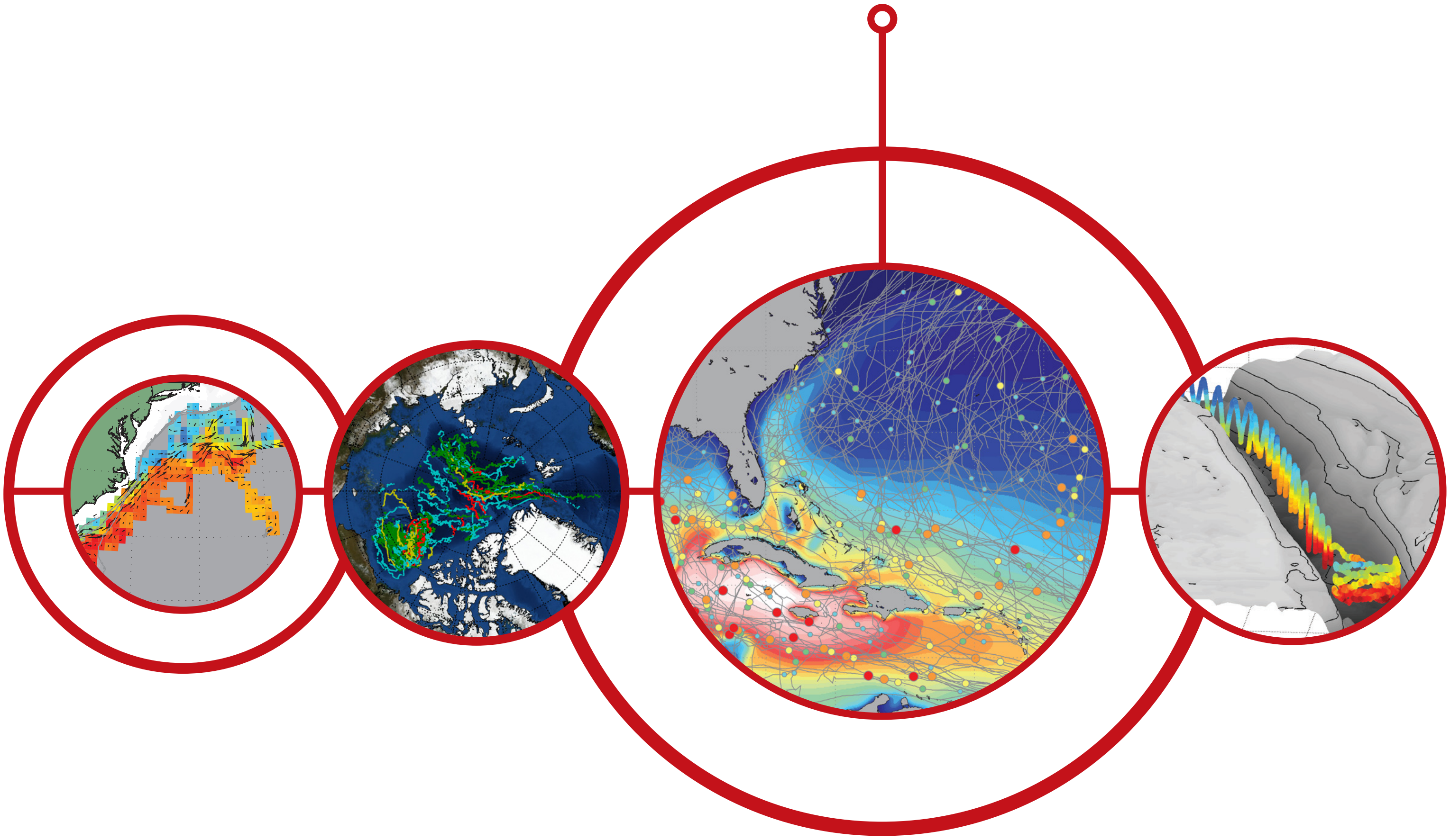

ALPS in the Arctic Ocean

Mary-Louise Timmermans, Rick Krishfield, Craig Lee, and John Toole

Arctic ALPS should exploit synergy between the various platforms and approaches to maintain operations across the full range of seasonal conditions, from ice-free open water, through marginal ice zone conditions, to fully sea-ice covered. Ice-based ALPS, a critical tool for Arctic observing, must evolve in response to the anticipated continuing loss of multiyear sea-ice floes.

For decades, sea ice has been used successfully to support ALPS in the Arctic Ocean to monitor atmospheric, snow, sea-ice, and ocean properties year-round and in some cases across the entire Arctic basin. Because the Arctic is warming substantially faster than the global average and sea-ice decline is projected to continue, there is a critical need for sustained observations of this rapidly evolving system to characterize and understand the changes. How will solar absorption, ocean heat storage, and ocean/atmosphere heat advection influence the sea-ice cover in the future? What are the associated feedbacks (e.g., ice albedo) and how are they changing? What processes control the upper Arctic Ocean stratification and freshwater content, and how will these change? How will the Arctic Ocean marine ecosystem and carbon cycle respond to the reduced sea-ice cover? Beyond science issues, uninterrupted observations of the Arctic system will become increasingly needed for forecasting and monitoring (e.g., pollutant dispersal) as the Arctic becomes more accessible to shipping and other activities such as resource exploration and extraction (NRC, 2014).

Although sea ice can impede sustained observation of the Arctic Ocean, conventional approaches to observation such as ships and profiling floats, and instrument systems mounted on or in sea ice have been immensely effective. For example, since the 1970s, the Arctic Ocean Buoy Program, later designated the International Arctic Buoy Program (IABP), has been returning sea-ice motion information, as well as atmospheric pressure and temperature information throughout the Arctic. These data have proven to be key to weather forecasting at high northern latitudes. Since publication of the first ALPS workshop report in 2003 (Rudnick and Perry, 2003), the variety and number of ice-based platforms and sensors have increased considerably, many of which were impelled by the International Polar Year (IPY) in 2007–2008. Systems currently operational include the Ice Mass Balance buoy (IMB, Perovich et al., 2013; a similar system is described by Jackson et al., 2013), designed for operation in multiyear sea ice to measure changes in sea ice and snow thickness, and the Autonomous Ocean Flux Buoy (AOFB; Shaw et al., 2008) that returns estimates of turbulent fluxes of heat, salt, and momentum at around 4 m below the ice-ocean interface. Recent enhancements to the AOFB system include sampling of the atmospheric boundary layer and ocean mixing measurements in the halocline. Several variants of under-ice sampling systems are also being fielded, including the Ice-Tethered Profiler (ITP, Toole et al., 2017), POPS (Kikuchi et al., 2007), Integrated Arctic Ocean Observing System (IAOOS) profiler (Provost et al., 2015) and the Measuring the Upper layer Temperature of the Polar Oceans (UPTEMPO) and Ice-Tethered Mooring (ITM) buoys. These systems typically provide ocean profiles (or samples at discrete depths) of salinity, temperature, and pressure from just below the ice-ocean interface to as much as 750–1,000 m depth. Some of these systems additionally sample dissolved oxygen (DO; Timmermans et al., 2010), bio-optical properties (Laney et al., 2013), and velocity (including mixed-layer turbulent fluxes; Cole et al., 2014). Another important development relates to predictions of air-ice-ocean CO_2 fluxes and ocean acidification, which is being addressed by interfacing CO_2 and DO sensors on these systems (Islam et al., 2016).

Advances in understanding Arctic system behavior have been made through the collocation of different ice-based systems on a single ice floe to form a multi-platform Ice-Based Observatory (IBO). The combination of data from the coupled atmosphere-ice-ocean environment allows, for example, the partitioning of heat sources and attribution of sea-ice melt, and determination of freshwater sources and distribution processes. But the continued losses of large, stable, multiyear sea-ice floes is threatening the future viability of IBOs due to the difficulty of deploying buoys on thin ice, buoy survivability during ridging events, and the enhanced fracturing of thin floes, which can disperse the systems. In recent years, several individual systems have been modified to be able to operate in thinner, seasonal ice conditions. A Seasonal Ice Mass Balance Buoy (SIMB) has an enhanced buoy design in order to survive complete sea-ice melt; ongoing SIMB refinements are aimed for a capability to operate reliably through the fall freeze-up. Similarly, the surface float of the ITP system has been redesigned for open-water deployments and to withstand seasonal freeze-up (although the tether through the ice remains a potential failure point during ridging). While these design changes are advancements for individual systems, the feasibility of collocated deployments continues to be at risk.

As multiyear and thicker ice floes suitable for safe support of Arctic ALPS become scarce, summer and fall deployments of measurement systems will likely need to take place in open water, precluding establishment of IBOs. Deployments on sea ice may continue to be possible during spring aircraft operations, but with shortened lifetimes of the ice-based systems as they melt out of their host floe each summer. Future developments need to consider the design challenges and cost of a system that can withstand sea-ice growth from open water and subsequent ridging. The most practicable approach may be to devise cost-effective systems, designed with shorter lifetimes and ease of deployment in mind. This would allow for a larger number of systems to be distributed every year, increasing the odds of useful long-term data return.

ALPS that operate independent of the ice, including autonomous underwater vehicles (AUVs), gliders, profiling floats, drifters, and tagged animals (Roquet et al., 2017), provide complementary approaches that will be increasingly relied upon with further decrease of perennial ice cover. For geolocation and communication in ice-covered regions, these systems can rely on underwater acoustic networks, long used to track arrays of drifting subsurface floats (e.g., Rossby et al., 1986). A hierarchy of acoustic systems operate over a broad span of frequencies (ANCHOR Working Group, 2008). Current generation O(1 kHz) systems (e.g., Webster et al., 2015) have provided real-time under-ice navigation and telemetry over hundreds of kilometers for regional-scale studies. More complex 10–100 Hz systems would be required to provide pan-Arctic geolocation (e.g., Mikhalevsky et al., 2015). The Arctic presents challenges beyond those faced at lower latitudes, including reduced signal range due to surface ducting of sound and the resulting reflection off the rough ice bottom. Marine mammal concerns must be integral to the planning of any acoustic networks, with proper care taken to assess and mitigate potential impacts.

Profiling float technology holds promise as a scalable, cost-effective way to achieve sustained, widely distributed sampling. Argo-type air-deployable profiling floats have been fielded in the Arctic's Chukchi Sea that incorporate ice-avoidance schemes (Jayne and Bogue, 2017). Nguyen et al. (2017) show there would be significant improvements in numerical state estimates with the establishment of an Argo float program in the Arctic, finding that the additional water-column measurements would be valuable even if floats could not surface to return position information in the sea-ice covered winter months.

Long-endurance gliders provide a mobile capability that is best used for focused sampling, such as process studies and sustained observations of boundary currents, fronts, and other critical regions dominated by large spatial gradients.

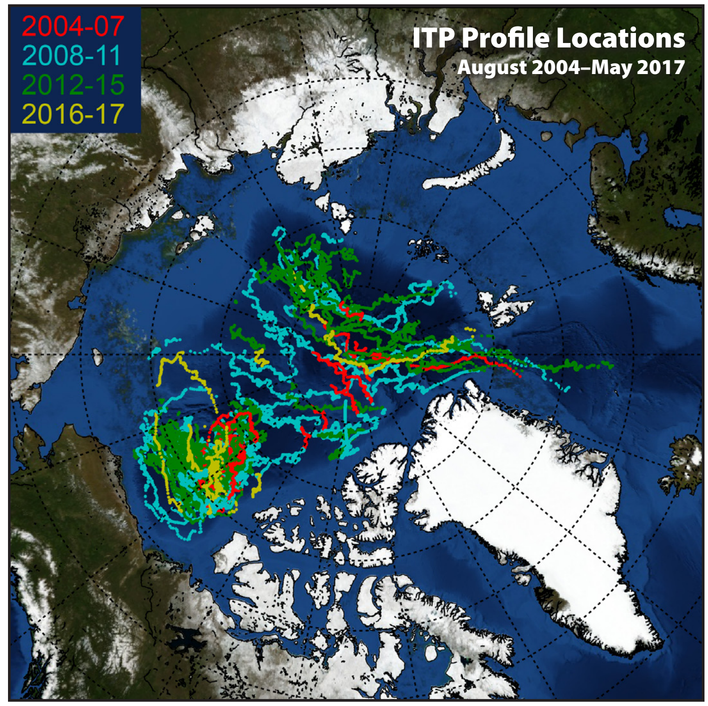

Figure 1. Map showing all ocean temperature-salinity profile locations from Ice-Tethered Profilers (ITPs) since the first ITP was deployed in 2004 through May 2017. The data coverage illustrates the absence of water-column profiles of temperature and salinity in the shallow continental shelf regions.

Acoustically navigated Seagliders with ice avoidance and enhanced autonomy have been used for year-round measurements in ice-covered straits (Curry et al., 2014) and for sampling across open water, marginal ice zone, and into the pack of the spring/summer Beaufort Sea.

While the spatial and temporal coverage of observations, as well as the types of properties sampled by ALPS, have increased in recent years, major gaps remain. A critical deficiency is the lack of year-round measurements at the continental boundaries of the Arctic Ocean (i.e., coastal margins and seas including the Chukchi, East Siberian, Laptev, Kara, and Barents Seas; Figure 1). Over 30% of the Arctic Ocean area is made up of shallow continental shelf regions. These regions are pathways for boundary currents and seasonal river influxes (carrying nutrients, heat, and freshwater), and are subject to great solar input in summer. At the same time, year-round sampling by ice-based ALPS is not feasible in boundary regions; ALPS have short lifetimes in these regions of intense seasonal variability, particularly dynamic and damaging sea-ice forcing, and strong ocean flows. A further complicating issue with respect to ALPS in the boundary regions of the Arctic and its marginal seas relates to observing in Exclusive Economic Zones. Policies and international agreements and/or partnerships need to be in place for sampling protocol and data return from these regions (see Calder et al., 2010).

An additional gap in observations that remains to be addressed by ALPS is sampling at the ice-ocean and air-ice interfaces. First-order physical and biological processes take place well within the top meter of the ocean under sea ice, which is a layer that remains particularly difficult to sample autonomously because of potential stresses to sensors of growing sea ice and ridging. Sustained physical measurements in the atmospheric boundary layer (including vertical profiles) are challenging to make autonomously (and therefore sparse) but are also essential for closing sea-ice mass and momentum budgets. The suite of sampling at these interfaces must also include incident solar radiation, gas transfer measurements, and robust bio-optical and geochemical measurements over a full seasonal cycle.

