PAPER

Developing Coordinated Communities of Autonomous Gliders for Sampling Coastal Ecosystems

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ABSTRACT

Underwater autonomous gliders have transitioned from exotic experimental systems to becoming a standard platform capable of collecting data over a critical range of spatial and temporal scales in the ocean. The data are proving to be extremely valuable for addressing a wide range of basic and applied research questions. This evolution has led to a growing international community of glider laboratories and offers the potential of increased opportunities to leverage efforts across this "young" growing community. To that end, we review the evolution of the glider communities and share our opinions of opportunities and hurdles. These communities grew from distributed research and/or education groups. It is crucial as systems continue to evolve that there is an effort to "harmonize" data products while preserving the diversity of approaches/science/experimentation. As the gliders have matured and new battery solutions provide additional energy, there is an increased focus on the integration of a wider range of sensors to be incorporated into gliders. Many of these new classes of sensors will be particularly effective for characterizing biological processes in the coastal ocean. As biological sensors generally provide proxy estimates of a parameter, developing robust quality control and assurance procedures is critical. These new sensors will be more power intensive, thus requiring the development of planning tools for increasing energy efficiency during missions. Given the significant growth in the highly distributed glider community, efforts are now focusing on the development mission planning tools to allow for efficient operation of glider fleets.

Keywords: autonomous underwater gliders, ocean observing

The Need

Many basic and applied research questions facing humanity require a better understanding of the physical, chemical, and biological interactions in coastal waters. This small region (~8% global areal extent) is disproportionately important to humanity. Coastal zones represent ~25% of the total global primary productivity and 90% of the world fishery production (Ryther, 1969; Sherman, 1994), ~35% of the world's population live within 100 km of the coast line (Vitousek et al., 1997),[1] and over two thirds of the world's largest cities (populations >1.6 million[2]) are located in coastal areas. Given the pressures associated with a growing human population, the associated anthropogenic environmental impacts are significant and are only expected to increase as coastal populations continue to grow (De Souza et al., 2003; Rockstrom et al., 2009). Understanding of the ocean's physical,

[1]This number is expected to grow to 75% over the next few decades.

[2]http://www.census.gov/ipc/www/idb/worldpop.php

chemical, and biological responses, particularly in the context of anthropogenic forcing (climate change, resource extraction and utilization, waste production, and nutrient pollution), remains a difficult problem that limits our ability to predict and manage coastal waters.

The data most relevant to understanding/supporting critical coastal processes (ocean productivity, water quality, fisheries, weather, climate, shipping, recreation, and energy production) span a range of temporal (days to years) and spatial (meters to thousands of kilometers) scales. These scales cannot be affordably resolved using traditional (ships, moorings) oceanographic sampling approaches alone. There is a greater need to combine monitoring efforts with adaptive sampling in time and space as many of the critical processes are ephemeral. Autonomous underwater gliders (Davis et al., 2003) are mobile platforms that can be steered adaptively from shore. Several different gliders exist (Figure 1), but generally, they are 1- to 2-m-long platforms that maneuver up and down through the water column through the ocean at a forward speed of 20–30 cm/s. The propulsion comes from a sawtooth-shaped gliding trajectory by means of a buoyancy change where wings translate the sinking and climbing motion, due to gravity, into the forward direction. These systems have proven to be robust platforms for sampling coastal systems (Schofield et al., 2007).

