ARTICLE

Buoyancy Gliders Opening New Research Opportunities in the Southern Ocean

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ABSTRACT

Polar systems are experiencing major changes that has significant implications for ocean circulation and global biogeochemistry. While these changes are accelerating, access to polar systems is decreasing as ships and logistical capabilities are declining. Autonomous underwater buoyancy gliders have proven to be robust technologies that are capable of filling sampling gaps. Gliders have also provided a more sustained presence in polar seas than ships are able. Along the West Antarctic Peninsula, one of the most rapidly warming regions on this planet, gliders have proven to be a useful tool being used by the international community to link land research stations without requiring major research vessel ship support. The gliders are capable of adaptive sampling of subsurface features not visible from satellites, sustained sampling to characterize seasonal dynamics, and they increasingly play a central role in the management of natural resources. Future challenges to expand their utility include: (A) developing robust navigation under ice, which would allow gliders to provide a sustained bridge between the research stations when ship support is declining, and (B) expanding online resources to provide the international community open access to quality data in near real time. These advances will accelerate the use of gliders to fill critical sampling gaps for these remote ocean environments.

Keywords: gliders, polar, ocean observing, climate

History

Polar oceans are remote, harsh, and unique environments characterized by extreme winds and large ocean-atmosphere heat fluxes, seasonal variability in sea ice extent, infestation by icebergs, and a limited ship presence. Polar marine ecosystems are regions of high seasonal biological productivity supporting unique organisms adapted to extreme conditions, and are driven by local, regional, and remote physical forcing. Over the past 200 years, these ecosystems have provided society with food, fuel, and fiber (Ainley & Pauly, 2013; Chapin III et al., 2005) and play a disproportionately large role, relative to their size, in global biogeochemical cycles (Gruber et al., 2019; Hauck et al., 2015; Moore et al., 2018). For example, the Southern Ocean alone is responsible for 40% of the annual global ocean uptake of anthropogenic CO_2 from the atmosphere (Gruber et al., 2019). These unique systems are regulated by complex interactions between the ice, atmospheric, and oceanic forcing that are difficult to sample using traditional sampling approaches given the limited number of ships in these remote locations.

The limited data collected in polar oceans is problematic as they are among the most rapidly changing on Earth, with changes to temperatures (Meredith et al., 2019; Schmidtko et al., 2014), eddy energy (Hogg et al., 2015), and biological systems (Brown & Arrigo, 2012; Morley et al., 2020; Schofield et al., 2010). These systems are sentinels of climate and ecosystem change, with charismatic species (penguins, polar bears, etc.) serving as public symbols of global change. Therefore, developing a coherent sampling strategy is critical to documenting changes in polar ocean systems and the regional to global consequences of those changes. While satellites have long proven to be an effective tool for documenting surface dynamics of polar systems (Arrigo et al., 2017, 2015; Crawford et al., 2020), these regions are often cloudy (Wang & Key, 2005; Wood, 2012), which often requires data averaging over weeks to months to provide full images. Moorings can provide high-resolution time series of great value (Brearley et al., 2017; Dickson, 2006; Martinson & McKee, 2012; McKee & Martinson, 2020; Mikhalevsky et al., 2015; Yang et al., 2021) and are important in the collection of physical, chemical, and biological data. However, moorings do not provide spatial data, and systems with near-surface measurements can be damaged by the passage of icebergs or the presence of heavy sea ice.

By the late 1990s, underwater autonomous gliders transitioned from a concept first imagined by Stommel (1989) to being a robust tool for conducting oceanographic research (Davis et al., 2002; Schofield et al., 2007), filling data gaps in subject areas ranging from boundary current dynamics to ocean-atmosphere interactions during storms to ecological dynamics in coastal shelves (Rudnick, 2016). In northern high latitudes, gliders have quantified the hydrography and circulation between the Nordic and Atlantic Ocean waters (Beaird et al., 2013; Fraser et al., 2018; Hoydalsvik et al., 2013; Ullgren et al., 2014). Additionally, sustained sampling with repeat surveys helped quantify fluxes through the Davis Strait (Curry et al., 2014) and is being integrated into marine mammal research (Aniceto et al., 2020; Baumgartner et al., 2020). In the Arctic, gliders have also been operated as a central part of a sea ice ocean observing network (Lee & Thomson, 2017; Lee et al., 2019). Using gliders to sustain sampling has been a focus in the Southern Ocean as well (e.g., du Plessis et al., 2019; Nicholson et al., 2022), and this article will highlight the range of applications that gliders have addressed specifically along the West Antarctic Peninsula (WAP) by the international community.

