C H A P T E R

# 8

# Glider Technology Enabling a Diversity of Opportunities With Autonomous Ocean Sampling


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O U T L I N E



Gliders have been demonstrated to be robust and effective tools for addressing fundamental and applied science needs (see Chapter 5.1). As the platforms have matured over the decade they offer the opportunity to assess how these systems are changing how and what these platforms can fulfill. A major advantage of gliders is their modularity, which allows them to evolve rapidly as new sensors are incorporated into the platforms, as an autonomous underwater vehicle is only as useful as the sensors it carries. Historically, the types of sensor available to gliders were limited by the size and energy consumption of the sensor. Fortunately, there is a revolution occurring in instrument miniaturization, which is now opening the door for potentially a new suite of sensors for gliders. Another opportunity is that as the platforms have matured they are now robust enough to be deployed during periods when traditional shipboard sampling is not feasible. This includes extreme weather events when dangerous conditions limit how and when ships can conduct science operations. This is of special value as these storms play a significant role



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in structuring the physics, chemistry, and biology of the ocean. Finally, as marine science enters the 21st century it is critical to entrain the general public in the adventure of exploring this planet's oceans. Ocean robots offer a unique tool to engage the imagination of the public and we believe they can provide an effective means for entraining the next generation of oceanographers. Based on our experience of close to 15 years of Slocum glider operations (see Chapter 5.1), we focus this chapter on providing examples of how they will address these issues. We specifically discuss the process of incorporating a new sensor in a glider and the insights gained by deploying a glider in a hurricane to fill critical observation gaps. Finally, we provide a range of education/outreach topics that directly leverage off glider observations in the sea.

## 8.1 INTEGRATION OF A NEW SENSOR INTO A SLOCUM GLIDER

Chlorophyll fluorometers are now a standard sensor used by the oceanographic community for mapping phytoplankton biomass in the oceans. Despite their utility, standard chlorophyll measurements have limitations, which include being sensitive to numerous physiological processes in the phytoplankton [1], making a universal correlation with phytoplankton biomass difficult to impossible. Additionally, while a proxy for biomass, it does not, as conventionally measured, allow for estimates of photosynthetic rate processes, which is a critical piece of knowledge given the extremely high turnover rates in phytoplankton. In the mid-1980s, benchtop instruments were built to measure the kinetics of fluorescence, and this allowed for estimates of the optical cross-section of photosynthesis, photosynthetic quantum yields, and photosynthetic electron transfer [2,3]. These measurements are sensitive to a cell's physiological state and since their advent have allowed oceanographers to study how changes in the environment drive changes in phytoplankton physiology and corresponding cellular rate processes [2,4]. Since its introduction has become an increasingly important shipboard measurement, however, the ability to provide sustained measurements over time has not been possible and to date could not measure photosynthetic performance under in situ conditions.

In a partnership between Teledyne Webb, Satlantic, and Rutgers University, an existing commercially available desktop Fluorescence Induction and Relaxation (FIRe) instrument was substantially modified so it could be carried and operated onboard a glider [5] (Fig. 8.1). This required a complete redesign of the optics and electronics from the large benchtop model to fit within the internal compartment dedicated for science sensors. The standard glider science bay for carrying sensors has a diameter that is approximately 8.25 inches and a length of 22 inches. Beyond the redesign of the sensor it was necessary to integrate the instrument directly to the glider's computers to allow the sensor to be operated remotely during a glider mission. These considerations are similar to other sensor integrations that have been done, and it points out the importance of having a team that includes the academic partner, as well as the sensor and glider manufacturers.

A major consideration for determining amenable sensors for gliders, beyond their physical size, is their overall power requirements. Missions are most valuable if they are of sufficient length to allow them to map a geographic or time domain area of scientific value given the slow travel speeds of the glider. For the FIRe, the sensor is based on fluorescence signals being induced by flashes from blue (450 nm) light-emitting diodes (LEDs). The computer-controlled LED driver delivers pulses with varied duration from 0.5 μs to 50 ms, which ensures fast saturation of the photosystem II complex within the phytoplankton that is within the single photosynthetic turnover (<100 μs). The fluorescence signal, isolated by the red (680 nm) interference filter, is detected by a sensitive avalanche photodiode module [6]. This measurement is power intensive requiring a peak of ~6 W of power, roughly 9 times more energy compared to standard fluorometers, which can considerably shorten the glider mission lifetime from months to days