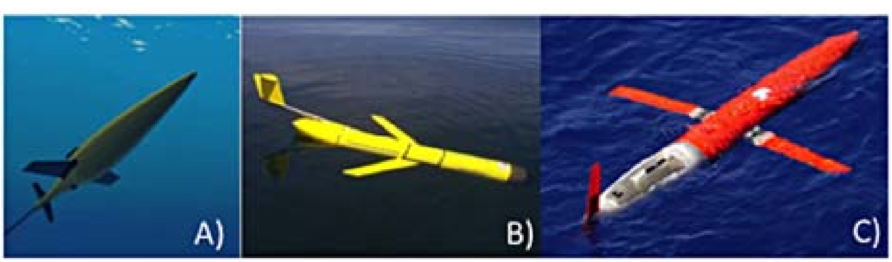
A Short Glider History

Gliders, as currently configured, were first detailed in Doug Webb's laboratory book on 2/8/86. The concept matured during many backyard discussions with Henry Stommel who, in 1989, publicized his science fiction vision of the future of a smart fleet of instruments being coordinated by graduate students (Stommel, 1989). These systems, a cousin to the Argo profiling float, were developed in parallel at several academic institutions and commercial companies through support from the Office of Naval Research. They have now matured to the point that they are available for commercial purchase from several companies. A decade after Henry Stommel's vision, gliders had demonstrated their capabilities to the point that they were highlighted in the international OceanObs'99 Conference (Testor et al., 2010) as "a potential effective solution for repeated sampling through narrow, swift boundary currents…." In 2005, the Office of Naval Research in the United States formed three glider technical centers with each focused on maturing one of the three available glider types (Seaglider, Slocum, and Spray; Figure 1). Each of the centers was composed of an academic and commercial partner to not only evolve the capability of the glider platform but also simultaneously to translate any new capabilities into commercially hardened products. In addition, the three technical centers actively shared expertise, and they leveraged their efforts. This innovative approach greatly accelerated the development of the platforms, command, and control capabilities, as well as accelerated the incorporation of new sensors into the platforms.

The evolution of glider capabilities was mirrored in Europe, where the capabilities developed in individual laboratories were subsequently leveraged through the formation of the European Gliding Observatories network (EGO) since 2005. The EGO effort was first focused on facilitating technological, scientific, and organizational cooperation to enhance capacities for sustained observations of the oceans with gliders. It was supported by the COST Action ES0904 (2010–2014) and provided coordination, training, liaison between providers and users, advocacy, and provision of expert advice. Today, it is more appropriate to call it "Everyone's Gliding Observatories" (http://www.ego-network.org/), while teams from Australia, Canada, Chile, Mexico, Peru, South Africa, and the United States have joined with this community. EGO is now an international forum for discussing scientific and technological issues related to the glider activity that helps to organize the glider community at the global scale for

FIGURE 1

The three autonomous gliders used by the international community. Pictures in alphabetical order are the (A) SeaGlider developed by the University of Washington, (B) Slocum glider developed by Webb Research, and (C) Spray developed by the Scripps Institution of Oceanography.



the benefit of marine sciences and applications.

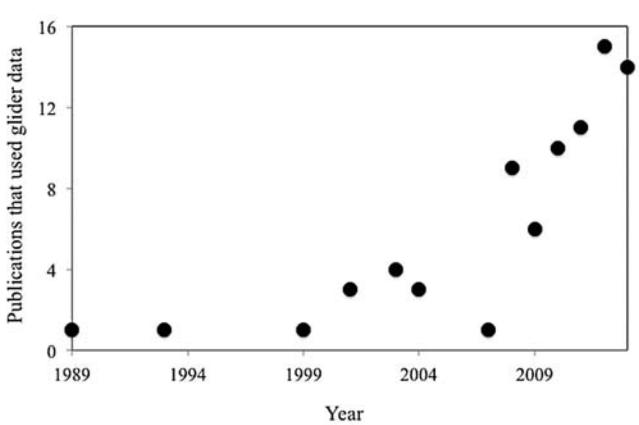
Through this time of development, academic laboratories largely operated gliders for specific experiments and represented the primary user of these platforms. Their activity has subsequently resulted in steady rise in peer-reviewed publications that incorporate glider data (Figure 2). Due to successes in the field, federal agencies in the United States, Europe, Australia, and South Africa have begun to adopt gliders for a range of more applied and operational needs. The community is highly distributed and continues to grow. To explore the potential for more cooperative efforts, Europe focused on defining requirements for setting up a sustainable European glider infrastructure through the Gliders for Research, Ocean Observation and Management (GROOM) program.