The use of ALPS to observe the Arctic Ocean in the backdrop of climate change poses new challenges and opportunities for advances. The overarching problem is how to continue sampling reliably in the face of future inevitable sea-ice losses. Ice-based observatories remain the only approach capable of simultaneously sampling atmosphere, ice, and ocean, motivating efforts to redesign these systems for operation in seasonal ice cover. Without reliable sea-ice floes, and while the Arctic Ocean and marginal seas remain entirely ice covered in winter, systems that are air-deployable may become a more practical option. Ice-free regions will be more expansive and open for longer duration, and traditional profiling floats will become viable. Mobile platforms, including long-endurance gliders and AUVs, can provide measurements that span open water, the marginal ice zone, and well into the sea-ice pack. While ice-tethered acoustic sources are becoming less feasible, bottom-moored acoustic sources can provide geolocation for platforms operating beneath the ice. Continued advances should be made through analyses of remote-sensing data in conjunction with ALPS measurements. As the Arctic region becomes more accessible to shipping and resource extraction, integration of ALPS data into models for long- and short-term forecasts and monitoring for operations (e.g., oil-spill tracking) is essential.

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Authors

Mary-Louise Timmermans, Yale University, New Haven, CT, mary-louise.timmermans@yale.edu

Rick Krishfield, Woods Hole Oceanographic Institution, Woods Hole, MA, rkrishfield@whoi.edu

Craig Lee, University of Washington, Seattle, WA, craig@apl.washington.edu

John Toole, Woods Hole Oceanographic Institution, Woods Hole, MA, jtoole@whoi.edu

ALPS in the Antarctic

Sarah Purkey and Pierre Dutrieux

Antarctica and its surrounding oceans play a critical role in global climate. The Southern Ocean circulation acts as a door into the deep ocean, driving the upper and lower cells of the meridional overturning circulation (MOC) that controls the exchange of heat, carbon, and nutrients between the surface and the deep ocean. In addition, Antarctica holds the largest reservoir of glacial ice, some of which is retreating rapidly, with large implications for sea level rise. Yet, the Antarctic region remains poorly sampled owing to harsh conditions, inaccessibility during most months of the year, and treacherous evolving icescapes. This has made Antarctica a desirable region to utilize ALPS technology to overcome existing monitoring challenges. These challenges include increased ability to navigate in complex and enclosed cavities under ice shelves, operate around and under rapidly evolving sea ice, and resolve the Southern Ocean's physical and biogeochemical spatial and temporal scales that are important to climate.

Many autonomous platforms including gliders, floats, autonomous underwater vehicles (AUVs), and animal tags have been adapted for use in this unique environment, but many impediments still lay ahead. Here we discuss some of the advancements and applications of ALPS technologies and how they might be used in the future to continue to advance our scientific understanding of the physical and biogeochemical processes operating in this unique region.

Overarching Scientific Questions

The Southern Ocean is the center of the global MOC, lifting carbon-rich waters from the deep ocean through wind-driven Ekman divergence and converting these deep waters into abyssal and intermediate water through buoyancy exchange with the atmosphere. This process results in a strong meridional gradient in the flux of heat and carbon into and out of the ocean. Despite this region's climatic importance, monitoring these fluxes and any change in the ocean reservoirs has proven difficult to determine due to limited spatial and temporal data.

Another important climatic process that occurs along the Antarctic coastline is melting of the ice shelves that buttress the flow of ice from land to the Southern Ocean. In steady state, this flow of ice is balanced by precipitation over the ice sheet. However, over the past few decades, satellite observations have demonstrated a persistent and accelerating contribution to global sea level rise from diminishing ice sheets (Shepherd et al., 2012). This ice loss is driven by oceanic melting in West Antarctica, and in particular the Amundsen Sea (Depoorter et al., 2013; Rignot et al., 2013), where ocean heat content is large and efficiently reaches the ice shelves (Jenkins et al., 2010; Jacobs et al., 2011; Dutrieux et al., 2014a) leading to growing concerns about future contributions to sea level rise and the large associated uncertainties (Scambos et al., 2017).

Floats

Core (2,000 m), Deep (6,000 m), and Biogeochemical (BGC) Argo floats are key ALPS platforms that have enabled monitoring of the Southern Ocean. The Southern Ocean remains more sparsely covered than the tropical and subtropical oceans. It has not yet reached the Argo goal of 3° x 3° spatial coverage, but better ice-avoidance technology and current scientific interest in the region are paving the way to rapid progress. A number of pilot studies have placed Argo floats under seasonal ice with great success. In addition, Argo, ALAMO, and EM-APEX floats have been placed in polynyas on the Ross Sea, the Sabrina Coast, near the Adélie Depression and the Amundsen Sea, and over Maud Rise. Some of these are locations of past and current deep-water formation while others are areas where the ocean actively melts the ice sheet. In both cases, these instruments are providing the first full-depth, full-year monitoring of these climatically essential regions.

The under-ice Argo floats are able to detect possible surface freezing conditions during their assent and can decide to not surface until conditions are more favorable. One remaining issue with these floats is the large uncertainty in profile position during the winter months given that under-ice profiles cannot get a GPS fix. Techniques for deriving under-ice position include linear interpolation, interpolation informed by numerical models, using bottom bathymetry where floats come aground, and uses of RAFOS acoustics triangulation where available.

Work is currently underway to expand the core Argo array into the deep ocean and add BGC sensors. The Southern Ocean Carbon and Climate Observation and Modeling (SOCCOM) project is currently in the process of deploying 200 Argo floats with BGC sensors (oxygen, pH, phosphate, and optics) throughout the Southern Ocean, including seasonal ice zones (see Gray, 2018, in this report). Preliminary results have already revealed seasonal cycles in carbon fluxes and shown large discrepancies in the annual net Southern Ocean carbon uptake from previous studies (Grey et al., in prep*)*. These data are being incorporated into biogeochemical models to further quantify the Southern Ocean's role in the carbon cycle (Mazloff et al., 2010). In addition, the first deep Argo floats in the Southern Ocean are planned for deployment in the Australian-Antarctic basin in January 2018, directly downstream from deep-water formation sites along the Adélie coast. If successful, this will allow for continuous and direct monitoring of Antarctic Bottom Water properties and volume near the initiation of the bottom limb of the MOC.

Finally, work is also underway to use float technologies under ice shelves. While chances of instrumental loss remain high in mostly unknown ice cavity geometries, the demonstrated persistence of floats and their low cost compared to moored instruments through ice drilled holes opens interesting possibilities for exploration and monitoring. Underwater acoustic geolocation and software development are being implemented to make such missions possible.

Gliders

Gliders have also been use to resolve the physical environment across boundaries and on the continental shelf around Antarctica. Some gliders have been deployed along the West Antarctic Peninsula to supplement annual ship-based hydrographic work to quantify pathways of relatively warm Southern Ocean deep water onto the shelf (Mckee et al., in prep) or the processes involved (Thompson et al., 2014). In addition, gliders equipped with microstructure sensors along the southern end of Drake Passage measure mixing and water mass transformation (Ruan et al., in review). Finally, sparse glider sections have mapped ocean properties near ice shelves (Miles et al., 2016).

All missions to date were conducted in summer and mostly in open water. However, some ventured, voluntarily or not, under the ice for small amounts of time, so they did not involve specific technological developments to persistently obtain observations under ice during winter. Projects are now underway to try to make progress in these areas using a combination of underwater acoustic geolocation and software development to manage complex geometries and drifts.

Instrumented Seals

Tagged marine mammals armed with temperature-salinity sensors capable of profiling under ice, with dive depths up to 2,000 m and wide rooming ranges from the coast to open water covering most of the Southern Ocean, are also currently being used to radically increase the number of CTD profiles south of 40°S. These additional CTD data greatly improve Southern Ocean assimilation models by providing under-ice data (see Roquet and Boehme, 2018, in this report). They also provide crucial winter observations in areas that are mostly devoid of them (Årthun et al., 2012; Heywood et al., 2016; Williams et al., 2016). One major issue with these data is sensor accuracy. Current and ongoing work to improve the precision and accuracy of the sensors has shown promising results, and animal platforms will likely be a major source of quality Southern Ocean data in the future.

Autonomous Underwater Vehicles (AUV)

Owing to their relatively short endurance, AUVs are not yet suited for studying systems over more than a week at a time. But their large payloads and ability to reach otherwise inaccessible areas makes them platforms of choice to explore cavities under ice shelves and therefore radically expand on the visions previously obtained from point observations. Following a preliminary loss of Autosub2 under the Fimbul ice shelf (Nicholls et al., 2008), Autosub3 successfully mapped over 500 km of ocean properties (Jenkins et al., 2010), seabed (Graham et al., 2013), and ice shelf base (Dutrieux et al., 2014b) geometries under Pine Island ice shelf in West Antarctica in the austral summer of 2009 and 2014. These first, detailed observations of two unexplored cavities will undoubtedly inspire many others using similar technologies, and many groups are preparing to do just that.

Other platforms with similar technologies and payloads have also been deployed near and under Antarctic ice shelves and sea ice. The majority remain tethered for insurance purposes or to test future deployment and retrievals through ice shelf drilled holes. These more local explorations are limited to a few kilometers from where they are deployed, but offer very interesting perspectives to explore detailed boundary layer processes as well as the local biogeochemistry.

Challenges for the Next Decade

While the past decade has seen amazing advances in the use of floats, gliders, AUVs, and tagged animals, challenges remain to fully utilize ALPS technology to monitor Antarctica and the Southern Ocean. Some of the key issues to address in the coming decade include:

- Improved coverage of Core (>2,000 m) and Deep (>6,000 m) Argo throughout the Antarctic oceans, including under seasonal ice for full monitoring of the Southern Ocean
- Improved estimates of the positions of under-ice Argo floats
- Continuous monitoring of Circumpolar Deep Water circulation near and under ice to improve our understanding of ocean driven basal melting
- Monitoring Antarctic Bottom Water formation regions and understanding the processes controlling production rates
- Improved accuracy of marine mammals data to reach Argo standard of quality

The deployment of ALPS technology in Antarctic settings remains expensive and fraught with danger for the instruments. Yet experience has been gained, and recent explorations have demonstrated that the scientific benefits largely outweigh potential losses. Thus, we are sure to see a continuation in the positive trajectory of the use of ALPS technology in and around Antarctica in the coming decade.

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Authors

Sarah Purkey, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA, spurkey@ucsd.edu

Pierre Dutrieux, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, USA, pierred@ldeo.columbia.edu

ALPS in Coastal Oceanography

Nicholas Nidzieko, Catherine Edwards, and Robert Todd

Coastal ecosystems contain energetic and diverse habitats that are a challenge to observe. An overarching goal for researchers working in the coastal zone is to understand the interaction between continents and the global oceans. What are the fates of terrestrial materials in the ocean? How do open-ocean processes affect the physics, chemistry, and biology of the coastal margin? What ecological and evolutionary processes are at work in these habitats? The range of spatial and temporal scales that must be sampled to answer these questions can be difficult to achieve with traditional sampling methods. Moorings under-resolve processes that vary across complex bathymetry, whereas shipboard sampling can be prohibitively expensive and limited by adverse weather and the ability to sample close to shore. The novel observational capabilities of ALPS have made them indispensable research tools for coastal scientists (Schofield et al., 2010; Boicourt et al., 2012). To date, coastal ALPS research applications have skewed toward studying ocean physics, but emerging sensor technologies are enabling biologists and biogeochemists to pioneer new techniques for ALPS-driven sampling. We expect that ALPS will have a major impact on coastal interdisciplinary studies, combining ocean physics, chemistry, biology, and ecology as new sensors, imaging techniques, vehicle capabilities, and sampling practices mature. In this chapter, we provide examples of how ALPS have been used in coastal research, describe some of the challenges for their operation, and consider how these opportunities and limitations might evolve in the future.

In the middle to inner continental shelf, common research questions focus on cross-shore and alongshore fluxes of momentum and materials, air-sea momentum transfer, benthic fluxes of sediment and organic matter, and fisheries ecology. Many platforms are used for such studies, including drifters, gliders, and propeller-driven autonomous underwater vehicles (AUVs). For all of these platforms, the main operational risks include collision with both commercial and recreational traffic, as well as entanglement, damage, or accidental bycatch from fisheries activity. With increasing distance from shore, communications become limited by satellite bandwidth, and recovery challenges increase.

There is a long history of using Lagrangian drifters to track coastal and nearshore circulation (Stevenson et al., 1969, 1974; Davis, 1985). Coastal drifters are typically deployed at a fixed depth in a small array, often with the expectation of recovery. The movement and deformation of the array is used to calculate mean flows, dispersion, and submesoscale features (Winant et al., 1999; Rypina et al., 2016; Ohlmann et al., 2017). Drifters are particularly well suited to study the Lagrangian evolution of scalar fields such as temperature, chlorophyll, and dissolved oxygen, and quantify habitat connectivity (Carlson et al., 2016). Miniaturized Lagrangian drifters with buoyancy control (Jaffe et al., 2017) allow the vehicle to mimic behavior of larvae and other nearshore and coastal plankton.

In the past decade, gliders (and to a lesser extent AUVs) have become the primary means of mapping coastal shelf hydrographic structure (Castelao et al., 2008; Todd et al., 2009; Rudnick, 2016), harmful algal blooms (Schofield et al., 2008; Zhao et al., 2013), and hypoxia (Adams et al., 2016; Perry et al., 2013) on time scales of days to weeks. At present, the utility of buoyancy-driven gliders typically decreases as bottom depths shoal in the inner shelf: peak through-water horizontal speeds of 20–50 cm s^{-1} may be insufficient to deal with strong coastal currents. Strong stratification (e.g., due to river plumes) reduces the power of the buoyancy engine, and gliders typically require a few meters vertically to transition from descending to ascending flight. The integration of auxiliary propellers in "hybrid" gliders and ongoing work focused on adaptive path planning (Smith et al., 2010; Chang et al., 2015; Smedstad et al., 2015) will likely reduce some of these constraints in the near future.

Propeller-driven AUVs are readily capable of operating in these shallower areas as their peak speeds of more than 2 m s^{-1} are sufficient for overcoming most coastal currents. These speed gains come at the cost of deployment duration, however, and AUVs are typically deployed for hours to days. Owing to the battery requirements for propeller-driven vehicles, AUVs can carry a heavier instrument payload, including Doppler velocity logs or inertial motion units that greatly aid navigation. These advanced navigational capabilities are well matched to the need for more precise measurements of features as depths become shallower or the features of interest become smaller or more dynamic, such as thin layers (Wang and Goodman, 2009, 2010).