Glider Technology and Capabilities

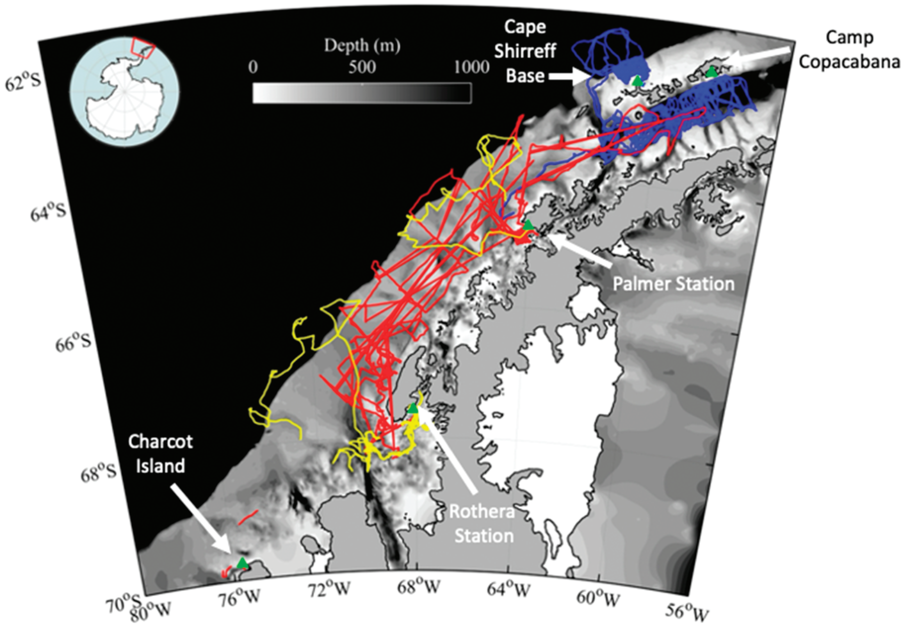
Gliders are 1- to 2-m-long autonomous underwater vehicles (AUVs) that maneuver vertically through the water column at a forward speed of 20–30 cm/s (Davis et al., 2002). The vertical motion of the platform is regulated by changing the buoyancy of the platform, and wings translate the forward motion providing the ability to sample the full water column ranging from 15- to 1500-m depths. The primary navigation system is an on-board GPS/iridium receiver coupled with an attitude sensor, depth sensor, and altimeter to provide dead-reckoned navigation, with backup positioning and communications provided by an Argos transmitter. Given this, communication is only possible when the vehicle is at surface. The mission duration of a glider is limited by battery life and is largely a function of the number of sensors and the water depth. The largest power drain in the glider involves the operation of the buoyancy pump, and, therefore, the battery life is shortest in shallow seas. Several of the gliders are modular, allowing sensor packages to be customized depending on the specific science mission. The glider duration is variable and largely a function of the number and type of sensors being carried. For gliders that have low sensor payloads Conductivity-Temperature-Depth (CTD) sensor, they have conducted missions for over a year; however, it should be noted that overall battery lifetime is dependent on the water temperature. Customized lithium batteries can extend the duration of the mission. The recent development of rechargeable lithium batteries offers the potential for rapid redeployment of systems not requiring significant ballasting efforts; however, currently, these systems have a shorter battery life.