In the United States, the 2010 Deepwater Horizon oil spill in the Gulf of Mexico event helped mature the glider community. A voluntary consortium of federal, industry, and academic partners provided a fleet of gliders in support of region-wide subsurface observations of temperature, salinity, and velocity. These data supported efforts to determine where oil was likely to be taken by currents. Data were made available in real time to modeling centers and anyone in an open-access data base. Fluorometers were outfitted to measure colored dissolved organic matter (CDOM), which was used as a proxy for plumes of hydrocarbons. This response demonstrated a national glider surge capacity. This incident, in part, stimulated the community to begin discussions about the potential for a national glider network for United States. Glider community leaders working with National Oceanic and Atmospheric Administration's (NOAA's) Integrated Ocean Observing System (IOOS) have been developing a draft national glider plan (http://www.ioos.noaa.gov/glider/strategy/glider_network_whitepaper_final.pdf).

While discussion about a potential national plan continues to evolve, there remains a need to continue to harmonize and accelerate collaboration among the growing glider community. As an example of this community-based coordination, a series of grassroots regional *ad hoc* experiments were conducted in 2013 and 2014. These efforts termed "gliderpalooza" represented coordinated individual experiments, funded by diverse federal and state sponsors, working together to provide regional data to modelers. These data supported their own local objectives while contributing to regional scale questions that could not be addressed by any one institution alone. For example, each participating deployment assisted in monitoring fish migration programs as gliders were loaned Vemco tagged-fish listening systems from the Ocean Tracking Network. This expanded the listening network in both time and space along the eastern seaboard of the United States and into the Gulf of Mexico. These efforts were successful with 11 partners (United States and Canada) flying 14 gliders in 2013 and expanding to 18 partners (United States, Canada, and the United Kingdom) flying 27 gliders in 2014 (Figure 3). These and other community efforts have demonstrated that glider platforms are mature and the national/international communities exist to ensure gliders will play an increasingly large coordinated role in observing networks for decades to come.

FIGURE 2

Glider publications as a function of year. Data were collected from Appendix A from the U.S. IOOS National Underwater Glider Network Plan (http://www.ioos.noaa.gov/glider/strategy/glider_network_whitepaper_final.pdf).

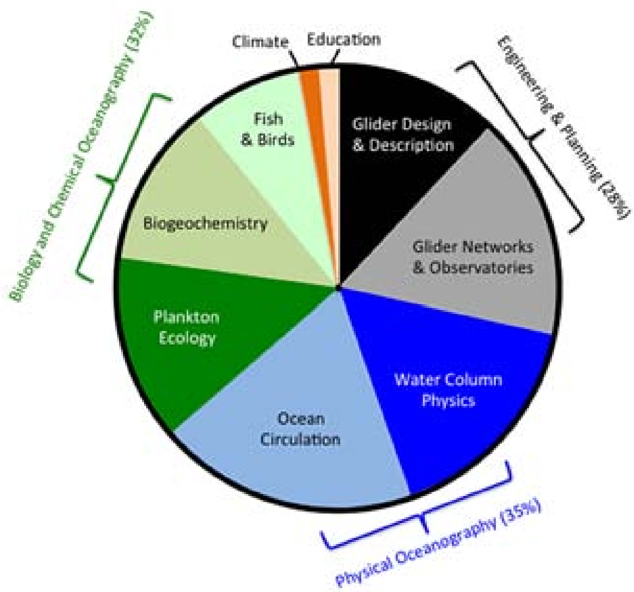


Applications for Glider Technology

There is a growing body of peer-reviewed literature that demonstrates the myriad of ocean processes that gliders can be used to study. Reviewing all the potential applications is beyond the scope of this manuscript; however, we can summarize the application of glider technology that has been adopted by the physical, biological, and chemical oceanographic community as judged by the focus of current manuscripts published in the peer-reviewed