Closer to shore, buoyant coastal plumes from rivers and estuaries can occupy variable portions of the shelf. Because these coastal plumes can rapidly transport terrestrial material tens to hundreds of kilometers along the coast, their fate and the mechanics that drive their variability are of great interest. A variety of ALPS have been used to study these features including drifters (Warrick et al., 2007), gliders (Schofield et al., 2010, 2013) and AUVs (Rogowski et al., 2012; Figure 1).

On the inner shelf and in the nearshore, the diversity of habitats increases as benthic topography becomes more varied in composition and form as a result of, for example, kelp forests, rocky reefs, deep coral reefs, and sand flats; sediment composition varies from sand to mud with proximity to rivers. AUVs have been readily employed to map these benthic habitats (Raineault et al., 2012) and their flow structures (Jones and Monismith, 2008) and to understand how fish utilize habitats (Grothues et al., 2008; Haulsee et al., 2015). Drifters are commonly used to understand surf zone dynamics (Ohlmann et al., 2012; Herdman et al., 2017). A growing area of research uses tagged animals to carry sensors through these environments (see Roquet and Boehme, 2018, in this report). In more protected coastal waters—estuaries, fjords, barrier lagoons, and mangrove swamps—currents are swifter, bathymetry is more complex, and the risks posed by recreational and commercial vessels are more acute. Despite these challenges, AUVs have been used to study the evolution of estuarine hydrographic structure (Giddings et al., 2012; Figure 2)

Lagrangian drifters have been used to measure circulation and dispersion (Spencer et al., 2014). As with nearshore subtidal habitats, these ecosystems are ripe for rapid innovation of ALPS in support of scientific questions. With properly equipped vehicles or drifters, we will see measurements connecting biogeochemical fluxes between adjoining marshes and open channels and research that brings new insights into how estuaries are linked to open coasts. Modeling across these domains is challenging due to the need for very high grid resolution, and ALPS will provide important validation and assimilation data.

A common theme for all of the habitats and platforms mentioned above is that the energetics of these environments pose operational challenges. Drifters may remain in an area of interest for only a short period of time, gliders may be swept off course, and the ability to drive a vehicle to keep up with these currents comes at the cost of endurance. But it is this same dynamic environment that will drive innovation in the use of ALPS as part of a suite of measurement and modeling tools.

We speculate that the continuing development of ALPS technologies coupled with the emergence of low-cost electronics and sensors will drive innovation in the use of ALPS. The most significant innovations that enable new research directions will be related to operating software, vehicle design, and the development of new sensors.

Coastal research will benefit significantly from smart mission and path planning. It will become commonplace for ALPS to use numerical forecasts in order to optimize the goals of the researcher, not just with regard to power efficiency but also with regard to scientific data collection. While large-scale experiments have been conducted that incorporate planning along these lines (Curtin et al., 1993; Leonard et al., 2010), it seems likely that such capabilities will become built-in features of the next class of robot operating systems. Current research in swarm capabilities will be extended into the realm of heterogeneous fleets, which will facilitate the development of networks of ALPS (and

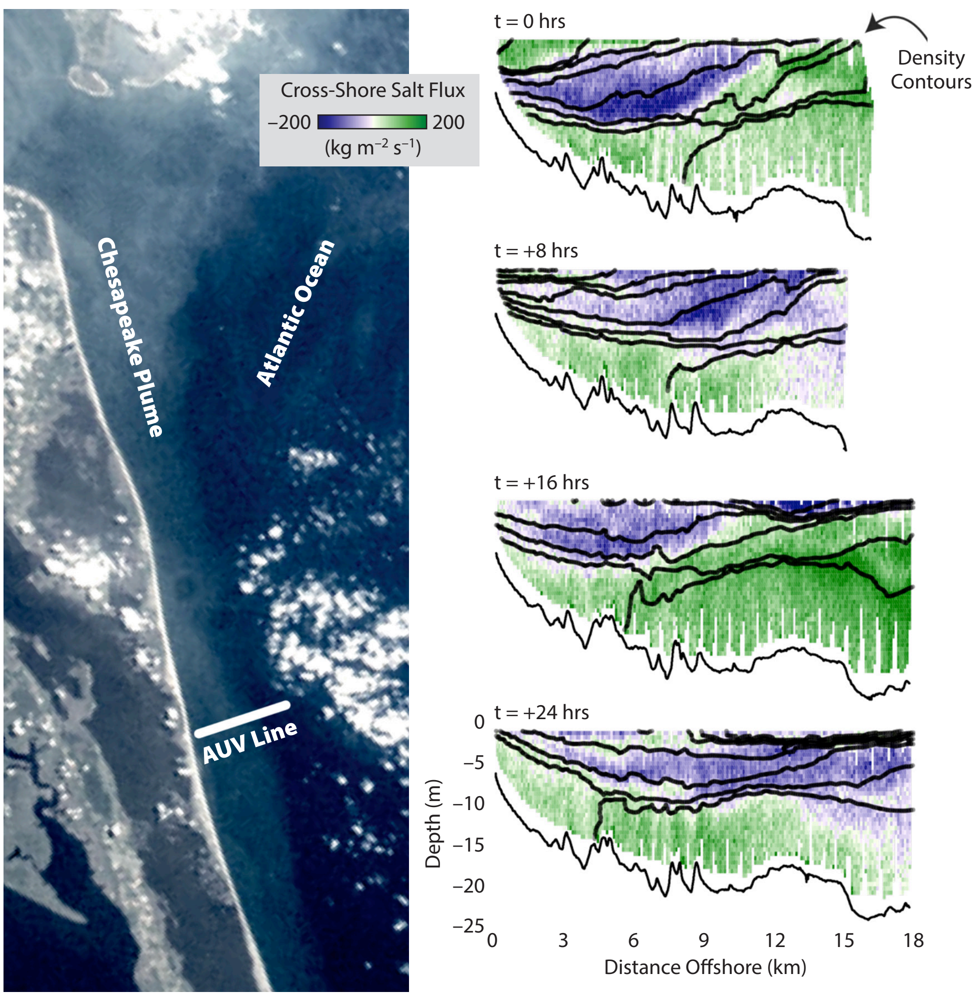

Figure 1. High-resolution observations of the buoyant Chesapeake Bay plume made with a REMUS 600 during the transition to upwelling. Four cross-shore transects over 32 hours highlight the ability of coastal ALPS to carry a suite of sensors. Here, the cross-shore salt flux (positive onshore) is computed from the onboard current profilers and vehicle profiles of salinity. The offshore extent of the transects were determined adaptively during the mission via an onboard computer.

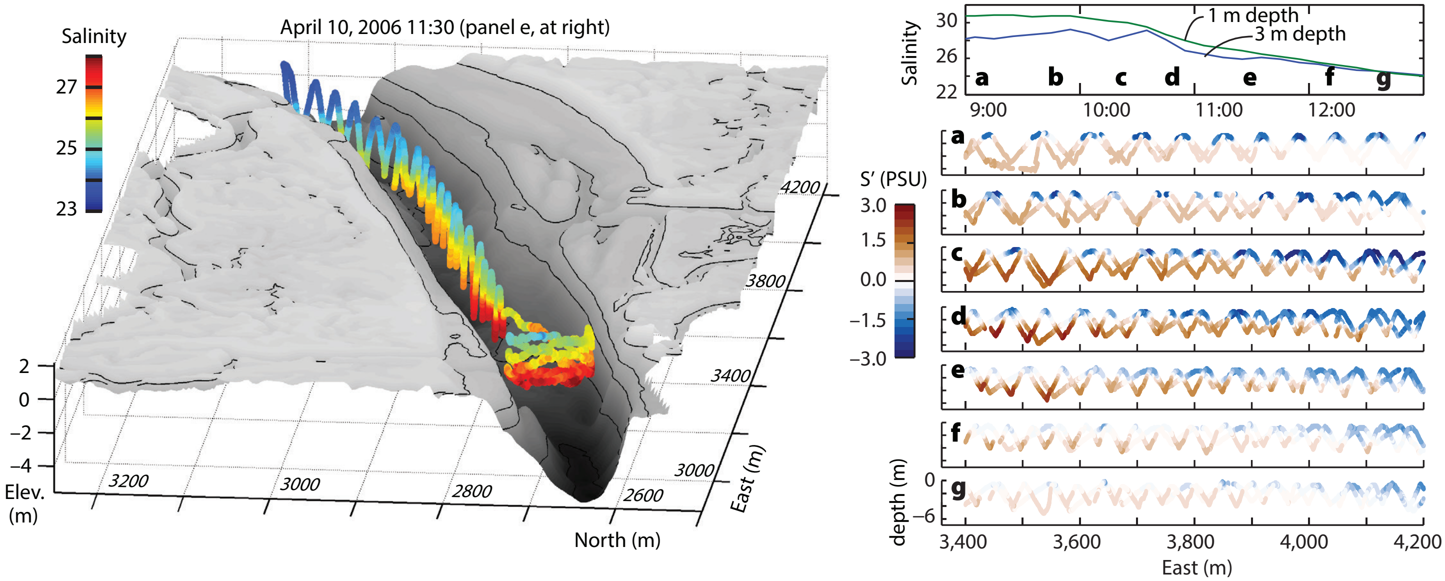

Figure 2. Repeat transects of salinity structure taken with a REMUS 100 during ebb tide in Elkhorn Slough, California, highlight the ability of autonomous underwater vehicles to operate in complex, energetic coastal environments. (left panel) Salinity observations mapped onto vehicle location, during transect in panel (e). (right panels) Time evolution of salinity deviation from mean transect salinity, S′ = S – mean(S). Time of transects is shown in top panel, with moored salinity traces from 1 m and 3 m depth.

UAVs) that can sample cooperatively, leveraging the strengths of different platforms.

More robust operating suites will enable the development new vehicle forms. One such vehicle could be a hybrid drifter/lander, in which the vehicle can selectively use forecast currents to move throughout the ecosystem, alternating between collecting moored time series at the bed, vertical profiles, and Lagrangian tracks. Another possible vehicle could follow the "flying fin" form factor of the Sentry vehicle. While existing AUVs tend to be torpedo-shaped for efficient forward travel, shortening this form and stretching the vehicle vertically increases mobility and stability, particularly with the inclusion of ducted thrusters. Such a platform would be equipped with advanced imaging equipment and capable of tracking and studying individual organisms, profiling vertically in complex terrain, and performing detailed bottom mapping. These and other ALPS will be further advanced as researchers and engineers repurpose existing and emerging sensors into oceanographic applications. These innovations will be enabled, in part, by the popularity of low-cost electronics (e.g., Arduino) and technologies developed for mobile computing and smart phones. Technological developments in the self-driving car industry will lead to a rapid expansion of biological and ecological studies where benthic imaging is important, owing to advances in image processing and new applications of machine learning. Collectively, these new capabilities will enable advanced animal behavior studies using vehicles that would typically only be possible with scientific diving.

Taken together, these technological changes may have the greatest impact on research in nearshore subtidal habitats. The maturation of image processing and recognition software will drive new research in benthic studies, and biologists and ecologists will be an important driving force of AUV capabilities. Likewise, because vegetation and steep, complex terrain pose navigational challenges to underwater vehicles in these environments, innovations that enable vehicles to better cope with these challenges will significantly advance research applications. Finally, these nearshore habitats are also ideal locations for UAVs to be used for surfzone dynamics, water sampling, low-level remote sensing applications, and wildlife surveys.

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Authors

Nicholas Nidzieko, Department of Geography, University of California, Santa Barbara, CA, USA, nidzieko@ucsb.edu

Catherine Edwards, Skidaway Institute of Oceanography, University of Georgia, Savannah, GA, USA, catherine.edwards@skio.uga.edu

Robert Todd, Physical Oceanography Department, Woods Hole Oceanographic Institution, Woods Hole, MA, USA, rtodd@whoi.edu

Boundary Current Observations with ALPS

Robert E. Todd, Daniel L. Rudnick, Luca R. Centurioni, Steven R. Jayne, and Craig M. Lee

Oceanic boundaries are where society interacts with the ocean through fisheries, transportation, oil and gas extraction, and recreation. These boundary regions are also where intense oceanic currents play a key role in the transport of mass, heat, salt, biogeochemical constituents, and plankton. In the large ocean basins, western boundary currents dominate the poleward transport of warm water or equatorward transport of cold water and are major drivers of climate variability. Eastern boundary currents are often upwelling systems that comprise some of the most biologically productive regions in the world. Boundary currents in marginal seas provide the major means of exchange with the open ocean and impact regional ecosystems. Finally, boundary currents that flow along the continental slopes mediate communication between the coast and open ocean, affecting ecosystems, flood levels, erosion, and commercial activity. Sustained observations of these highly dynamic boundary current regions are a necessary component of a global ocean observing system; over the past decade, autonomous platforms, particularly drifters, profiling floats, and gliders, have become key tools for collecting long-duration measurements in boundary currents.

Drifters have long been used to study boundary current systems (e.g., Fuglister, 1963; Davis, 1985a,b). By following the flow, either at the surface or at the depth of a drogue, networks of drifters can effectively map circulation patterns. Drifters drogued at 15 m depth, part of the Global Drifter Program (GDP; Niiler, 2001), reveal northwestern Pacific surface circulation (Figure 1), including a variety of boundary currents in both the open ocean and the marginal seas, as well as associated eddy fields. Several studies have investigated the kinematics and dynamics of boundary current systems and their interactions with marginal seas (e.g., Centurioni et al., 2004, 2009; Vélez-Belchí et al., 2013). GDP drifters are routinely equipped to measure temperature and sea level pressure (Centurioni et al., 2016) along their trajectories. A subset of GDP drifters also measures surface salinity, surface winds, subsurface temperature and pressure, and directional wave spectra; additional sensing capability may be anticipated as cost-effective sensors emerge.