Spatial/Temporal Coverage Provided By Gliders in the WAP

Gliders have become a critical tool for sampling polar systems. Along the WAP over the last 15 years, gliders have maintained a sustained presence in the field (Figure 1). These platforms have been used to study a variety of processes (see below) when ships are unavailable or when the region of interest is out of the safety limits of small boats launched from shore stations. To date, gliders have conducted over 75 missions over 1000 days at sea and spanning > 20,000 kilometers of the WAP (Figure 2). Given their semi-Lagrangian sampling capabilities, these platforms are filling critical data gaps spanning mesoscale circulation, biological dynamics, and storm-ocean interactions (cf. Rudnick, 2016). Shore-based field stations are maintained by the international community along the WAP with ocean sampling conducted from small vessels (Figure 1). These smaller vessels have limited spatial coverage (measured in tens of kilometers) in large part for safety considerations because weather in the WAP is subject to rapid change and it is not rare for wind intensity to increase by an order of magnitude on time scales of less than an hour. Gliders have provided a unique tool

FIGURE 1

Deployments of gliders along the West Antarctic Peninsula. Yellow lines indicate glider missions from the British Antarctic Survey, red lines indicate the surveys of Rutgers University, and blue lines indicate the missions from the National Oceanic and Atmospheric Administration. The green symbols indicate gliders' locations anchored by land-based stations or ships.



to maintain a sustained spatial presence in the coastal regions surrounding these shore stations.

The Palmer Long Term Ecological Research (LTER) program is focused on how long-term change associated with climate will ripple through the food webs. Figure 2 shows the multiyear presence of gliders deployed from the United States Palmer Station collected as part of the National Science Foundation LTER program. Sampling at Palmer Station is focused on understanding how biophysical interactions influenced by an irregular seafloor topography (especially associated with the Palmer Deep sea floor canyon, Figure 2A) support a biological hotspot with high primary productivity and abundant higher trophic levels (whales, seals, penguins). The sustained sampling in this region (Figure 2B), despite strong local currents (Oliver et al., 2013), is possible given the ability of the glider to remain for long periods in location. The glider presence is allowing for the first time the construction of a summer season climatology of phytoplankton biomass showing an initial summer phytoplankton bloom and then a secondary bloom in the late summer months (Figure 2C).

Further south along the peninsula at the UK Research station of Rothera (Figure 1), small boat-based year-round CTD and biological observations have occurred since 1998 as part of the Rothera time series (RaTS) (Venables et al., 2023). While these measurements take place within a deep coastal embayment (520 m), knowledge initially remained limited around the physical and biological connectivity of the coastal station with the wider WAP shelf, in particular its relationship with the deep Marguerite Trough (up to 1400 m) that provides a pathway between the open Southern Ocean and the inner shelf up to George VI ice shelf. Since 2012, gliders have formed an important part of the RaTS sampling, providing a clearer understanding of this connectivity and its implications for both ocean circulation and near-surface productivity (Venables et al., 2017).