FIGURE 3

The glider publications sorted by topical focus. Topical focus was based on the key area of interest of the paper. Data were collected from Appendix A from the U.S. IOOS National Underwater Glider Network Plan (http://www.ioos.noaa.gov/glider/strategy/glider_network_whitepaper_final.pdf).



literature (Figure 4). Interestingly, based on publications, the gliders have been adopted almost equally by the physical and biological/chemical oceanographers (Figure 4). Using our group as an example, gliders have been used to study many of processes along the East Coast of the United States (ocean-atmosphere interactions during large storms, sediment resuspension and transport, fishery dynamics, coastal hypoxia/anoxia, internal waves at the shelf slope front, coastal predictive skill for physical and biological parameters, freshwater transport from the Hudson River, prediction of ocean optical properties), along the West Coast of the United States (poleward flows upon upwelling relaxation, coastal predictive skill for physics-optics-biology), in the Gulf of Mexico (oil dispersion, distribution of harmful algal blooms), in the Arctic (coastal jets, fjord bird ecology), in the Antarctic (polynya ecology, penguin foraging ecology, shelf heat budget and heat transport, fish ecology, topographic influences on phytoplankton ecology), in European waters (ocean optical properties, predictive skill assessment), and in Australian waters (eddy transport). In addition, the real-time data from the gliders have proven to be an extremely powerful magnet to attract K-12 and undergraduate students into oceanography. Undergraduates have helped pilot gliders to cross ocean basins and used the data to assess ocean model predictive skill (Dobson et al., 2013; Glenn et al., 2011; Sacatelli et al., 2014). Our group is but one snapshot of the glider activities and applications supported through other groups around the world. This global community, taken as whole, has demonstrated that gliders are amenable to address a wide range of basic and applied questions.

Path Forward

Increasing the utility of glider technology will be based on increasing the number of sensors available for these platforms. As the sensor suite expands, we expect community efforts to shift from mainly hardware/software development to tools that allow for more effective operation of individual or fleets of vehicles. Coordinated fleets will be more common and efficient as it is likely that lifetime costs of gliders will be dominated by the cost of operating them, rather than the cost of purchasing the vehicles.

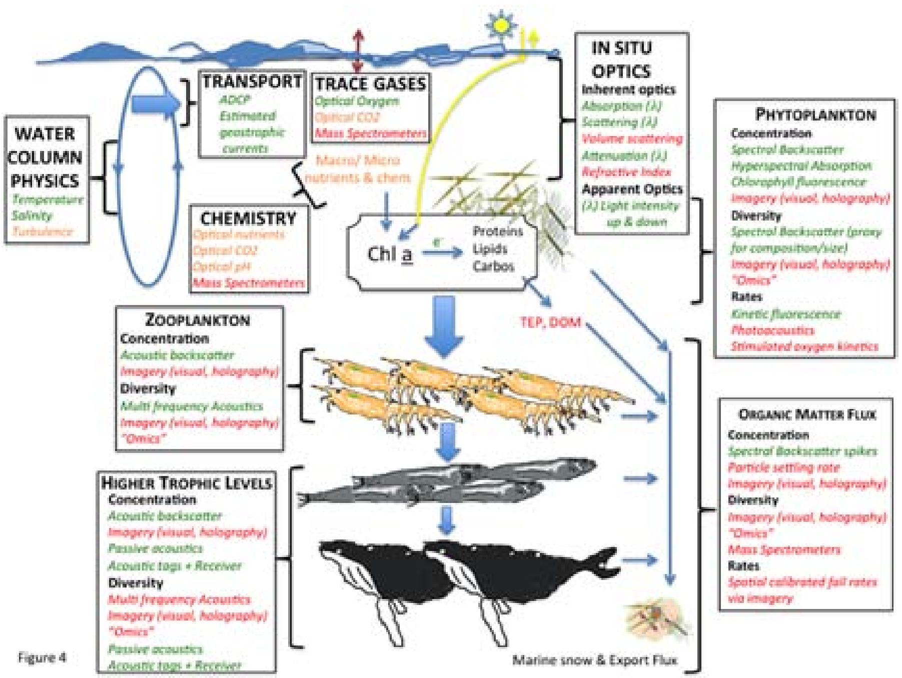
An ocean research platform is only as useful as the sensors it can carry. Historically, the type of sensor has been limited by the size and energy consumption of the sensor. Fortunately, there is a revolution occurring in instrument miniaturization. In addition, the increased availability of high-density energy lithium batteries has increased the power availability over traditional alkaline-based batteries. This has opened the door for the potential to integrate a new suite of sensors into gliders in the coming decade.