The sustained, subsurface sampling provided by the network of Argo profiling floats has allowed for new insights into circulation along ocean boundaries. For example, the subthermocline circulation of the western boundary current system in the low-latitude western Pacific has been substantially revised in light of Argo observations (Qiu et al., 2015), and Argo observations have contributed to identifying the fate of the Deep Western Boundary Current in the Atlantic (Garzoli et al., 2015). Observations from Argo also capture spatial and temporal evolution along the flanks of boundary currents where there are recirculation gyres in which mode waters often form and spread (e.g., Wong, 2005; Qiu et al., 2006; Billheimer and Talley, 2013; Rainville et al., 2014) and where eddy fields are often

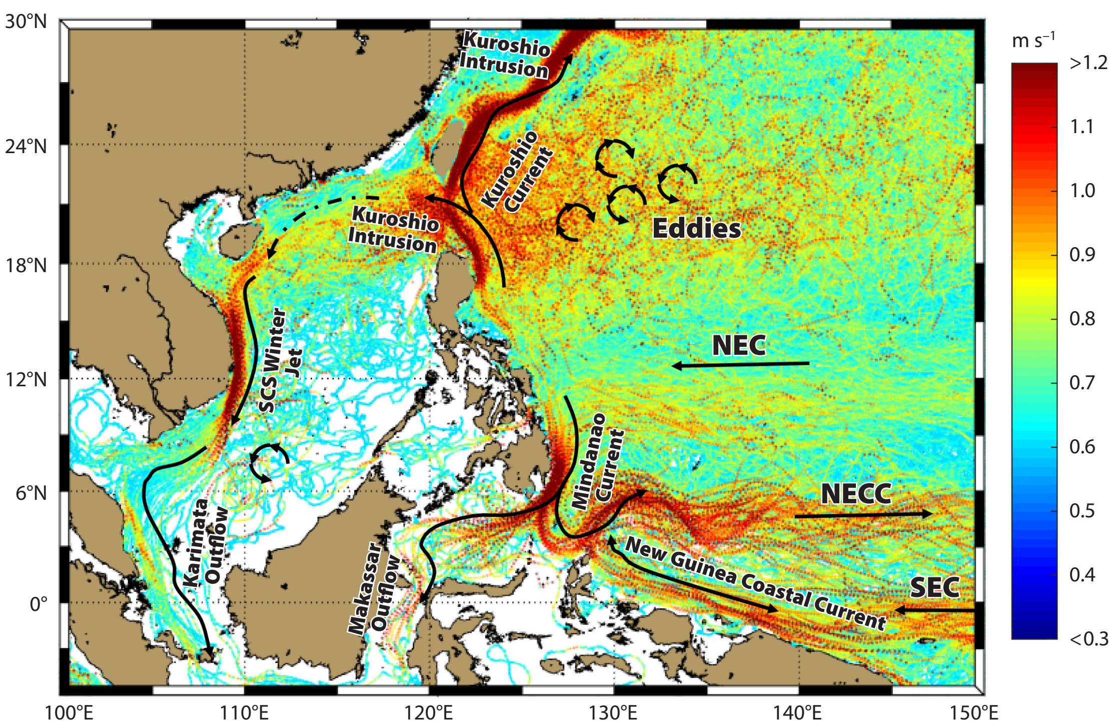

Figure 1. Trajectories and near-surface velocity estimates from Global Drifter Program drifters in the western Pacific and marginal seas. Paths of various boundary currents are clearly visible, as is the rich eddy field to the west of the Kuroshio.

particularly strong (e.g., Castelao, 2014).

Autonomous underwater gliders (Rudnick, 2016) have proven to be effective platforms for collecting sustained, high-resolution observations boundary currents. In typical use, gliders profile from the surface to 500–1,000 m, taking three to six hours to complete a cycle from the surface to depth and back. Deployments of three to six months are now routine, during which time a glider's survey track extends well over 2,000 km. Crucially, because gliders can move through the water, they are able to measure the property gradients at scales relevant to boundary current regions. Velocity, averaged over the depth a glider profile, can be estimated by differencing displacement calculated from a hydrodynamic flight model (motion in still water) from observed displacement over the dive. Absolute geostrophic velocity then can be calculated by referencing geostrophic shear, derived from lateral density gradients quantified by gliders, to these depth-average velocities. Comparisons between velocities observed from mooring arrays and glider-derived absolute geostrophic currents (e.g., Lien et al., 2014) show excellent agreement, confirming that glider-based sections can successfully quantify boundary current transports.

Gliders are routinely deployed in a variety of boundary current systems globally. The California Underwater Glider Network (CUGN; Figure 2), which consists of three cross-shore transects that have been continuously occupied for a decade (Rudnick et al., 2017), exemplifies sustained glider observations in an eastern boundary current system. CUGN observations fill a gap between the coast and Argo observations in the interior ocean (Figure 2a), and have allowed for examination of interannual variability (e.g., Figure 2b) and development of various climatologies (e.g., Figure 2c–e). Western boundary currents typically have depth-averaged currents that are significantly faster than a glider's speed through the water, so gliders surveying western boundary currents generally cross those currents obliquely. Multiyear glider surveys of the Kuroshio and Gulf Stream (Figure 3) have demonstrated the feasibility of using gliders to routinely survey across western boundary currents. While the strong and variable currents lead to less well-repeated transects (Figure 3a,c), various methods have been used to combine observations from many glider missions in western boundary currents to produce both maps of the mean flow (e.g., Figure 3b,d) and mean vertical sections (e.g., Figure 3b; Todd et al., 2016; Schönau and Rudnick, 2017). Gliders capable of full-depth profiling (e.g., Deepglider) offer the possibility of occupying

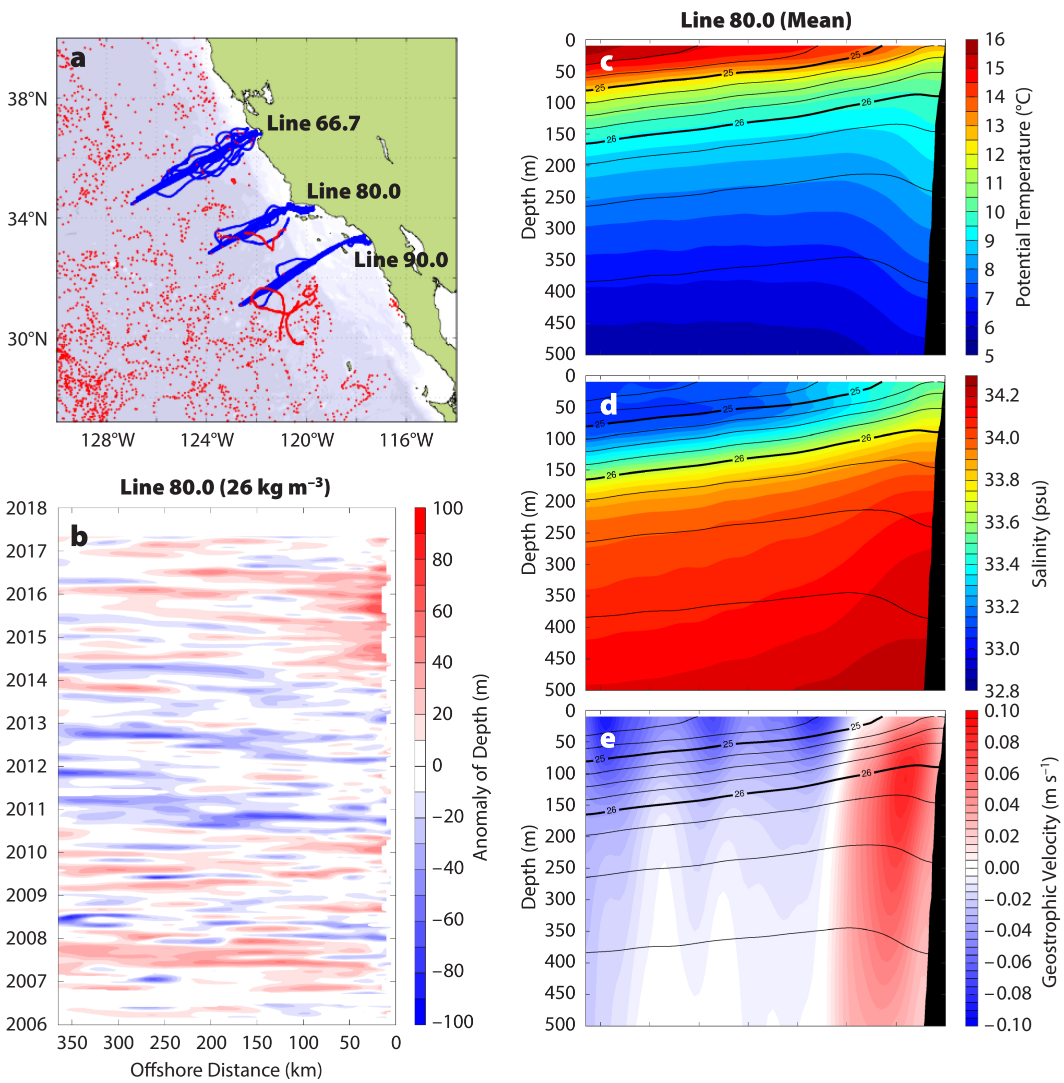

Figure 2. Observations from the California Underwater Glider Network (CUGN). (a) Trajectories of CUGN gliders along CalCOFI Lines 66.7, 80.0, and 90.0 since 2006 (blue) with locations of Argo profiles during the same time period (red). (b) Temporal variability in the depth of the 26 kg m^{-3} isopycnal relative to its mean annual cycle along Line 80.0. (c–e) Mean cross-shore transects of (c) potential temperature, (d) salinity, and (e) alongshore geostrophic velocity along Line 80.0. Panels b–e are based on the CUGN climatology of Rudnick et al. (2017) and are available from https://doi.org/10.21238/S8SPRAY7292.

transects perpendicular to a western boundary current at the cost of spatial and temporal resolution.

The numerical modeling community has expressed a need for additional observations in boundary currents to constrain models; the sustained, high-resolution observations that can be provided by ALPS are ideal for constraining and validating numerical models and have been used in a variety of boundary current regions to date (e.g., Centurioni et al., 2008; Todd et al., 2011; Rudnick et al., 2015; Schönau et al., 2015; Todd and Locke-Wynn, 2017). Drifters, floats, and gliders return observations in near-real time, thus making those observations available for operational usage. Though observations from autonomous platforms are routinely assimilated into various numerical simulations and appear to provide useful constraints, quantitative assessment of observation impact in the models remains a challenge; for instance, the importance of subsurface observations from gliders relative to that of satellite remote sensing observations for constraining frontal positions should be determined.

Autonomous and Lagrangian platforms have the potential to form the backbone of a global boundary current observing system that connects the coast and boundary currents to the interior ocean. Such a system would complement the global coverage of the Argo and Global Drifter Programs and expand the footprint of the OceanSites moorings that provide high-frequency measurements of many variables at specific sites. Building on repeated ship-based surveys, some of which have endured for decades, a boundary current observing network built on autonomous and Lagrangian platforms would allow for observations in difficult locations and conditions while improving spatial and temporal resolution. At present, sustained boundary current measurements from gliders and drifters are largely comprised of physical (pressure, temperature,

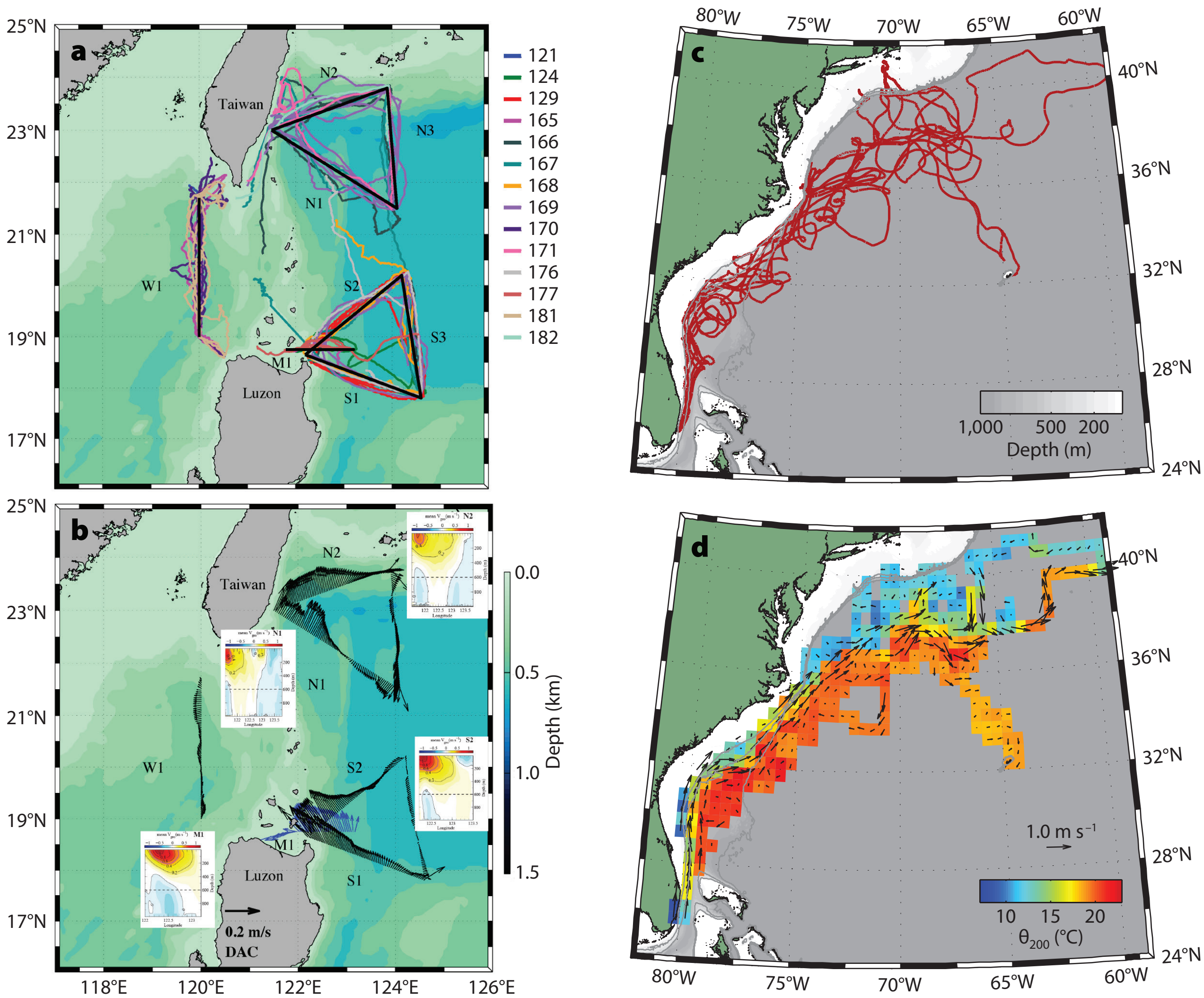

Figure 3. Multiyear glider observations in two mid-latitude western boundary currents. (a) Trajectories from 20 Seaglider missions in the Kuroshio during 2011–2013. (b) Mean depth averaged currents in the upper 1,000 m from gliders (black) and a moored array (blue) and mean cross-track geostrophic currents along select transects (insets). (c) Trajectories of 12 Spray glider missions in the Gulf Stream from 2004–2017. (d) Averages of potential temperature at 200 m and depth averaged currents in 0.5° x 0.5° boxes. (Panels c–d are adapted from Todd, 2017)

salinity, velocity) and a limited set of bio-optical or bio-acoustic properties (e.g., chlorophyll, chromophoric dissolved organic matter, acoustic backscatter, passive acoustics for mammals or fish). As additional sensors suitable for long-duration (or even expendable) deployment on autonomous and Lagrangian platforms become available (e.g., phosphate, silicate, species-level classification of plankton, biomass, or turbulence), a global boundary current observing network could become truly multidisciplinary.