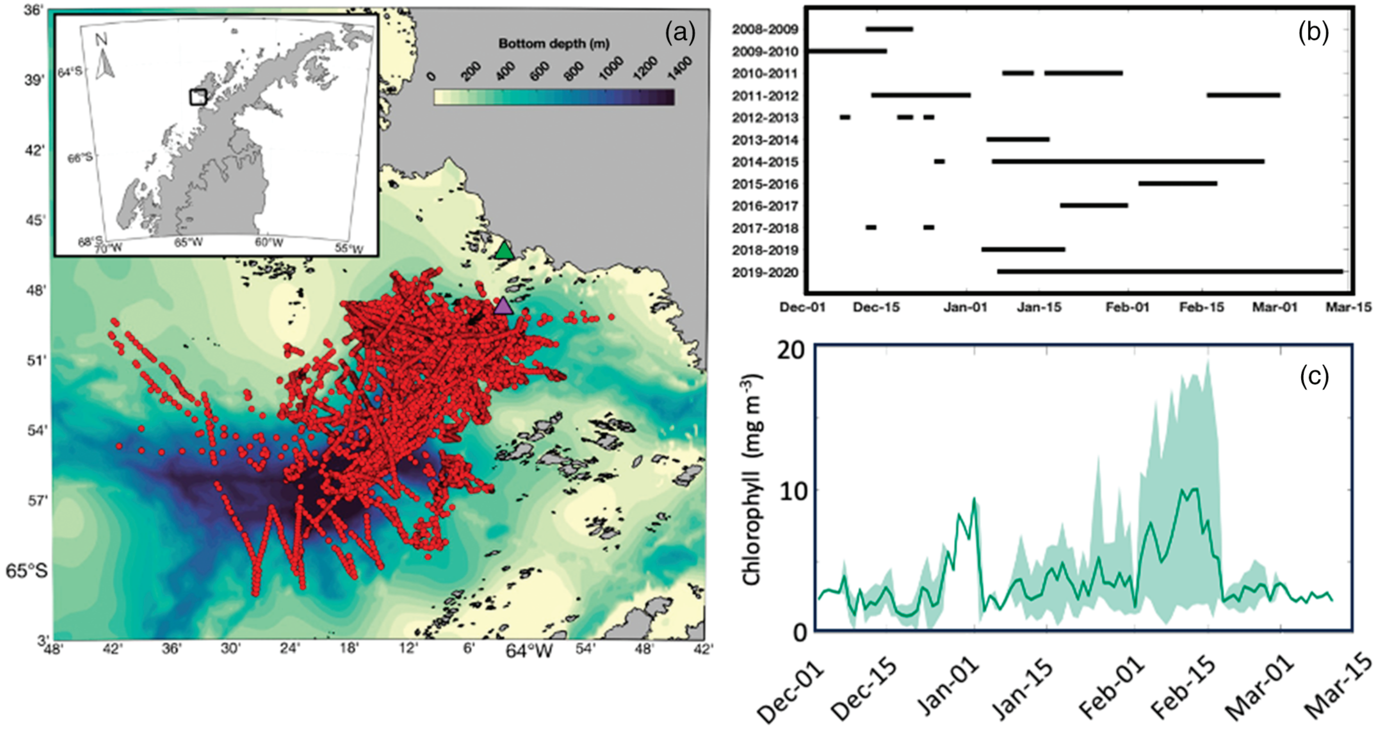
While ship-based sampling is a critical tool for mapping regional biological patterns, efforts chronically under sample of the system, reflecting the relatively low availability of research vessels for these remote locations. One strategy to overcome these limitations is to combine gliders from the numerous field stations spanning the WAP. This offers the unique opportunity for developing an international robotic network. The strategy is based on flying gliders between the shore-based field stations where they can be recovered, rebatteried, and redeployed to then fly back to the original field station. This provides a means to map broad swaths of the WAP continental shelf without significant ship support for sustained periods of time. The potential of this approach was demonstrated when a glider was launched from the United States Palmer Station and flown to and recovered by the United Kingdom Rothera research base (Figure 3). Given that the number of available research vessels is decreasing with the United States moving from a two research vessel operation to a single research operation, this strategy will provide an opportunity to maintain a sustained presence in a remote region.

Adaptive Sampling of Mobile Subsurface Features

The WAP is one of the fastest winter warming locations on the

FIGURE 2

Glider coverage at Palmer Station. (A) Spatial sampling at Anvers Island located over the Palmer Deep sea floor canyon, which is critical for penguin ecology (Schofield et al., 2013). The triangles indicate the long-term time series locations collected using traditional zodiac water sampling. (B) The temporal glider coverage of 12 years at Anvers island. (C) The fluorescence-derived chlorophyll climatology for the region (black line) with the green shading representing the maximum and minimum around the mean.