A common problem confronting sensor engineers when asking an ocean scientist "What do you want to measure?" is that the response invariably will be everything everywhere all the time. Given this, this review will summarize the sensor capabilities presently deployed, the soon to be introduced, and the highly desirable data products that currently cannot be measured on a glider. We have mapped these stages of capabilities onto a simplified food web perspective that is typical for many regional and global models (Figure 4).

Not surprisingly, the most complete suite of sensors is available for physical properties of the water (temperature, salinity, and currents). These measurements are routine with a range of sensors available for purchase. Measurements have proven to be effective

FIGURE 4

A simplified marine food web with energy flowing from the sun through the primary producers to secondary and higher trophic levels. Breakout boxes listing the relevant measurements to specific parts of the food web are indicated. The level of readiness is indicated by the color of the text within the breakout box with (A) green indicating a routine measurement currently made by gliders today, (B) orange indicating a measurement that has been made on higher powered remotely operated vehicles (ROVs) or propellered AUVs or has been flown on glider rarely only by a specialist, and (C) red indicating one that has not been made on glider and may not have been made on an ROV or AUV. (Color versions of figures are available online at http://www.ingentaconnect.com/content/mts/mtsj/2015/00000049/00000002.)



for defining the general hydrography and for calculating physical transport either estimated through geostrophic currents from density section and/or directly utilizing a mounted acoustic Doppler current profiler (ADCP). Turbulence, as estimated through shear probes, has been measured on a glider; however, this measurement is relegated to a few specialists in the field. Turbulence measurements have been made and should become more common in the near future (~3–5 years).

A critical science need is to characterize the propagation of light into the ocean as it is central to heating surface layers as well as driving phytoplankton photosynthesis that fuels the marine food web. The optical measurements available today can be decomposed into the inherent (absorption, attenuation, and backscatter) and apparent (downwelling irradiance, upwelling radiance) optical measurements. An advantage of the inherent optical properties is that they can be measured at night and at depth when there is no light present. Radiative transfer models can be used to link the inherent and apparent optical properties and used to derive optical parameters of interest that are not measured. These measurements are often available as either a single wavelength (attenuation), multispectral (optical backscatter, downwelling irradiance, upwelling radiance), or hyperspectral (absorption, downwelling irradiance, upwelling radiance). The larger number of wavelengths measured, the more sophisticated signal processing techniques that can be applied to derive optical proxies for a range of critical properties such as phytoplankton concentration and particle/phytoplankton composition. A measurement that shows promise but has yet to be measured onboard a glider is the volume scattering function, which could be used to provide information on particle size and/or composition. In addition, measurements of the refractive index of particles appear to be promising for characterizing the composition of the particles present.