Because boundary currents invariably reside within Exclusive Economic Zones (EEZs), their observation must depend upon regional efforts that are respectful of coastal countries. As such, a global boundary current observing system would consist of a coordinated set of regional observing networks. Efforts to coordinate boundary current observing at the international level are currently underway through the Global Ocean Observing System (GOOS) and related groups. For example, there is currently a growing effort to organize sustained boundary current measurements with gliders under the OceanGliders Boundary Ocean Observing Network initiative within GOOS. Included in this international coordination should be building financial support for sustained boundary current observations in coastal countries, establishment of (and support for) an Argo-like data distribution system for integrated boundary current observations, and defining protocols for public release of observations within EEZs.

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Authors

Robert E. Todd, Woods Hole Oceanographic Institution, Woods Hole, MA, USA, rtodd@whoi.edu

Daniel L. Rudnick, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA, drudnick@ucsd.edu

Luca R. Centurioni, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA, lcenturioni@ucsd.edu

Steven R. Jayne, Woods Hole Oceanographic Institution, Woods Hole, MA, USA, sjayne@whoi.edu

Craig M. Lee, Applied Physics Laboratory, University of Washington, Seattle, WA, USA, craig@apl.washington.edu

Underwater Glider Observations for Atlantic Tropical Cyclone Studies and Forecasts

Gustavo Jorge Goni, Scott Glenn, Jili Dong, Ruth Curry, Robert E. Todd, Travis Miles, Julio Morell, Hyun-Sook Kim, Becky Baltes, Glen G. Gawarkiewicz, and Joleen Heiderich

In the North Atlantic basin, tropical cyclones (TCs) originate and intensify from June to November with approximately 12 tropical storms and two to three hurricanes forming each year. These storms frequently affect highly populated coastal areas, causing large economic and social impacts (Figure 1). Under appropriate atmospheric conditions, TC intensification and weakening have been linked to ocean properties, such as upper-ocean heat content (Mainelli et al., 2008) and stratification (Seroka et al., 2016), which can be estimated using both in situ and satellite observations. Autonomous underwater gliders (Rudnick, 2016) offer cost-effective opportunities to assess these and other upper-ocean conditions by collecting targeted and sustained observations.

Several programs in recent years have used gliders to better understand air-sea processes during high-wind events, with a specific goal of improving hurricane intensity forecasts. Observations collected by these efforts are transmitted in real time to the Global Telecommunication System (GTS) and distributed through institutional web pages and the Integrated Ocean Observing System Glider Data Assembly Center. Delayed-time data are also used for in-depth analysis and studies of ocean-atmosphere interactions due to hurricane-force winds. Glider missions have already returned tens of thousands of profiles of temperature, salinity, dissolved oxygen, and chlorophyll. Data sets obtained from these missions include unique temperature and salinity observations sampled under tropical cyclone wind conditions for Tropical Storm (TS) Barry (2007), Hurricane Irene (2011), Hurricane Sandy (2012), Hurricane Arthur (2014), TS Bertha (2014), Hurricane Gonzalo (2014), Hurricane Fay (2014), TS Erika (2015), Hurricane Joaquin (2015), Hurricane Hermine (2016), and Hurricane Matthew (2016). This article describes these efforts and their principal scientific accomplishments with the intent of laying the foundation for a coordinated, distributed and sustained observation system to improve TC research and forecasting capabilities.

Caribbean Sea and Tropical Atlantic Ocean

Glider operations along predetermined tracks off Puerto Rico in the Caribbean Sea and tropical Atlantic Ocean are conducted by the National Oceanographic and Atmospheric Administration (NOAA) Atlantic Oceanographic and Meteorological Laboratory (AOML) in conjunction with the Caribbean Coastal Association for Coastal Ocean Observations (CARICOOS). TC Gonzalo developed in the tropical North Atlantic on October 12, 2014, and then passed ~85 km northeast of the location of one of these gliders as it intensified from a Category-2 hurricane into a

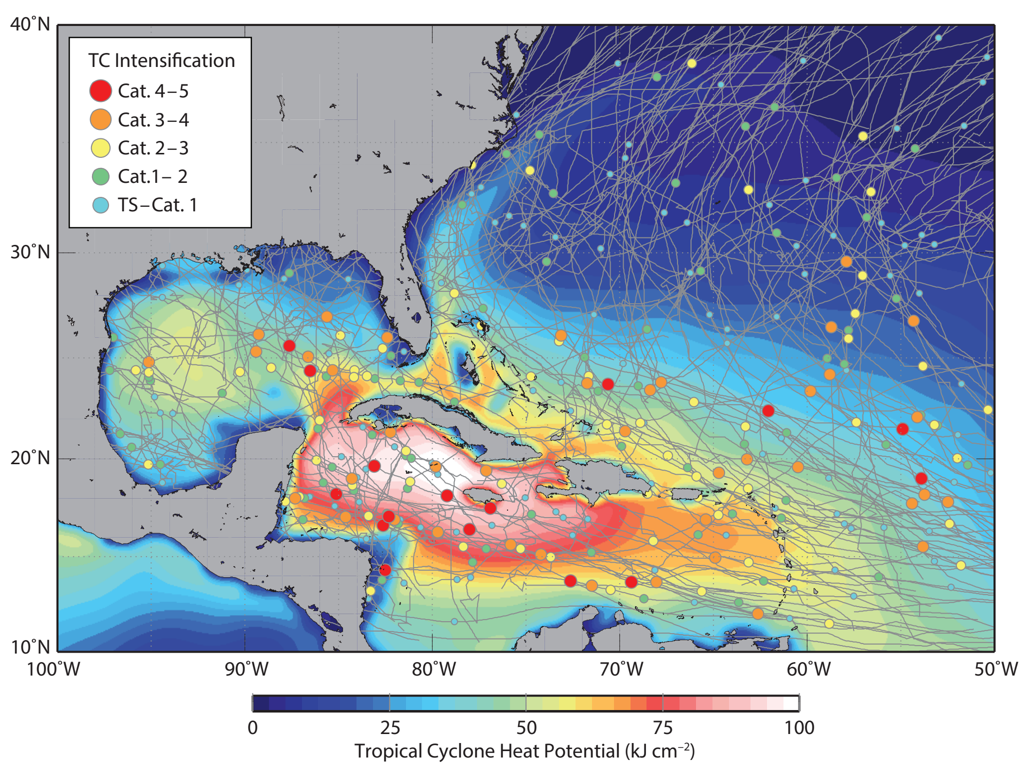

Figure 1. Atlantic hurricane tracks during the period 1993–2010, with color circles indicating the position where they intensified. The background color shows the average Tropical Cyclone Heat Potential during the same period. *From Goni et al. (2017)*

Category-3 hurricane. As Gonzalo passed north of Puerto Rico, sea surface temperature cooling was largely suppressed by the presence of a low-salinity layer in the upper 20 m of the ocean (i.e., a barrier layer). Maximum observed upper-ocean cooling was limited to 0.4°C when Gonzalo was closest to the glider. The presence of this barrier layer may have favored the storm's intensification; Gonzalo continued intensifying into a Category-4 hurricane (Goni et al., 2015). Glider observations collected before, during, and after the passage of Gonzalo were assimilated into the high-resolution Hurricane Weather and Research Forecast (HWRF)-Hybrid Coordinate Ocean Model (HYCOM) coupled forecast system at the NOAA Environmental Modeling Center to assess the impact of underwater glider and other ocean observations on Hurricane Gonzalo intensity forecasts. Results indicated that assimilation of underwater glider observations significantly improved the pre-storm thermal and saline model initializations, in particular of the barrier layer (Figure 2a,b). The main result of this work was that the errors in maximum wind speed and minimum pressure for the 126-hour forecast when its center was northeast of Puerto Rico were reduced by 50% to 90% (Figure 2c–e) by assimilating underwater glider data and conventional ocean observations, including satellite altimetry observations.

Subtropical North Atlantic

In October 2014, Hurricanes Fay and Gonzalo hit Bermuda during the same week. One glider deployed by the Bermuda Institute of Ocean Sciences (BIOS) two days after the passage of Fay was directly under the eyewall of Category-3 Hurricane Gonzalo. Within the cold wake created by the two TCs, gliders observed a 4°C surface temperature drop, a 50 m deepening of the mixed layer, and breaking internal waves along its boundary. Each storm resulted in heat storage reductions of approximately 3–4 J m^{-2} in the upper 250 m. Surface heat flux was a factor in the intensification of Fay from a tropical storm to a hurricane as it passed Bermuda. A key result obtained from the glider observations is that Hurricane Gonzalo weakened from Category-4 to -3 as it traveled over the cold wake produced by Hurricane Fay (Figure 2a).

Middle Atlantic Bight Shelf

The passage of TCs over the continental shelf of the Middle Atlantic Bight has been observed by gliders for several years. Rutgers University conducted glider missions during hurricanes Irene (2011) and Sandy (2012). Observations during Hurricane Irene (2011) revealed that ahead-of-eye-center surface cooling and thermocline deepening may have contributed to weakening of this cyclone over the continental shelf (Glenn et al., 2016). In addition, onshore wind stress ahead of the storm caused two-layer circulation under stratified summer conditions on the continental shelf and resulted in shear-induced mixing across the thermocline that led to surface cooling. Sensitivity studies in an atmospheric model showed that this rapid surface cooling and resulting air-sea flux changes contributed to the weakening of Irene before landfall (Seroka et al., 2016).

A glider deployed five days ahead of the forecast landfall location of Hurricane Sandy (2012) on the New Jersey coast also carried an acoustic Doppler current profiler to measure vertical shear to assess the upper-ocean mixing. Observations showed that downwelling-favorable winds as Sandy approached limited the supply of cold bottom waters to be mixed upward, and surface cooling was limited to 1°–2°C (Zambon et al., 2014), contributing only slightly to the weakening of Sandy over the continental shelf. In the aftermath of Hurricane Sandy, the multi-institution TEMPESTS program was initiated to collect observations that would improve forecasts of the intensity of storms impacting the US Northeast.

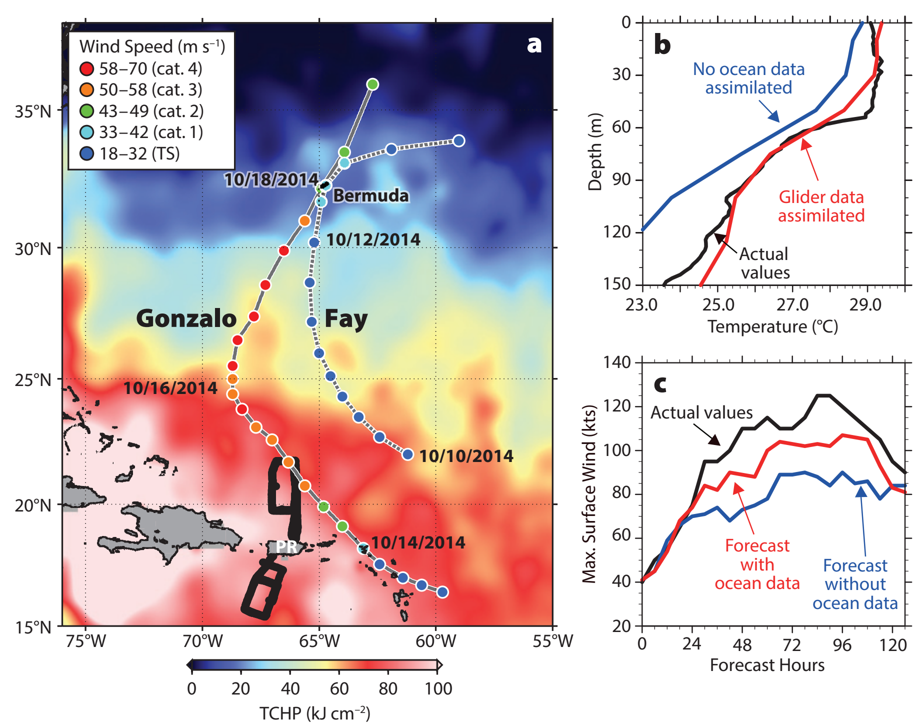

Figure 2. (a) Underwater glider transects (black lines) superimposed to the altimetry-derived upper-ocean heat content (Tropical Cyclone Heat Potential) for mid-October 2014, with Hurricane Gonzalo (2014) and Fay (2014) tracks (circles). (b) Impact of a glider temperature profile in the initialization of HWRF-HYCOM. (c) Impact of glider and other ocean data to reduce error in tropical cyclone intensity (maximum wind speed) during the forecast of Hurricane Gonzalo tested on October 13, 2014. *From Goni et al. (2017)*

Rutgers University, Woods Hole Oceanographic Institution, the University of Maine, and University of Maryland each operated gliders in rapid-response mode during the 2014–2016 hurricane seasons. These gliders measured the continental shelf response to Hurricanes Arthur (2014) and Hermine (2016). Both storms caused cooling, mixed layer deepening, and westward flow over the continental shelf. Hurricane Arthur traveled through the region much more quickly than Hurricane Hermine, which stalled and dissipated south of New England; only Hermine produced inertial oscillations following its passage (Figure 3).

Gulf of Mexico

Several glider observational and analysis efforts are currently in place in the Gulf of Mexico. During the 2012 and 2013 summer seasons, a collaborative effort between NOAA, universities, and private industry included the validation of NCEP global RTOFS (global operational Real-Time Ocean Forecast System at the NOAA National Centers for Environmental Prediction) forecasts using available glider observations in the northern central Gulf of Mexico. The purpose of this work was to carry out targeted observations of the ocean conditions before, during, and after the passage of a hurricane and to conduct assessments of RTOFS. Comparison results show that ocean model upper conditions agreed with the observations, having highly correlated sea surface temperature, mixed-layer depth, and depth of 26°C isotherm, with RMS differences of 0.4°C, 8 m, and 19 m, respectively. From 2010 to 2013, gliders operating under this effort collected more than 2,100 profiles to 1,000 m depth, and covered a distance of over 2,400 nautical miles in the Gulf. In addition to temperature and salinity measurements, gliders also collected water column salinity, dissolved oxygen, and chromophoric dissolved organic matter.