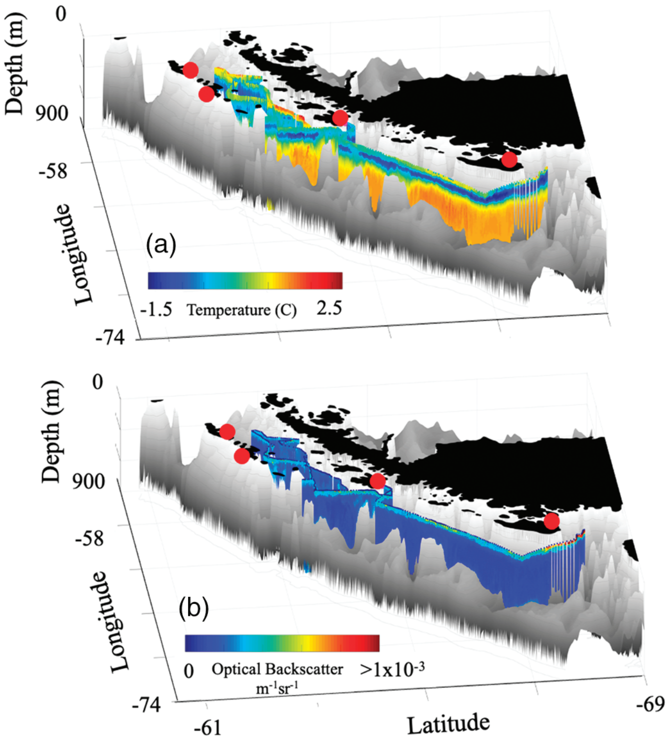


planet with the majority of glaciers in full retreat (Cook et al., 2005) and the annual sea ice exhibiting decadal declines (Stammerjohn et al., 2008). One dramatic example of this was that Rothera had no period of fast ice in the winter of 2022, which is the first time since recording started in the mid-1990s. These changes have been linked to a warming atmosphere and ice melting from below with the heat associated with onshore transport of offshore water (Cook et al., 2016; Couto et al., 2017; McKee et al., 2019; Pritchard et al., 2012; Rignot & Jacobs, 2002). The Upper Circumpolar Deep Water (UCDW) is the largest source of heat to the WAP continental shelf (Hofmann et al., 1996). While upwelling has been suggested as the potential delivery mechanism of UCDW (Dinniman et al., 2011; Martinson et al., 2008), higher resolution data (Martinson & McKee, 2012; Moffat et al., 2009) and models (Graham et al., 2016) suggest the delivery is associated with coherent eddies that move onto shelf and dissipate heat as they move onshore. These subsurface eddies are small with diameters of 10–15 km, cannot be detected by satellite, and move across the shelf, making them difficult to resolve using traditional oceanographic sampling approaches.

Gliders have proven unique tools for studying these dynamic subsurface features. Warm-core, subpycnocline, primarily anticyclonic eddy-like features have been observed and modeled several tens of kilometers from the shelf break, particularly in the vicinity of Marguerite Trough (Brearley et al., 2019; Couto et al., 2017; Graham et al., 2016; McKee et al. 2019; St-Laurent et al., 2013). Glider surveys were designed to sample these dynamic features by first documenting gradients along the axis of advection for any eddies encountered along the way, and then identifying and tracking an eddy in real time through data-adaptive sampling using the warm modified UCDW temperature as a hydrographic fingerprint. This allowed, for the first time, high-spatial and temporal resolution transects directly through some of these eddies and a real-time quantification of the attenuation of their core properties. The transects revealed a composite vertical structure, lateral size, and rotation consistent with theoretical instabilities. To quantify attenuation, a glider occupied a "fence" perpendicular to the

FIGURE 3

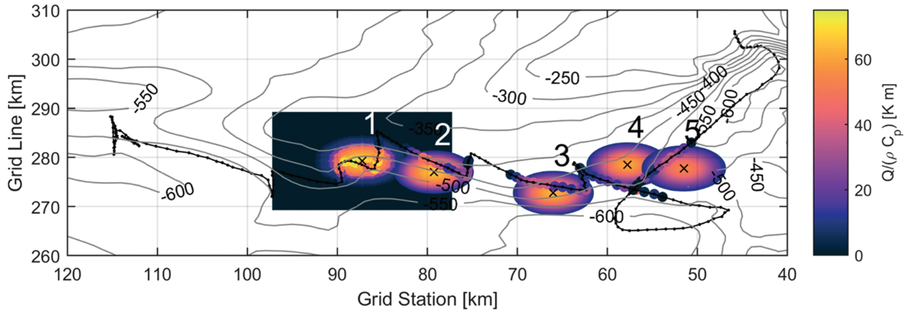
Gilder survey of the West Antarctic Peninsula. Panel A shows temperature with the characteristic winter water structure. Panel B shows the optical backscatter with particles largely found in the surface layer. Red circles indicate the land-based field station. The glider was launched from Palmer Station and was remotely piloted to the British Rothera Base in the south.