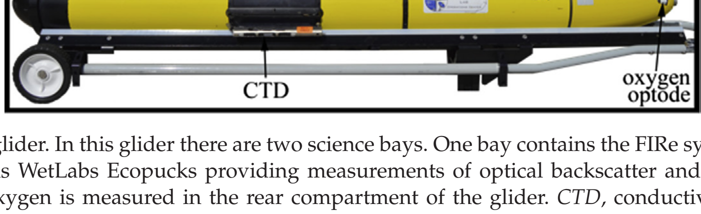


FIGURE 8.1 The FIRe Slocum glider. In this glider there are two science bays. One bay contains the FIRe system and photosynthetically active radiation. The second bay contains WetLabs Ecopucks providing measurements of optical backscatter and standard chlorophyll and colored dissolved organic fluorescence. Oxygen is measured in the rear compartment of the glider. *CTD*, conductivity, temperature, and depth; *FIRe*, fluorescence induction and relaxation.

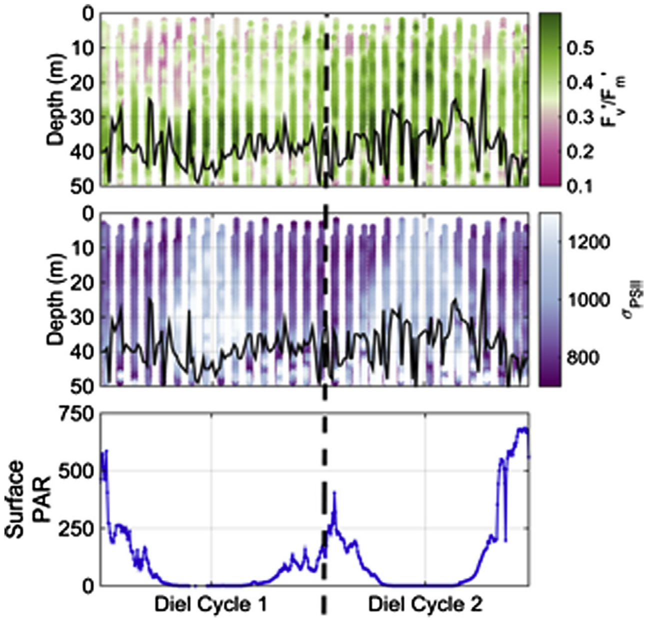


**FIGURE 8.2** The daily changes in phytoplankton physiology as measured by a glider-mounted FIRe sensor. *Top panel* shows the maximum quantum yield (Fv′/Fm′) as a function of depth and time. *Middle panel* shows the optical cross-section of photosystem II as a function of time and depth (σPSII). *Bottom panel* shows the photosynthetically available radiation at the sea surface as a function of time. *FIRe*, fluorescence induction and relaxation; *PAR*, photosynthetically active radiation.

if the sensor is run continuously. This requires the operator to optimize the duty cycle of the sensor to maximize the lifetime of the mission. For the FIRe, one strategy is to operate the glider only at night, which minimizes the impacts of light-induced nonphotochemical quenching of chlorophyll fluorescence and doubles the length of the mission, while also collecting data that allow for the calculation of maximum quantum yield for photosystem II activity (Fig. 8.2). To operate in this mode, the operator turns the FIRe on and off via the glider, which is possible due to integration of the sensor into the glider hardware/software. Fig. 8.2 shows 2 days of FIRe data collected in the coastal waters of the West Antarctic peninsula. The decreases in the maximum quantum yield (Fv′/Fm′, top panel) and in the optical cross-section of photosystem II ($\sigma_{PSII}$, middle panel) during daylight hours (bottom panel) reflect physiological adjustments to the ambient light conditions experienced by the in situ phytoplankton. Taken together these results show that we can use gliders to estimate fundamental biological rate processes.

## 8.2 USING GLIDERS TO STUDY PROCESSES DURING EXTREME EVENTS

Few studies have investigated the variability of the physics in coastal waters during a hurricane due to the severe operational conditions. This is problematic as it has been shown that the prediction of hurricane intensity at landfall is strongly dependent on resolving realistic conditions in the water column that currently cannot be resolved by operational ocean-atmosphere models [6,7]. This gap is to a large extent an indictment of the lack of in situ observations. The few available in situ observations in the deep ocean, combined with satellite imagery, have shown that an intense, slowly moving hurricane may cool the sea surface by 2–6°C due to hurricane-induced mixing [8]. This cooling has been shown to influence hurricane intensity.