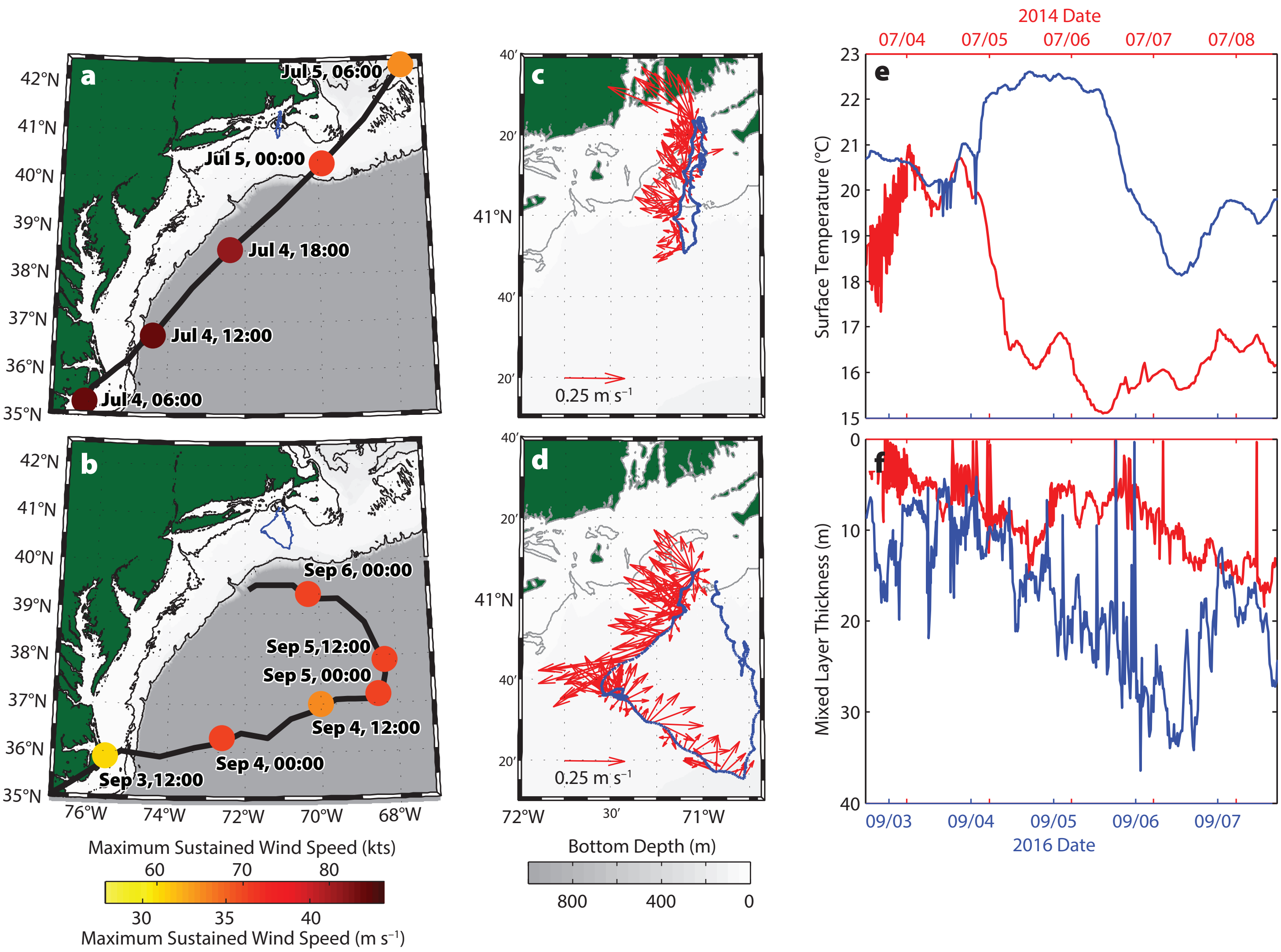

Figure 3. Glider observations of the effects of Hurricanes Arthur (2014) and Hermine (2016) in the Middle Atlantic Bight. Tracks of (a) Arthur and (b) Hermine with maximum sustained winds indicated by colors and tracks (blue) of Woods Hole Oceanographic Institution-operated gliders deployed in response to the storms. (c–d) Vertically averaged currents measured by the gliders before, during, and after the storms as the gliders moved offshore; only Hermine generated inertial oscillations (d). Time series of (e) surface temperatures and (f) mixed layer thicknesses measured by the gliders during Arthur (red) and Hermine (blue). *From Goni et al. (2017)*

Outlook and Recommendations

Gliders deployed in the tropical Atlantic during hurricane season continue to provide key upper-ocean observations to initialize numerical ocean-atmosphere coupled forecast models, to properly identify areas that may be responsible for storm weakening and intensification, and to improve intensity forecast model output. In addition, gliders provide a means to better understand the processes responsible for the rapid evolution of the ocean and its important feedback on the atmosphere during the passage of cyclones. In 2017, glider deployments are planned in the Caribbean, the Gulf of Mexico, and along the entire US East Coast during the Atlantic hurricane season; observations collected under a variety of programs will be coordinated under the NOAA Hurricane Field Program.

Though gliders have been successfully deployed in rapid-response mode ahead of storms in the Middle Atlantic Bight, the logistical hurdles for such operations are significant. With lead times typically less than one week based on forecast accuracy, gliders used in rapid-response mode are usually deployed within two to three days of storm arrival. This short lead time prevents comprehensive measurement of pre-storm conditions (e.g., complete cross-shelf transects) and suboptimal placement of gliders during storm passage. Sustained glider operations during the storm season (such as in those currently in place in the Caribbean Sea and near Bermuda) have provided critical information to appropriately initialize numerical ocean models during pre-storm conditions. Given the positive impact of the upper-ocean observations collected by these projects, the following recommendations are provided to further increase their contributions with the aim of improving Atlantic hurricane intensity studies and forecasts:

- Continue to assess the impact of glider observations in conjunction with observations from other components of the ocean observing system, to determine the most appropriate and cost-effective sampling strategies
- Maintain or enhance the Caribbean Sea, Gulf of Mexico, and tropical North Atlantic glider network to enable impact assessment studies
- Further investigate the impact of implementing a comprehensive underwater glider rapid response to aid in the monitoring of upper ocean heat content assessments prior to the passage of Atlantic hurricanes
- Conduct numerical ocean simulation experiments to assess the impact of glider data, and all upper-ocean thermal data, on Atlantic hurricane intensity forecasts
- Include additional sensors on the gliders, when possible, to enable multidisciplinary studies geared toward assessing the impact of hurricanes on ecosystems, carbon dioxide fluxes, fisheries, etc.

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Authors

Gustavo Jorge Goni, Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, Miami, FL, USA, gustavo.goni@noaa.gov

Scott Glenn, Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ, USA, glenn@marine.rutgers.edu

Jili Dong, Environmental Modeling Center, National Oceanic and Atmospheric Center, College Park, MD, USA, jili.dong@noaa.gov

Ruth Curry, Bermuda Institute of Ocean Sciences, St. George's, Bermuda, ruth.curry@bios.edu

Robert E. Todd, Woods Hole Oceanographic Institution, Woods Hole, MA, USA, rtodd@whoi.edu

Travis Miles, Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ, USA, tnmiles@marine.rutgers.edu

Julio Morell, University of Puerto Rico, Mayaguez Campus, Mayaguez, Puerto Rico, julio.morell@upr.edu

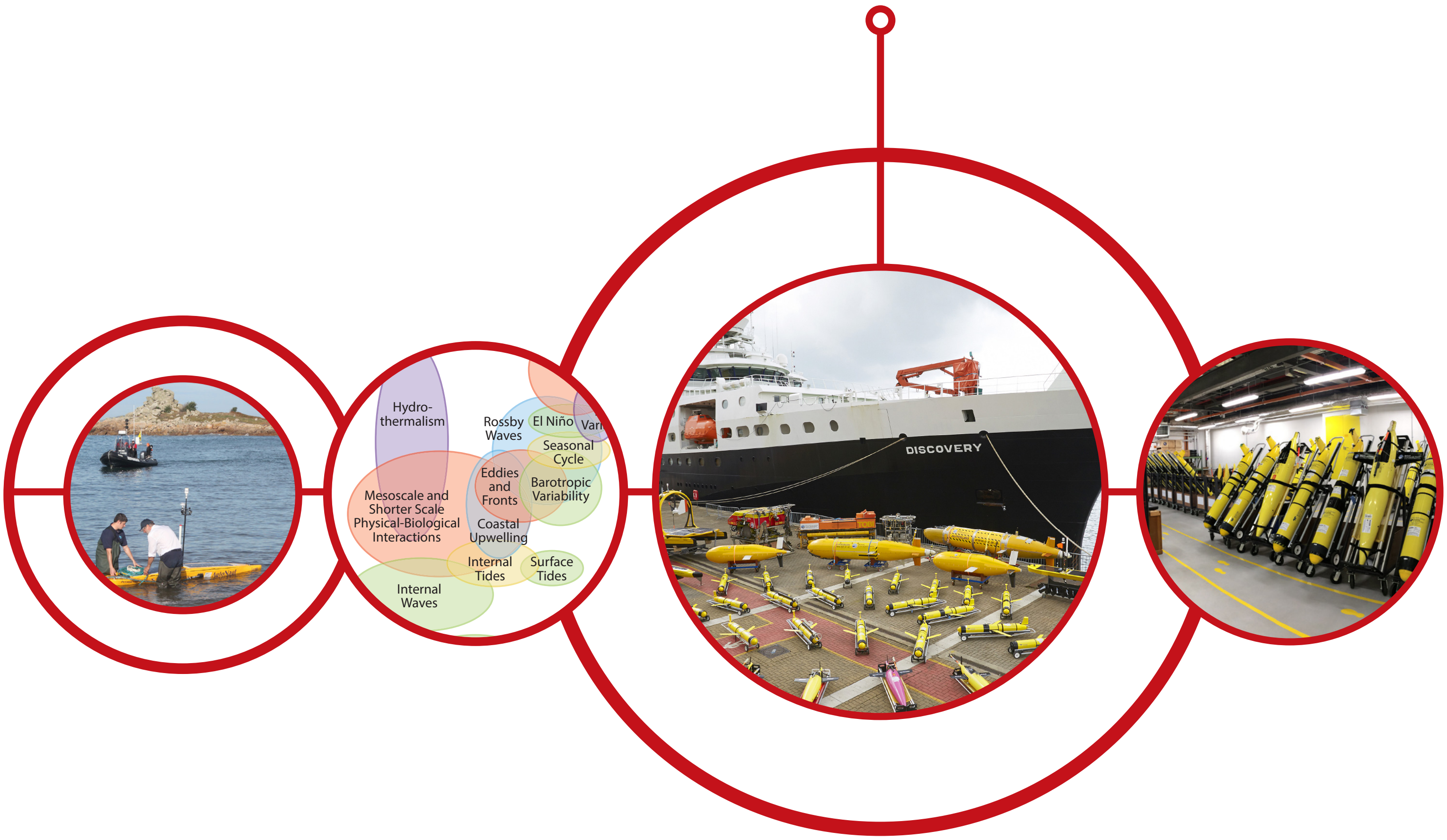
Hyun-Sook Kim, Environmental Modeling Center, National Oceanic and Atmospheric Center, College Park, MD, USA, hyun.sook.kim@noaa.gov

Becky Baltes, US Integrated Ocean Observing System Program, National Oceanic and Atmospheric Administration, Silver Spring, MD, USA, becky.baltes@noaa.gov

Glen G. Gawarkiewicz, Woods Hole Oceanographic Institution, Woods Hole, MA, USA, gleng@whoi.edu

Joleen Heiderich, MIT-WHOI Joint Program, Woods Hole Oceanographic Institution, Woods Hole, MA, USA, joleenh@mit.edu

Infrastructure



Developing the Infrastructure for a World-Class Marine Robotics Fleet

A Case Study from the UK National Oceanography Centre

Russell B. Wynn and David White

Introduction

The rapid uptake of marine autonomous systems (MAS) by research institutes, offshore industry, and government agencies across the globe is raising the questions of how best to manage and operate these new technologies, and how to integrate them with existing observational tools such as ships and moorings. Here, we provide an overview of how the UK has focused investment and resources on a centralized MAS facility based at the National Oceanography Centre (NOC; Figure 1), and how this facility is being used to provide a "capability pathway" to industry and government partners who are also looking to invest in MAS fleets.

History

The National Oceanography Centre was established in 1995 and is owned by the Natural Environment Research Council (NERC), the main environmental science funding body in the UK. NOC employs ~560 staff across two sites in Southampton and Liverpool, and is widely regarded as one of the top six oceanographic institutes globally, particularly for integrated marine science and technology in the deep ocean. For example, NOC developed the Autosub autonomous underwater vehicle (AUV) in the late 1990s that has been used for over 200 pioneering deep-ocean and under-ice missions.

In 2012, NERC transferred its MAS assets into the UK National Marine Equipment Pool (NMEP), and NOC was given the responsibility of running this new MAS capability alongside existing NMEP assets (including two ocean-going research vessels). This decision was partly in response to several UK research organizations purchasing new submarine gliders with NERC funds and operating them independently, which was potentially inefficient and hard to monitor. By placing new and existing MAS platforms within the NMEP, NERC ensured they would be available to the wider UK research community and that usage statistics could be monitored. NOC subsequently established the Marine Autonomous and Robotic Systems (MARS) group within its National Marine Facilities (NMF) division to provide a focus for MAS development and operations, and to bring together the existing remotely operated vehicle (ROV), AUV, and submarine glider teams into one group.