eastern wall of Marguerite Trough (Figure 4) and, when it encountered a feature with the warm signature of the UCDW, the glider sampled the water until the hydrographic feature was no longer detected. The glider was then directed to fly shoreward in the trough to move ahead of the eddy and resample it again. This adaptive sampling strategy was able to look at the heat loss of these eddies for almost 4 days, finding the rate agreed well with that of a simple diffusion model initialized with the eddy's initial structure and governed by diffusivity coefficients parameterized from historical density and velocity data (McKee et al., 2019, Figure 4). The results suggest eddies lose heat both laterally and vertically downward, which preserves the subsurface heat capable of melting marine-terminating glaciers (McKee et al., 2019). Closer to those marine-terminating glaciers, Scott et al. (2021) have used a microstructure instrument on a glider to quantify directly the turbulent diffusivity and vertical heat fluxes out of the CDW layer. While these heat fluxes were low (~1.3 Wm^{-2}), significant enhancement was observed during strong wind events and over a shallow sill linking Ryder Bay (where RaTS is based) with Marguerite Bay.

FIGURE 4

Glider-adaptive sampling of Marguerite Trough. The black line indicates glider trajectory, and dots indicate profile locations, with larger dots indicating presence of modified circumpolar deep water and their color indicating integrated heat content. Color contours indicate vertically integrated heat content from a numerical diffusion model initialized with the eddy's initial condition (box shows domain size), with eddy location at each time step (1–5) determined by grid search algorithm as the location that minimized mismatch between glider sampling of the real and modeled fields. The inferred trajectory (along-isobath) and speed are consistent with regional currents.

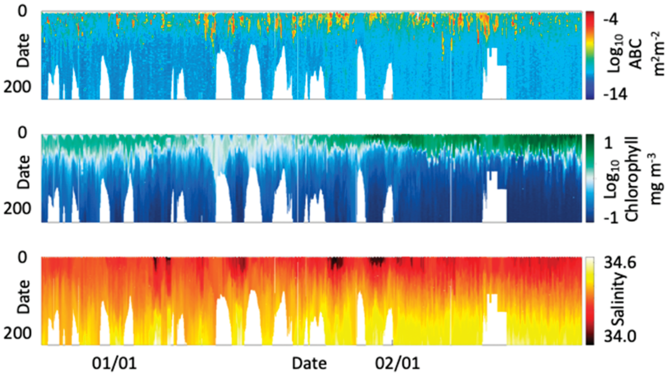


Providing Ecosystem Data to Support Management Requirements

Polar systems are very productive with rich biological resources that have provided great value to society and will continue to do so (Ainley & Pauly, 2013). Managing these resources is difficult given the extreme locations, and many of the key fishing regions are in remote international waters. Management practices are critically important given the historical evidence that humans can overexploit the natural resources. Antarctic krill (*Euphausia superba*) is the principal meso-zooplankton and is critical to Southern Ocean ecology, and it is the target of a large commercial fishery

FIGURE 5

Contour plot of (A) $\log_{10}$ acoustic backscatter coefficient (ABC $m^2\ m^{-2}$), (B) $\log_{10}$ chlorophyll-a fluorescence (mg m^{-3}), and (C) salinity during typical seasonal (mid-December through mid-February) glider deployments off Cape Shirreff Livingston island, Antarctica. Krill aggregations are visible in the upper 100 m of the water column in Panel A, with few large aggregations observed at depth. Glider-based echosounders provide opportunity to examine fine-scale water column relationships between krill, primary production, and the physical environment throughout the water column over deployments spanning multiple months.



(Nicol & Endo, 1997). This fishery is expanding given the growing demand for krill to supply the increasing demand by fish aquaculture and krill oil/nutraceutical industries (Meyer & Kawaguchi, 2022). This is increasingly important as many regions of krill fishing are exhibiting significant change that includes warming temperatures, declining sea ice, and retreating glaciers (Schofield et al., 2010).