One of the major factors that influence tropical cyclone intensity is the interaction between the atmosphere and the ocean. Air/sea interactions are dominated by atmospheric forcing through the air/sea interfacial fluxes of heat, momentum, and buoyancy. Vertical mixing in response to wind forcing can feed back on the storm given the potentially large temperature change if deeper waters are mixed with the surface. So estimating the heat budget of surface water under a hurricane is important in understanding the heat transport, as well as for predicting hurricane intensity and path. Slocum gliders are effective tools for sampling storm conditions, especially in the coastal ocean [9,10,13] but it is only recently that they have been demonstrated to fill observational gaps during a hurricane [6,7,14]. Beyond the standard measurements of temperature, salinity, oxygen, and optical backscatter, gliders can also provide measurements of depth- and time-averaged water column currents (see later). A single hour-long sampling segment during a glider mission might collect 5–10 profiles depending on water column depth (see Chapter 5.1 for a description of glider operation). The difference between the calculated horizontal displacement from the final pre-dive location and the actual surfacing location divided by the time underwater provides an estimate of depth- and time-averaged velocity of the water that the glider experienced.

In a recent study, glider measurements of depth-averaged water-column currents were combined with surface currents collected by shore-deployed high-frequency (HF) radars to study nearshore circulation patterns during the approach of Hurricane Irene to the northeast of the United States [6]. The Mid-Atlantic Bight (MAB) is unique in that it is characterized by an extremely strong vertical stratification, with summer surface water temperatures ranging from 25 to 28°C and summer bottom waters being 8–10°C [11]. With an extremely tight thermocline (meters), it is effectively a two-layer system. Given this, [6] combined full water column depth-averaged currents from gliders and HF radar surface current to estimate bottom currents along the glider track when the hurricane approached and passed overhead. This assumes that the HF radar surface currents are representative of the surface layer above the thermocline (defined as the maximum vertical temperature gradient along each profile) and require that the depth-weighted average surface and bottom layer currents must equal the total depth-averaged currents experienced by the glider:

$$U_b = \frac{U_g\,(H_s + H_b)}{H_b} - \frac{U_s H_s}{H_b} \tag{8.1}$$

$$V_b = \frac{V_g\,(H_s + H_b)}{H_b} - \frac{V_s H_s}{H_b} \tag{8.2}$$

where $H_s$ and $H_b$ are the layer thicknesses above and below the thermocline, respectively, $U_g$ and $V_g$ are along- and cross-shelf depth-averaged currents, respectively, from glider dead-reckoning, $U_s$ and $V_s$ are surface layer-averaged currents from HF radar, and $U_b$ and $V_b$ are the calculated bottom layer-averaged currents. Glider data can also be used to provide model initial conditions, especially when clouds associated with the encroaching storm do not allow for satellite imagery to be collected.

Hurricane Irene formed east of the Caribbean's Windward Islands on August 22, 2011 and made initial US landfall in North Carolina as a Category 1 hurricane on August 27. It reemerged over the ocean in the MAB before a second landfall in New Jersey as a tropical storm on August 28. Irene accelerated and lost intensity as it crossed the MAB, moving parallel to the coast with the eye over inner continental shelf waters. Irene reveals the regional pattern of MAB sea surface cooling. Irene passed over the underwater glider RU16 deployed on the New Jersey continental shelf (Fig. 8.3). Glider-observed subsurface temperatures (Fig. 8.4B) indicate that initially typical MAB summer stratification was present, with a seasonally warmed surface layer and cold pool water below the thermocline.

Integrated ocean observations and calculations during Hurricane Irene (2011) reveal that the wind-forced two-layer circulation of the stratified coastal ocean, and resultant shear-induced mixing, led to significant and rapid ahead-of-eye-center cooling (at least 6°C and up to 11°C) over a wide swath of the continental shelf. Significant cooling of the surface layer (5.1°C) and deepening of the thermocline (>15 m) were observed under the leading edge of the storm. Little change in thermocline depth and much less cooling (1.6°C) of the upper layer were observed after eye passage. The glider observations suggest that much of the satellite-observed sea surface temperature cooling (over ~100,000 km$^2$ of continental shelf) occurred ahead of eye center.