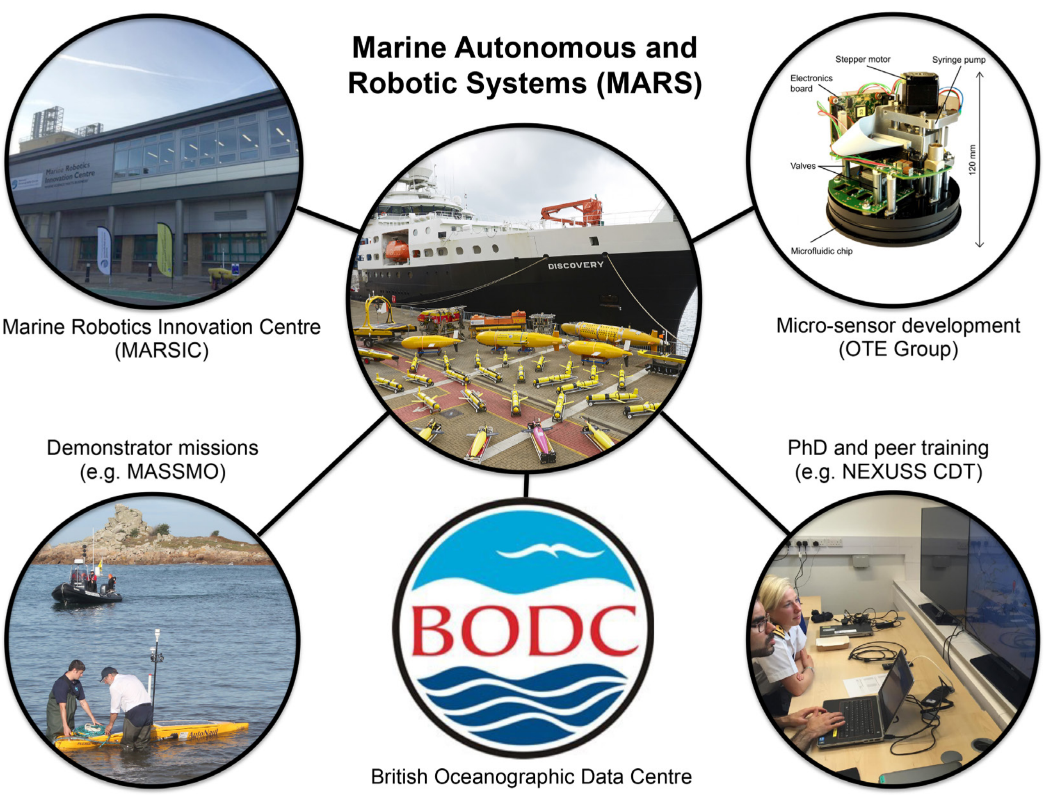


Figure 1. The marine autonomous systems infrastructure based at the UK National Oceanography Centre.

A Focus for Investment

As a result of the recent global upsurge in MAS products and applications, the UK government recognized the potential for driving economic growth in this area. Consequently, the NMF-MARS facility at NOC is providing a focus for >£25M of capital investment in MAS platforms, sensors, and software in the period 2012–2021. The aim is to establish a world-leading MAS fleet that will both deliver cutting-edge technology to the UK research community, and provide opportunities for UK government and industry partners to exploit and uptake the technology. The NMF-MARS fleet currently comprises almost 50 individual platforms (Figure 1), making it the largest MAS research fleet in Europe. It includes more than 30 submarine gliders, four unmanned surface vehicles (USVs), two tethered deep-ocean ROVs, and the Autosub family of AUVs. This fleet is supported by a rapidly growing team of ~40 development and operations engineers.

Although NOC now provides a focus for UK MAS development and operations, it should be noted that additional MAS assets (mostly submarine gliders) are still operated by research partners at the British Antarctic Survey (BAS), the Scottish Association for Marine Science (SAMS), and the University of East Anglia (UEA). NOC also hosts a rapidly expanding Ocean Technology and Engineering (OTE) group that has world-leading expertise in development of miniaturized biogeochemical sensors (Figure 1). Together with other UK research organizations, this group is producing a pipeline of innovative sensors that are typically platform-agnostic and can therefore be deployed across the NMF-MARS fleet.

Supporting the UK Research Community

Any UK researcher can apply to access NMEP assets for specific projects, including NMF-MARS vehicles and associated technical support. Once an application is submitted and the project funded (either by NERC or another funding body), the principal investigator (PI) will work with the NERC program group to define and schedule the mission. This "bidding" process originally revolved around requests for ship time and associated ship-deployed vehicles, but has evolved rapidly as researchers are increasingly requesting smaller MAS platforms that can be deployed from shore or from small vessels. The PI is expected to pay for user costs from their funding source, for example, glider batteries or Iridium data transfer, but all other costs (including NMF-MARS staff resources) are paid for centrally by NERC as part of an annual allocation. NMF-MARS supports all research projects irrespective of their funding source, but NERC- and EU-funded science projects are given highest priority in the program (combined these account for >90% of applications).

The level of operational support provided to researchers by NMF-MARS varies between projects, with less-experienced users requiring the full spectrum of support from vehicle setup through to deployment/recovery, piloting, and data transfer. NMF-MARS also provides development support to the community, through design and build of new AUV platforms, for example, Autosub Long Range (aka "Boaty McBoatface") and integration of novel sensors onto vehicles to meet specific project requirements. In addition, the NOC site at Liverpool hosts the British Oceanographic Data Centre (BODC; Figure 1), which provides a centralized, secure, and long-term repository for all data collected using NMF-MARS assets, and ensures it is subsequently available to the UK end-user community for future use.

Supporting UK Government and Industry

To ensure that the significant levels of capital investment in the NMF-MARS fleet generate economic benefit for UK industry and government, NOC built a £3M Marine Robotics Innovation Centre (MRIC; Figure 1) that provides a hub for MAS activity in the UK and brings together NOC engineers and scientists with industry partners. This facility houses the NMF-MARS fleet, engineers, and associated state-of-the-art workshops (including testing facilities, ballasting tanks, and vehicle storage/display areas; Figure 2), and also provides desk space for companies engaged in MAS; these range from small and medium-sized enterprises (SMEs) such as ASV and Planet Ocean, to large multinational corporations such as BP and Boeing.

Figure 2. The submarine glider storage and ballasting area within the Marine Robotics Innovation Centre.

Demonstrator Missions and Showcases

Since 2014, NOC has coordinated a series of annual high-profile demonstrator missions (Marine Autonomous Systems in Support of Marine Observations, or MASSMO), in order to trial and demonstrate new MAS technologies to research, government, and industry end users. These missions have evolved from deployment of new USVs to test their robustness in an open-ocean environment (MASSMO1 and 2; Figure 1), to large-scale multivehicle missions in hostile offshore environments for periods of up to two weeks, involving a wide range of partners (MASSMO3 and 4; Figure 3). The MASSMO missions have also enabled the command-and-control (C2) infrastructure for MAS fleets to be developed and tested in an operational setting, including the MARS portal where live vehicle positions and incoming real-time data can be viewed on top of auxiliary data layers to support operational decision-making (e.g., bathymetry, weather, tidal prediction models, satellite observations, AIS vessel information).

The MASSMO missions have generated significant media exposure and, together with the recent pioneering deep-ocean missions of "Boaty," have successfully highlighted the positive environmental benefits of MAS to the general public. NOC also convenes an annual Marine Autonomy and Technology Showcase (MATS), which is a forum for MAS developers, operators, and end users to exchange knowledge and gain access to the latest innovations.

Figure 3. Organogram showing the range of partners in Marine Autonomous Systems in Support of Marine Observations 4 (MASSMO4), including funding and coordinating bodies, industry, and operational partners, and research and data management organizations.

Training the Next Generation

To ensure a continued talent pipeline for the expanding NMF-MARS operation (and MRIC partners and other UK industry MAS operators), NERC has invested in a new PhD training program called NEXUSS (Next Generation Unmanned Systems Science). This program will see up to 50 PhD students graduate in the period 2020–2022, each with hands-on experience of MAS development, operations, and science application. Knowledge transfer is also realized through direct hands-on training of government and industry partners, for example, Royal Navy glider pilots during MASSMO missions (Figure 1).

Conclusions

Although there was, understandably, some initial resistance to a centralized MAS facility from other established MAS operators in the UK, there is no doubt that development of NMF-MARS has provided a focus and stimulus for ongoing UK government capital investment that has benefited the whole of NERC. The housing of the NMF-MARS fleet within a state-of-the-art and visitor-friendly facility at MRIC also provides an efficient and inspiring workplace, and allows different NMF-MARS teams (ROV, AUV, USV/glider) and MRIC industry partners to regularly interact and share experiences and ideas.

New and experienced researchers alike now benefit from access to a stable, sustainable, cutting-edge MAS fleet that is resilient to short-term funding irregularities, occasional vehicle loss, and staff turnover, and that benefits from development of novel sensors by NOC-OTE and partners. Although overheads (and therefore overall costs) are higher than other smaller facilities, this is offset against access to highly trained engineers and pilots and higher platform reliability.

Authors

Russell B. Wynn, National Oceanography Centre, Southampton, UK, rbw1@noc.ac.uk
David White, National Oceanography Centre, Southampton, UK, dwh@noc.ac.uk

Data Services for ALPS: Challenges and Opportunities

Victor Zykov and Allison Miller

Thousands of autonomous and Lagrangian platforms and sensors (ALPS) operating throughout most of the global ocean (Roemmich et al., 2009; Rodero Castro et al., 2016) have transformed ocean science in the years following the original ALPS workshop (Rudnick and Perry, 2003). New ALPS technologies have enabled persistent in situ observation of many important ocean properties. More complex data are being captured, of greater variety, and at a faster rate today than ever before. The growing flow of ALPS data offers unprecedented opportunities to advance ocean sciences. It also creates challenges with storage, transmission, processing, and analysis of the data. Such challenges are not unique to ALPS, as the rise of Big Data (Marr, 2015) has affected many areas of human endeavor. Created to address the problems of Big Data, global networks of interconnected data centers provide critical support infrastructure for the scalable storage, transmission, and analysis of large, dynamic, and distributed data sets (Yang et al., 2017). These services are referred to as cloud computing. To support the development of effective data services for ALPS applications, here we review the challenges of Big Data in ALPS and new technologies that are becoming available to help address them.

Sources of Big Data in ALPS

Thanks to improved reliability, energy efficiency, and endurance, modern marine robotics are becoming capable of persistent high-resolution ocean observing across a wide range of spatiotemporal scales (Figure 1). ALPS sensors have diversified to enable autonomous in situ measurement of ocean properties that previously required manual characterization. These include, for example, concentrations of dissolved oxygen (Martz et al., 2008), nitrates, pH (Wanninkhof et al., 2016), chlorophyll fluorescence, downward irradiance, and optical backscattering (Claustre et al., 2010), a proxy for colored dissolved organic matter (Cyr et al., 2017). The rate of oceanographic data collection has been amplified by the increasing spatial, temporal, and spectral resolutions of new sensors, such as synthetic aperture (Hayes and Gough, 2009) and imaging (Langkau et al., 2012) sonars, laser-based three-dimensional mapping systems (Duda et al., 2016), cameras (Roman et al., 2011), imaging spectrometers (Lucieer et al., 2014; Ekehaug et al., 2015), and holographers (Talapatra et al., 2013). Spatiotemporal analysis of oceanic phenomena via numeric modeling of acquired sensor data produces even more Big Data (Alvarez and Mourre, 2012; Sabo et al., 2014; Chen and Summers, 2016). This accelerating influx of data prevents new data analysis and interpretation from keeping up with the rate of data accumulation. Fortunately, powerful information technologies have been developed to help bridge this gap, as we discuss in the following sections.

Storage

Storing data on local personal computers or hard disk drives is risky and inefficient. Disks fail with age and RAID arrays won't scale as fast as incoming Big Data. Distributed file systems (DFS) (Silberschatz et al., 1998) have been developed for scalable fault-tolerant storage of large volumes of data spread across many networked servers for speed and redundancy. Some of them are proprietary, such as IBM's GPFS (Schmuck and Haskin, 2002) or Google's GFS (Ghemawat et al., 2003), while others are open, such as Hadoop DFS30, an open source clone of GFS. Distributed data storage is available as a service from many cloud service providers, such as Amazon, Google, and Microsoft at costs often lower than those of on-premise hardware, maintenance, and operational staff, yet with far superior reliability. Metadata are essential for cross-domain collaborations that

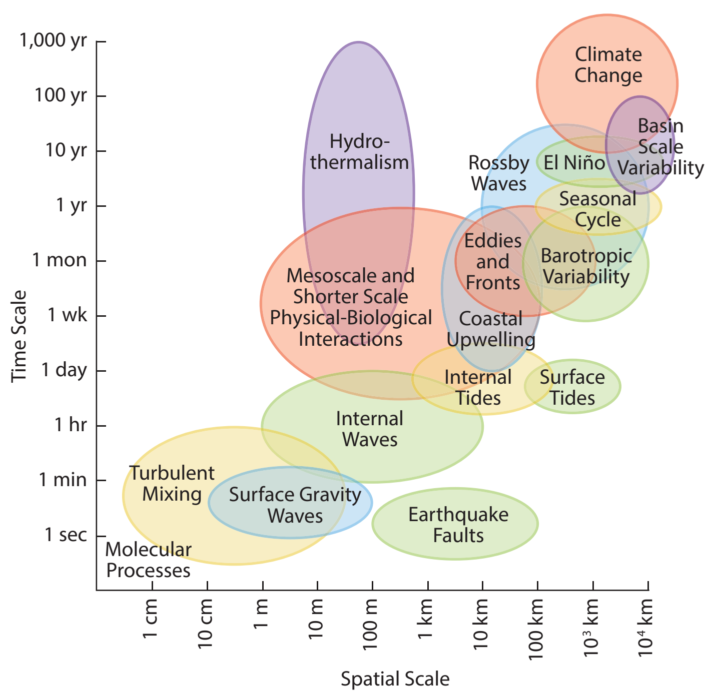


Figure 1. Overlapping spatial and temporal scales of major oceanic processes that are amenable to observation with ALPS. *Redrawn from Lampitt et al. (2010)*

require data integration, such as record linkage, schema mapping, and data fusion (Dong and Divesh, 2015). Metadata help to automatically resolve diverse data sources and facilitates large-scale interoperability and analysis across data sets (Agrawal et al., 2011). Automation of metadata creation and stewardship is an open issue that requires focused coordination among the ALPS and data services developers and operators.

Transmission

New ALPS data are often transmitted to storage via satellite communications (Bishop and Wood, 2009; http://www.argo.ucsd.edu/How_Argo_floats.html). While associated costs can be a concern, they have been declining for decades due to the expanding bandwidth capacity of new satellites (Williams, 2017). Some ALPS gather volumes of data that are too large for satellite or acoustic transmission, or may even create operational bottlenecks with offline upload (Holland et al., 2016). In these cases, in situ data processing and/or reduction can be advisable, such as pre-classification of observations by Ocean Carbon Explorers (Bishop, 2009) or sonar data processing on mapping autonomous underwater vehicles (Roman et al., 2011). By reducing data on board (with remote monitoring, where possible), transmission delays can be mitigated and inferences can be made available for automatic (or interactive) decision support in near-real time. Data may need to be reassembled from several storage locations for processing or analysis. For best efficiency, manual data transfers (such as file download or upload) should be minimized or eliminated to avoid bottlenecks in scaling up the performance of data services in step with the growth of Big Data. All major commercial clouds already come with high degree of automation for in-cloud data transfers, for example, from low to high availability storage, between storage and compute engines, automatic rebalancing within and across geographic regions, support for cross-cloud data transfer, and API interfaces for further workflow automation. If the volume of ALPS data is prohibitively large for ingress over the network, upload from physical media is also supported by the major cloud service providers.