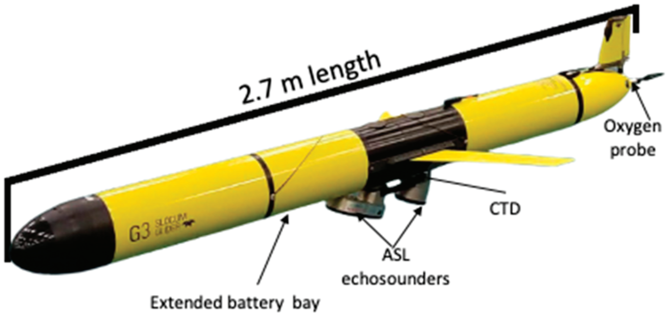
Biological resources in the Southern Ocean, including Antarctic krill, are managed using ecosystem-based approaches, through the Convention for the Conservation of Antarctic Marine Living Resources. For krill, this effort has been historically anchored by ship-based surveys combining net tows with acoustic surveys conducted by research or fishing vessels (Fielding et al., 2014; Hewitt & Demer, 2000; Krafft et al., 2021; Reiss et al., 2008). Globally, the costs for traditional fisheries independent surveys have become prohibitive and there have been efforts to conduct resource surveys autonomously (De Robertis et al., 2021; Reiss et al., 2021). The adaptation of both single frequency (Ainley et al., 2015; Guihen et al., 2014, 2022) and multi-frequency (Chave et al., 2018; Taylor & Lembke, 2017), single-beam or wideband (Benoit-Bird et al., 2018) echosounders onto gliders provides new opportunities to acoustically estimate the biomass of meso-zooplankton, specifically Antarctic krill (Reiss et al., 2021) across time and space scales required to manage resources and to link trophic scales from primary production through secondary production.

Modeling studies have demonstrated that gliders sampling with their sawtooth pattern can effectively recover the time series of biomass density of krill (Kinzey et al., 2022; Figure 5), though some observational evidence exists of avoidance behavior by krill to AUVs, which needs due consideration when designing sampling campaigns (Guihen et al., 2022). Ten years of ship-based acoustic survey data collected in the Antarctic were resampled by flying a virtual glider through the data and then calculating the mean biomass density for each of the ship surveys. A single glider diving to 150 m and acoustically sampling a further 100-m range recovered the temporal pattern of krill biomass density observed in ship-based surveys, and these estimates fell within 1 *SD* of the ship-based estimates nearly 100% of the time. Increasing the number of gliders decreased the variability, while increasing the glider dive depth increased the variability as fewer profiles through the krill swarms in the surface layer are conducted. The results of these simulations provide a roadmap for developing more robust sampling strategies that can be used to provide input in resource assessments.

The use of scientific echosounders to conduct ecosystem or resource surveys requires identification of acoustic targets in order to allocate acoustic energy to targets of interest and to convert acoustic energy to biomass density using appropriate target strength models. Gliders, with the capacity to sample the pelagic ecosystem autonomously for months at a time (Figure 6), are unlikely to always sample with information about the size and composition of planktonic targets. Using multi-frequency or broadband echosounders allows differencing models to be used to discern targets of interest from other acoustic scatters, where the difference in the return strength from different acoustic frequencies are used to provide information about the likely targets (Kang et al., 2002). However, as battery life increases, the addition of optical systems to verify the acoustic targets should become integral to the use of gliders in remote locations, like polar environments where

FIGURE 6

Standard U.S. Antarctic Marine Living Resources Program extended duration, multifrequency (38, 67.5, and 125 kHz), narrowband echosounder-equipped TWR Slocum glider used for estimating krill biomass density around the South Shetland Islands Antarctica during annual resource surveys.



other ecosystem surveys are less likely to be performed.

Challenges and Steps Moving Forward

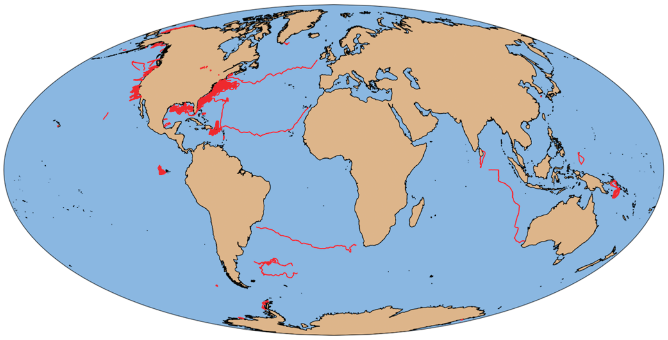
Under-ice navigation. Many changes in polar systems are associated with critical processes occurring under sea ice and ice sheets. As these ice-covered regions represent ~12% of the world's ocean, it is imperative to sample them for improved understanding of physical circulation, ecosystem structure, vertical mixing, and changes associated with long term anthropogenic change. Unfortunately, these are among the most difficult regions in the ocean to sample. Under-ice navigation has been achieved using fully capable AUVs (see Barker et al., 2020; Norgren et al., 2014) with strategies using acoustics from low-frequency sound sources, or multiple sound sources, and/or a surface vessel directing the robots. These approaches unfortunately are difficult for gliders given their long missions (hundreds of kilometers, multiple month missions), that the platforms undulate and the doppler navigation logs are not gimbled, and that ice complicates the use of surface vehicles.