Time series of atmospheric conditions (Fig. 8.4A) were recorded just inshore of the glider measuring subsurface ocean conditions along the track (Fig. 8.3, yellow line). Ocean surface currents measured by a CODAR HF radar network illustrated the rapid response of the surface layer to the changing wind direction. The cross-shelf components of the currents from CODAR data (Fig. 8.4C, red line) at the glider location indicate that the onshore surface currents (positive values) began building before the eye entered the MAB, increasing to a peak value >50 cm/s toward the coast before eye passage. After the eye, the winds changed direction and within a few hours the cross-shelf surface currents switched to offshore (negative values). Despite the strong observed surface currents, the depth-averaged current (Fig. 8.4C, green line) reported by the glider remained small during the storm's duration, with peaks barely exceeding 5 cm/s. These bottom layer currents (Fig. 8.4C, blue line) were estimated based on Eqs. (8.1) and (8.2) and suggest offshore transport as the eye approached and onshore after eye passage. This resulted in significant shear across the thermocline and affected the storm surge. These results show the value of glider data collected during an extreme event that is not possible using traditional ship sampling techniques.

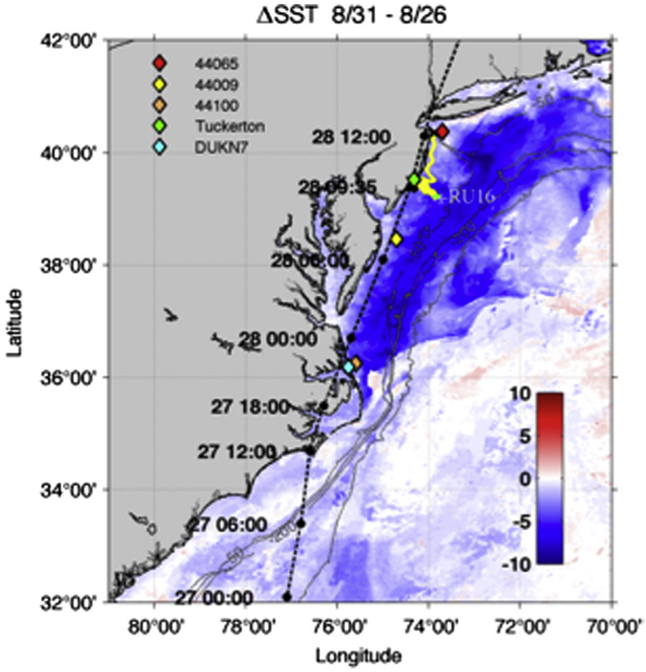


**FIGURE 8.3** SST difference map post-Irene (8/31) minus pre-Irene (8/26) with National Hurricane Center best track (*black dots* connected by *dashed line* labeled with August date and UTC time), weather buoys/stations (*colored diamonds*), underwater glider RU16 track (*yellow line with green dot* signifying location at eye passage), and bathymetry (*fine black lines*). *SST*, sea surface temperature; *UTC*, coordinated Universal Time.