Management

For data to be useful, they need to be easy to search, subset, query, annotate, clean, and append, and they should accept these and other transactions on arbitrary numbers of their elements, rows, or tables. It can be challenging, however, to guarantee accurate execution of these tasks, particularly if the data are voluminous, dynamic, and/or distributed across multiple servers, and relations among their components need to be preserved. These challenges are typically addressed using relational database management systems (RDBMS) controlled with structured query languages (SQL). Traditional SQL RDBMS solutions, such as MySQL (http://www.mysql.com) or IBM DB2 (http://www.ibm.com/analytics/us/en/technology/db2), use centralized software architectures, making them incompatible with distributed storage and processing needs of Big Data. Alternative NoSQL (Pokorny, 2013) architecture was developed to scale with the needs of Big Data, however, with no transactional consistency guarantees.

The latest NewSQL tools combine the benefits of Big Data scalability and SQL transactional consistency. Examples include MemSQL (http://www.memsql.com), VoltDB (http://www.voltdb.com), Google Spanner (Corbett et al., 2013), SAP HANA (https://en.wikipedia.org/wiki/SAP_HANA), and an open source Apache Trafodion (http://trafodion.incubator.apache.org). NewSQL RDBMS can be complicated to run on premise, however, they are available cost-efficiently as a service from several cloud providers. To optimize geospatial data analyses, some RDBMS have introduced spatial data indexing, for example, SQL Server (https://docs.microsoft.com/en-us/sql/relational-databases/spatial/spatial-indexes-overview) and H2GIS (http://www.h2gis.org). However, geographic information system software interfacing with RDMBS can define and maintain its own spatial indices, as is the case with ArcGIS (http://desktop.arcgis.com/en/arcmap/10.3/manage-data/geodatabases/an-overview-of-spatial-indexes-in-the-geodatabase.htm). Application of these and other advanced information technologies is the focus of EarthCube (Peckham et al., 2014), a US National Science Foundation-funded program to transform geoscience research (including ocean sciences) by developing cyberinfrastructure to improve access, sharing, visualization, and analysis of all geosciences data and related resources (https://www.earthcube.org).

Data Analysis

Most ocean scientists still analyze data by running custom scripts (often in MATLAB) on data sets on their local computers (Thomson and Emery, 2014). The growing volume, velocity, and variety of Big Data are making such approaches inadequate. Greater scalability can be achieved by analyzing large data sets with high performance parallel cloud computing as a service. This approach offering many benefits, such as the following:

- Analytical scripts and methods can be openly shared in the cloud and collaboratively developed as open source software. Persistent improvement and open availability of the analytical methods will stimulate their broader use, reduce barriers to entry into marine data analysis, and minimize the duplication of software development efforts.
- Hosting oceanographic data in the cloud ensures its safety and security. It is an effective approach to maximizing the data value for the scientific community. Sharing a data set with other cloud users makes it discoverable, searchable, and available for analysis, for example, with open source tools co-developed within the user/developer community.

- Cloud data services and access to cloud-hosted data can be automated with APIs.
- By running analytical software in the cloud, all the advantages of on-demand cloud computing can be leveraged. For example, compute resources can only be allocated and paid for when the scripts are running. The amount of resources can be fine tuned, often automatically, to match the needs. Analyses will complete faster thanks to elastic on-demand parallel computing, with no need to buy or manage servers.
- With algorithms and data co-hosted in the cloud, there is no need to download or upload data sets, which eliminates a key logistical bottleneck. Data transfers within the cloud are cheap or free and optimized for performance.
- The market of cloud computing is very competitive, pushing companies to improve the quality and expand the scope of services, while reducing the prices. This favorable dynamic is driven by much greater economic incentives than those available for technology development within the oceanographic community. This offers scientists a rare opportunity to benefit from very-well-funded rapid technical innovation.
- NewSQL RDBMS have been engineered from ground up to support a high volume of globally distributed data transactions with precision while simultaneously analyzing dynamic data and using inferences to automatically adjust various business processes in real time, for example, web content/traffic control. This infrastructure offers exciting opportunities for further automation (Stammer et al., 2016) of ALPS-based ocean research and data analysis.

Established analytical and modeling tools in marine sciences (Glover et al., 2011; Thomson and Emery, 2014) range from methods for initial data QA/QC and statistical error handling to principal component, factor, and frequency domain decompositions, spatiotemporal and dynamic analyses, and many modeling and visualization techniques. In deciding what tools should be implemented as cloud services first, one could consider what alternative implementations of the above established or new emerging tools (e.g., deep learning, clustering, semantic analysis, data annotation) may already exist and enjoy high demand in the community and could be moved into the cloud with incremental effort.

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Authors

Victor Zykov, Schmidt Ocean Institute, Palo Alto, CA, USA, victor@schmidtocean.org

Allison Miller, Schmidt Ocean Institute, Palo Alto, CA, USA, amiller@schmidtocean.org

Appendices

Appendix 1. ALPS II Workshop Agenda

February 21–24, 2017 | Scripps Seaside Forum, La Jolla, CA

Day 1, Tuesday, Feb 21

8:00 am	Breakfast
8:30 am	SIO welcome – M. Leinen (Director, SIO)
8:40 am	NOPP welcome – R. Beach (ONR)
8:50 am	An abridged history of ALPS and meeting objectives (36 MB .key file | 3.8 MB .pdf file) – D. Rudnick (SIO)
9:15 am	Biogeochemical sensors for autonomous, Lagrangian platforms: Current status, future directions (22 MB .ppt file) – K. Johnson (MBARI)
9:45 am	Break
10:15 am	Profiling floats for regional and global applications (160 MB .ppt file) – D. Roemmich, N. Zilberman (SIO), S. Jayne, (WHOI)
10:45 am	Underwater gliders (117 MB .ppt file) – C. Lee (UW)
11:15 am	Autonomous Underwater Vehicles in the 21st Century: Smaller, smarter, faster, longer range and more versatile (304 MB zipped folder of videos and .ppt files) – R. Wynn (NOC, UK)
11:45 am	Lunch
1:00 pm	Autonomous Surface Vessels and Drifters: Advancements, challenges and learning from each other (48 MB .ppt file) – C. Meinig (NOAA/PMEL), L. Centurioni (SIO)
1:30 pm	In-situ observations from tagged animals (61 MB .ppt file) – F. Roquet (Stockholm University)
2:00 pm	Measuring the ocean and air-sea interactions with Unmanned Aerial Vehicles (390 MB zipped folder of videos and .key files) – B. Reineman (SIO)
2:30 pm	Break
3:00 pm	Breakouts
4:00 pm	Reports
5:00 pm	Adjourn for day

Day 2, Wednesday, Feb 22

8:00 am	Breakfast
8:30 am	Reports
9:00 am	Ocean physics from autonomous and Lagrangian platforms and sensors (2.5 MB .pdf file) – A. Gray (Princeton)
9:30 am	Ocean biogeochemistry from autonomous platforms (46 MB .ppt file) – M. Estapa (Skidmore)
10:00 am	Advances, challenges and opportunities for autonomous biological observations and experiments (29 MB .ppt file) – M.J. Perry (U. Maine)
10:30 am	Break
11:00 am	Breakouts

Day 2 continued next page…

Day 2 continued…

12:00 pm	Lunch
1:00 pm	Carbon dioxide system measurements from ALPS (38 MB .ppt file) – T. Martz (SIO)
1:30 pm	Autonomous and Lagrangian studies of coastal and boundary current systems (76 MB .key file | 18 MB .pdf file) – R. Todd (WHOI)
2:00 pm	Ice-based observing (65 MB .ppt file) – M.-L. Timmermans (Yale)
2:30 pm	Break
3:00 pm	Breakouts
4:00 pm	Reports
5:00–7:00 pm	Reception

Day 3, Thursday, Feb 23

8:00 am	Breakfast
8:30 am	Reports
9:00 am	Use of acoustics for sensing, navigation and communications on autonomous ocean platforms (5 MB .ppt file) – L. Freitag (WHOI)
9:30 am	Autonomous sampling in ocean process studies (129 MB .ppt file) – E. D'Asaro (UW)
10:00 am	ALPS for managing Living Marine Resources (90 MB .ppt file) – T. Garfield (NOAA/SWFSC)
10:30 am	Break
11:00 am	Breakouts
12:00 pm	Lunch
1:00 pm	ALPS in state estimation and forecasting frameworks: A survey of science applications, error quantifications, and observing network design (5 MB .ppt file) – A. Nguyen (UT)
1:30 pm	Mission planning and control for autonomous and Lagrangian platforms (70 MB .ppt file) – Y. Chao (RSS)
2:00 pm	Using autonomous systems to entrain the next generation of scientists (105 MB .ppt file) – O. Schofield (Rutgers)
2:30 pm	Break
3:00 pm	Breakouts
4:00 pm	Reports
5:00 pm	Adjourn for day

Day 4, Friday, Feb 24

8:00 am	Breakfast
8:30 am	Reports
9:00 am	Discussion, next steps
11:00 am	Adjourn meeting

Appendix 2. ALPS II Participants

Kurapov Alexander, OSU
Will Ambrose, NSF
Jack Barth, OSU
Reggie Beach, ONR
Neil Bogue, MRV
Emmanuel Boss, Univ. Maine
Casey Brown, Alaska Sea life Center
Seth Bushinksy, Princeton
Luca Centurioni, SIO
Yi Chao, SeaTrec
Sylvia Cole, WHOI
Dan Costa, UCSC
Elizabeth Creed, Kongsberg
Eric D'Asaro, UW
Russ Davis, SIO
Catherine Edwards, Skidaway
Charlie Eriksen, UW
Meg Estapa, Skidmore
Andrea Fassbender, MBARI
Lee Freitag, WHOI
Toby Garfield, NOAA/SWFSC
Gustavo Goni, NOAA/AOML
Alison Gray, Princeton
Roberta Hamme, Uvic
Scott Harper, ONR
Patrick Heimbach, UT-Austin
Markus Horning, Alaska Sea Life Center
Luis Huckstadt, UCSC
Eric Itsweire, NSF
Steven Jayne, WHOI
Ken Johnson, MBARI
Greg Johnson, RBR
Ellen Kappel, Geo-Prose
Jochen Klinke, Sea-Bird Scientific
Craig Lee, UW
Drew Lucas, SIO
Todd Martz, SIO
Jean McGovern, ONR
Emily Medina, ONR
Chris Meinig, NOAA/PMEL
Sophia Merrifield, SIO
William Miller, NSF
An Nguyen, UT-Austin
David Nicholson, WHOI
Nick Nidzieko, UCSB
Breck Owens, WHOI
Enric Pallas Sanz, CICESE, Mexico
Terri Paluszkiewicz, ONR
Mary Jane Perry, UMaine
Sarah Purkey, LDEO
Luc Rainville, UW
Spencer Reeder, Vulcan Philanthropy
Dean Roemmich, SIO
Fabien Roquet, Stockholm University
Dan Rudnick, SIO
Oscar Schofield, Rutgers
Andrey Shcherbina, UW
Yui Takeshita, MBARI
Eric Terrill, SIO
Jim Thomson, UW
Mary-Louise Timmermans, Yale
Robert Todd, WHOI
Jim Todd, NOAA/OOMD
John Toole, WHOI
Neil Trenaman, Ocean Aero
Mete Uz, NSF
Chris Ward, Xylem
Mike Wardlaw, ONR
Sarah Webster, UW
David White, NOC, UK
Russell Wynn, NOC, UK
Victor Zykov, Schmidt

Appendix 3. ALPS II White Papers

All attendees were encouraged to produce a white paper on a topic of their choosing that is relevant to the ALPS II mission:

1. To survey progress in autonomous platforms and sensors for ocean research since the original ALPS meeting 13 years ago
2. To assess future prospects and challenges

The scientific application, technical development, and operations and management of ALPS are of interest.

The objective of soliciting white papers is to allow all participants to provide background material and new directions and perspectives on topics that they represent at the meeting. Ideally the white papers will be forward looking and identify new opportunities or directions in the use or development of autonomous platforms and sensors.

Click on the blue text links below to view white papers online.

Bogue and Maas » MRV Systems: Marine Robotic Vehicles

Boss » Coordination of Observing Assets for Improved Ocean Observations

Bushinsky et al. » Oxygen Measurements from Autonomous Vehicles: Applications and Challenges

Centurioni and Lumpkin » The Global Drifter Program: Evolution, Current Status, Impacts, and Future Directions

Clayson et al. » Observing Air-Sea Exchange with a Free-Drifting SPAR Buoy

Cole » Investigating Small-Scale Processes from an Abundance of Autonomous Observations

Davis et al. » Thoughts on Second Generation Gliders

Eriksen » Observing the Full Ocean Water Column with Deepgliders

Goni et al. » Underwater Glider Observations for Atlantic Tropical Cyclone Studies and Forecasts

Jayne » Air Deployable Profiling Floats

Johnson » RBR: Sensor Innovation

Nguyen et al. » Arctic Argo-Type Floats: The Needs, Potentials, and Challenges

Roemmich and Zilberman » The Deep Argo Program: Broad-Scale Sampling of the Full Ocean Water Column

Roquet et al. » In Situ Observations Using Tagged Animals

Schofield et al. » Distributed Ocean Robots are a Key to Entraining the Next Generation into Ocean Literacy and Lifelong Learning

Schofield et al. » Evolution-Informed Autonomous Networks to Characterize Biological Hotspots in the World's Ocean

Tenreiro et al. » Assessing Vertical Structure of the Anticyclonic Loop Current Eddies with Autonomous Underwater Gliders

Todd » On the Potential for Sustained Gulf Stream Monitoring with Autonomous Underwater Gliders

Toole et al. » Autonomous Observation of the Polar Oceans Below Sea Ice

Walsh et al. » Perspectives for Accuracy and Quality Assurance of CTD & Biochemical Data Streams from Autonomous Platforms

White » The EU BRIDGES Glider Project

https://alps-ocean.us

ALPS II

Autonomous and Lagrangian Platforms and Sensors

January 2018