There are generally two strategies for under-ice navigation by autonomous vehicles. One strategy is based on internal navigation sensors (inertial navigation, doppler velocity log) that estimate the location of the vehicle by tracking the velocity and accelerations. Navigation accuracy over time degrades as long under-ice missions can experience significant navigational drift associated with inertial sensors. Additionally, the types of navigational aids are limited on gliders due to constrained energy budget associated with gliders. The second strategy is based on external signals that often use sonar imaging or acoustic positioning to determine the vehicle position relative to geographic features (Claus & Bachmayer, 2015; Webster et al., 2015). This is a difficult problem given the relatively poor sea floor maps for most polar regions, the relatively low contrast features of ice compared to terrestrial systems, and because features, such as sea ice/icebergs, move (Bandara et al., 2016). Despite these challenges, ice-tethered acoustic navigation beacons have been able to coordinate under-ice missions of Seagliders for up to 12 days (Webster et al., 2015). A high priority and continuing efforts will expand these capabilities. Strategies include the potential use of fixed location beacon "runways" leading to land-based field stations for recovery. This could involve the placement of bottom, or ice, mounted navigation beacons, allowing the glider to track into location. This strategy will benefit from improved onboard processing and adaptive control of the systems (Duguid & Camilli, 2021).

Community cyberinfrastructure. The accelerating use of gliders has fueled the need to develop international open access data systems, allowing the wider community to utilize

FIGURE 7

The glider deployments that are currently available in the NOAA Glider DAC.



the data. This model of open access has been a hallmark and critical to the global success of the Array fir Real-Time Geostrophic Observatory (ARGO) network. The development of these systems is rapidly evolving. In the United States, the Glider Data Assembly Center (DAC) began development in 2013 and has been maturing over time driven by investments from the Integrated Ocean Observing System. Initial implementation of the DAC focused on physical data for submission to Global Telecommunication System, but in 2017, it began to accept submission of full deployments. Currently data flows to the National Centers of Environmental Information for permanent archiving. The system is also expanding the range of the data types available through the DAC. Use of the Quality Assurance/Quality Control of Real-Time Oceanographic Data protocols is a requirement for inserting data into the DAC. The system is open to anyone willing to provide the correct formats and required metadata. Currently, the DAC has 1,539 total data sets (1,059 real-time and 480 delayed mode data sets) (Figure 7). While the number of data sets is growing, it represents just a subset of the available glider deployments, and future efforts should collate and provide the full data sets as it is possible. A second major data system is the European Gliders for Research Ocean Observation and Management (GROOM). This system is designed to provide a multi-faceted cyberinfrastructure system designed to serve a wider range of autonomous systems and capabilities including system control and optimized links to operational numerical models. It is being developed to provide an integrated system supporting operations-maintenance, data sharing and harmonization, and piloting infrastructure. As systems such as the DAC and GROOM mature, a major challenge will be to ensure wide community adoption to provide a few centralized portals that leverage engineering, methods, and scientific analysis by the distributed community.

In conclusion, gliders are and will increasingly become an indispensable tool for studying polar systems. Given the rapid and accelerating changes in these regions, gliders will be a central tool to filling data and informational gaps. This comes at a critical time as polar systems are exhibiting accelerating change. These changes include hemispheric declines in sea ice (Eayrs et al., 2021) as was evidenced by the 6.4-sigma event in sea ice decline observed in 2023 (Cassella, 2023). The ramifications of these changes on the ocean biogeochemistry and ecology remain an open questions. Gliders will be a critical tool to addressing these important questions. Additionally, the open access data developments will provide a means to engage the wider science community in science discoveries as access to these remote locations is likely to decline in the near term with the declines in the available ship time.

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