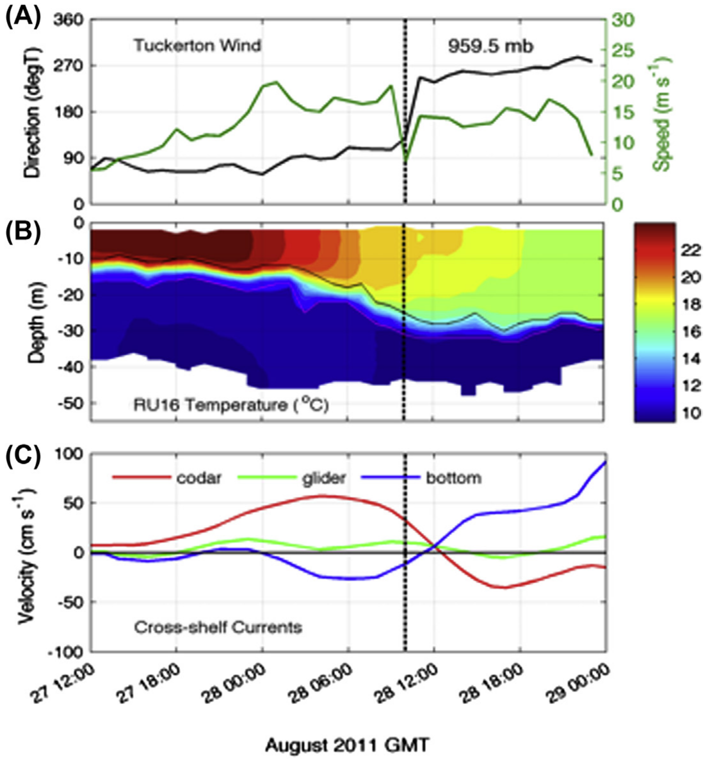


**FIGURE 8.4** (A) Tuckerton WeatherFlow, Inc. station 10 m wind speed (*green*) and direction from (*black*) with vertical *black dashed line*/label indicating the time/value of the minimum air pressure associated with the passage of Hurricane Irene's eye. (B) Glider temperature cross-section during storm conditions with lines indicating top (*black*) and bottom (*magenta*) of thermocline. (C) Cross-shore currents for the surface layer (*red*) from CODAR HF radar, depth averaged (*green*) from the glider, and bottom layer (*blue*) inferred by requiring surface and bottom layer transports to equal the depth-averaged transport.

## 8.3 ADVANTAGES AND EXAMPLES OF USING GLIDER TECHNOLOGY FOR EDUCATION AND OUTREACH

Robots are extremely effective tools for education/outreach (EO), and therefore we have been working with diverse collaborators to develop tools/curricula that use glider technology. We treat this effort with equal importance to the science and technology development in our team. Since 1996, we have focused on creating meaningful science experiences for middle and high school classrooms through data-rich activities that highlight how science research practices are conducted. These kinds of contribution are critical to current education reform efforts needed for compliance with the Next Generation Science Standards (NGSS). The goal of the NGSS is to move science instruction away from disconnected facts and toward interrelated ideas, which learners can use to explain scientific concepts and solve problems [12]. Observing systems, especially glider technology, represent an exciting new paradigm for these internet-based ocean explorations.

Our efforts early on were enabled through the National Science Foundation's Centers for Ocean Science Education Excellence Networked Ocean World (COSEE NOW) program that focused on building an online network of scientists and educators focused on using ocean data from emerging Ocean Observing Systems technologies for public education. The focus was on engaging learners in real-time data across a broad range of audiences, including community colleges, the K-12 formal education community, and informal learning institutions. COSEE NOW focused on surveying, summarizing, and distributing knowledge from educators and scientists on their use of ocean data with the overarching goal to build the ocean science community's ability to use real-time data in education and public outreach. This has resulted in myriad EO efforts, which we highlight in a range of programs that rely on glider data next.

### 8.3.1 Podcasts: Ocean Gazing

COSEE NOW and National Public Radio contributor Ari D. Shapiro worked together to develop a podcast series focused on ocean-observing technology called Ocean Gazing. The audio series consisted of 52 episodes interviewing prominent scientists and educators involved in ocean-observing science and technology development. Five of the episodes focused specifically on glider technology. Companion lesson plans were developed to help educators bring this cutting-edge science to their classrooms and inspire a generation of scientists and technologists. The Website, despite being a decade old (coseenow.net/podcast/),continues to receive visits from educators working in formal and informal learning contexts and who are interested in integrating research and data in their teaching.

### 8.3.2 Ocean Science Extended Laboratory Education Programs at Liberty Science Center, New Jersey

We have partnered with the museum at the Liberty Science Center in Jersey City, New Jersey. Our partnership has focused on creating programs that are then taught by the museum during 2-day programs focused on specific themes or topics for up to 25 students. These programs continue to be offered with one of the more popular classes being "seasonality in the ocean," which is anchored by glider data and technology.

### 8.3.3 Floor Activities With Ocean Robots

In addition, a simple glider activity called *Exploring Ocean with Robots* has been used as a floor activity at Liberty Science Center. This program uses hands-on activities to explain how buoyancy is used to propel the Slocum gliders, and introduces guests to the types of research data gliders collect. Center volunteers present the program 3–4 days a week to school groups and family groups of mixed-age children and adults. At the end of the program the Center distributes sheets with a picture of a glider that children can color, and with links to the Rutgers University glider blogs and the Center of Ocean Observing Leadership room. Finally, as an alternative approach for connecting guests with glider research once they leave the museum, Liberty Science Center has created an audio clip guests can access via their cell phone. The clip utilizes audio collected as part of the Ocean Gazing podcast series of scientists discussing their research with Slocum gliders. It has been available to guests since August 2011 via the National Science Foundation (NSF)-supported Science Now Science Everywhere capability in the museum.