For *in situ* gas and chemistry, a range of sensors that are rapidly evolving shows promise. Optically based estimates of oxygen are now common and provide a stable means for collecting data over the long duration of a glider deployment. Approaches for estimating nitrate, carbon dioxide, and pH also often employing optically based approaches and groups are currently beginning to incorporate these systems into gliders. As some of these sensors are now becoming standard on Bio-Argo profiling floats (for live data, go to http://www.mbari.org/chemsensor/floatviz.htm), they are very amenable for glider technology with a small spatial footprint and low power usage. Ultimately, a broader spectrum of chemistry would be enabled through the deployment of specialized mass spectrometers and/or wet chemistry systems, which have been deployed on other high power autonomous underwater vehicles (AUVs); however, this will require significant increases in the available onboard power given current commercially configurations.

Phytoplankton is the base of the marine food web, and other than water molecules, for most of the ocean, they represent the dominant optical constituent influencing *in situ* spectral properties. Not surprisingly, optical measurements (spectral backscatter and/or absorption) can be used as a proxy for phytoplankton biomass; however, caution must be applied to this approach when operating in waters where the presence of dissolved organic matter and/or inorganic particles might dominate the optical measurement. Given this, many in the field use chlorophyll *a* fluorescence as an estimate of the phytoplankton biomass, which is an easy measurement to make but can be difficult to interpret as the chlorophyll *a* fluorescence is sensitive to physiological status of the phytoplankton (cf. Dubinsky & Schofield, 2009). While several approaches exist for mapping phytoplankton biomass from gliders, deriving estimates of the composition of the phytoplankton is more problematic. The most effective means has been to use the spectral absorption signatures associated with specific phytoplankton pigments to provide information on the different phytoplankton species present (Kirkpatrick et al., 2000). Ultimately, better estimates of the phytoplankton diversity will require new sensors. *In situ* flow cytometers and holographic imagers are now becoming commercially available; however, they are currently not available for gliders given their large size and high power requirements. These approaches that can identify individual cells will be ideal given the societal and science needs. Finally, efforts are beginning to focus on capturing discrete samples of filtered biomass onboard gliders. This would allow for chemotaxonomic, microscopic, and genomic identification of the major phytoplankton present. While these approaches have been proposed, to date, there has not been a successful demonstration of discrete sample collection onboard a glider.

Beyond making measurements of the biomass and community composition, it will be critical to develop the means to assess the physiological status of phytoplankton populations as this relates directly to the overall growth rates of the phytoplankton. Photosynthetic activity in phytoplankton provides a suite of measurable signals that allow the estimates for the quantum yield of photosynthesis to be derived. The quantum yield provides a direct measure on the physiological status of the cells and can be used to estimate photosynthetic *rates* (Falkowski & Raven, 2007). The Fluorescence Induction and Relaxation system measures the kinetics of chlorophyll fluorescence under a saturating train of light flashes allowing derivation of the quantum yield, and this system has been integrated into gliders. This system has been integrated into gliders and, in recent years, has been deployed on missions in the coastal seas around Antarctica. Other approaches (photoacoustics and stimulated oxygen kinetics) show promise but are still in the early stages of development.

Measurements capable of characterizing secondary and higher trophic level activity are beginning to be incorporated into gliders. For zooplankton, acoustic backscatter from echosounders is being used and can provide a general proxy for biomass; however, identification of the specific zooplankton is not yet possible. This would require direct imaging, which currently is problematic based on current system sizes and power requirements. Multi-frequency acoustics is closer to reality and could provide some broad characterization of the secondary and higher trophic levels. Higher trophic levels (fish, seals, birds, and whales) offer the possibility of carrying acoustic tags, which allow the specific individuals to be identified by a glider outfitted with a listening device. This approach is being used by researchers at the University of Delaware to track sand tiger sharks and sturgeon off the east coast of the United States in near real time with a glider. Finally, passive acoustical recording of the *in situ* soundscape is offering a new means to characterize the ocean activity by identifying specific species and, possibly, individuals.