### 8.3.4 Polar Interdisciplinary Coordinated Education

More recently, our team has developed additional educational initiatives through the NSF-funded Polar Interdisciplinary Coordinated Education (Polar-ICE) program. This project aims to build the capacity of polar scientists in communicating and engaging with diverse audiences while creating scalable, in-person, and virtual opportunities for educators and students to engage with polar scientists and their research through data visualizations, data activities, educator workshops, webinars, and student research symposia.

Polar-ICE is working to help educators gain access to polar data, data activities, lesson plans, and media, explaining polar science and technology. Polar-ICE supports educators in developing skills in how to use real scientific data in their classrooms, as well as support them in utilizing online data software tools to help students learn how to orient to data, as well as interpret and synthesize data observations. Students (grades 6–16) participating in Polar-ICE programs conduct polar-related science investigations to enhance their comfort with using and analyzing data, as well as presenting their results to broad audiences (Fig. 8.5). The objective is to engage students in authentic experiences in the process of science to develop positive identities in science, technology, engineering, and math, and ultimately contribute to the lifelong trajectory of identity development as scientists. Next we discuss some key initiatives of Polar-ICE.

### 8.3.5 Science Investigator Program

The Science Investigator (Sci-I) program seeks to increase the understanding of teachers and students in grades 6–9 regarding the authentic process of science by supporting them through developing, conducting, and presenting a polar-related open-ended science investigation. By mirroring the process of science through such investigations and by developing personal relationships with scientists throughout the project, we hope to increase students' identification with and engagement in science. The Sci-I program starts with a 4-day professional development workshop for middle school teachers. The intention of the workshop is to unpack the nuances and realities of the process of science while enabling the teachers to experience first-hand participating in an open-ended polar science investigation. The workshop investigates various aspects of the Palmer Long Term Ecological Research project as the data are easily available online, allow for interesting time series analyses, and are interdisciplinary in nature. A real-time glider is often the most popular. Through hands-on activities, group discussions, scientist panels, and field trips the teachers explore the following daily themes: developing truly testable questions, finding and diving into data, making sense of data, and communicating initial results. Twenty-one educators from New Jersey and California participated from 10 different schools, with approximately 1500 students in 2015. Each teacher has at least one other teacher in their school participating to increase successful implementation rates. An effort is made to increase the diversity of the students. A selected group of students attends the annual Student Polar Research Symposium to present their research to their peers, teachers, students, and polar scientists from other schools in the project.

### 8.3.6 Looking Ahead: Workshops on Teaching With Data With College Professors

The Ocean Observatory Initiative (OOI) Teaching with Data project leverages data and links it to user-friendly, interactive, online activities. Use of real data enables students to deepen their understanding of a concept while


FIGURE 8.5 A grade school data team focused on analyzing real data collected from polar systems. Gliders are consistently a popular focus for students.

enhancing their scientific and data skills. The project merges available OOI data, data visualization theory, user interface best practices, and current learning research to create OOI Data Explorations. The explorations are short (15–20 min) and use near-real-time, professionally collected data to illustrate how scientists use data. Through professional development workshops and online resources, the project develops and then supports use of ocean data in undergraduate classrooms. Teachers can thus easily and effectively integrate OOI data into their teaching. OOI data are directly relevant to the content of 14 of the 16 chapters in *Essentials of Oceanography*, the market-leading textbook used by tens of thousands of students enrolled in 2-year community colleges and 4-year universities. This project focuses on mapping OOI Data Exploration to the 14 relevant chapters providing a direct link to the tens of thousands of community college and university undergraduates across the United States. Glider data are one of key data types.

In conclusion, gliders have matured to become central tools for the oceanographer. An added benefit of these systems beyond their ability to collect data in extreme and remote locations is that they can simultaneously provide a powerful tool for education and public outreach. The ability for shore-side scientists–teachers–citizen scientists to access data/imagery during an experiment as it is happening provides a powerful and compelling tool. Ultimately, this will hopefully help a wider cross-section of society to become ocean literate and better understand the process of conducting science. This is critical as humanity will increasingly have to confront many challenges associated with accelerating observed changes in the ocean.

## Acknowledgments

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## Further Reading

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