As the number of gliders sensors increase in oceanography, establishing solid quality assurance and quality control procedures for sensors and data collected from observatory platforms, including gliders, is essential (Fredericks et al., 2009). This includes the production of standard operating procedures (SOPs), quality assurance procedures such as a Quality Assurance Project Plan (QAPP) and Quality Assurance in Real Time Oceanographic Data (QARTOD), validating data, applying quality control in real time, and developing a data analysis/data management system for future glider monitoring. A QAPP has been successfully implemented for the glider-integrated Conductivity-Temperature-Depth (CTD) and monitoring dissolved oxygen using an optode integrated into gliders (http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100IVXI.txt). However, there are still several glider sensors that do not have established Quality Assurance/Quality Control (QA/QC) protocols. Many teams are actively working to fill the gaps and establish SOPs for quality assurance as well as quality control of real-time glider data. These SOPs should be publicly available. Formal groups such as the MTS or IEEE can and should play a critical role in the facilitating discussion in developing community agreement on the appropriate procedures and QA/QC protocols.

Incorporation of any sensor into a glider results in an immediate new "sink" of power, which limits the lifetime of a mission. Therefore, increasing energy efficiency is absolutely critical. Tools that allow for increased efficiency and assist in mission planning are becoming critical as the newer instrument suites tend to have high power requirements. With improvements such as the recent integration of the coulomb meter into the Slocum glider, measuring the discharge of the battery has become more accurate and critical to long-duration glider operations. Knowing the rate at which energy is used and how much remains is vital to mission planning. However, the glider's coulomb meter only measures whole vehicle current. To perform more precise mission planning, the energy consumption of individual components (especially power intensive sensors) is necessary. To that end, we have developed a measurement infrastructure, which captures the currents drawn from distinct components of the Slocum glider. The infrastructure has been deployed in test missions off the coast of New Jersey, and the data collected have been integrated into a Slocum glider simulator. This measurement board and simulation framework can be used to assist in the planning and decision making of missions and shows possible tradeoffs, for instance, between mission duration, speed, and energy consumption. The simulation environment incorporates energy, speed, and seafloor and ocean current models and is used to predict the flight path, longevity, and energy usage of a mission. The simulation environment has been validated against Teledyne Webb's Shoebox simulator and compared to a deployment on the continental shelf off the coast of New Jersey. Results between the three compared well (Woithe et al., 2010). Mission planning tools such as this will become increasingly important for glider operations in the coming years as more sensors are integrated into the glider.

In situations where the desired sensor activation profile of "everything, everywhere, all the time" is not feasible for the entire duration of a mission, mission planning tools will be particularly crucial. Mission planning tools can help oceanographers to assess the potential tradeoffs between different sensing activities in terms of overall energy consumption and peak power requirements. Sensor activity planning and path planning need to be done together while leaving enough energy reserves to ensure a safe recovery of the glider at the end of a mission. In some cases, the effectiveness of sensing activities can be improved by using lower power sensors to trigger high-power sensors only in situations where acquiring expensive sensing data is important. Such trigger chains have been recently proposed with promising results for triggering backscatter sensors of a Slocum glider while flying through a thermocline (Woithe & Kremer, 2015). Simulation results and results from two glider deployments off the coast of New Jersey show energy savings between 34% and 82% without significant loss of scientific relevant data. Mission planning tools have to consider all aspects of sensor activation including the desired spatiotemporal resolution, tradeoffs between sensing activities and their energy/power demands, and the applicability and effectiveness of sensor trigger chains.

Conclusions

Gliders have proven to be effective tools for mapping a wide range of critical processes in the coastal ocean. As the technologies have matured, so has the international user community with efforts now focused on developing distributed networks. These distributed communities are now conducting a range of *ad hoc* grass root collaborations. Increasing the utility of the gliders will be dependent on growing this community to provide coherent sampling for national and international ocean observing systems. In addition, it will be critical to increase the portfolio of sensors that are in gliders. As these distributed networks of operators and diverse sensors increasingly become available, tools for optimizing mission planning will increasingly become important; therefore, we recommend that efforts should also be focused on developing mission planning tools.

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