# Gliding into the Future

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## *A look at Canada's glider activities, challenges, and growth opportunities.*

### Who should read this paper?

The audience for this paper is anyone interested in ocean technology and how new technologies can be used to observe the ocean, especially for monitoring purposes. The content of the paper is appropriate for the general population who would like to know more about how governments monitor the ocean; scientists who want to know more about the glider technology, its application, and its clients; and stakeholders who want to invest in sustained ocean observations. This paper is of interest not only for Canada, but for other countries looking to launch their national glider program.

### Why is it important?

Societal needs for ocean observations have never been so great. Whether it is to inform the public on recreational hazards, to disentangle the impacts of overlapping commercial activity, to inform fisheries management and assess ecosystem services, or to improve weather forecast systems, observing the ocean has become an area of priority for many countries around the world. Monitoring is a very specific type of information that becomes critical in a time of rapid environmental changes: long-term monitoring time series are the only ones capable of resolving decade-to-century scale changes in climate. In this paper, the authors introduce ocean gliders as an emergent technology that can be used to better monitor coastal waters and fulfil some of the benefits mentioned above.

This work has been co-authored by Fisheries and Oceans (DFO) glider experts who have been using the glider technology to monitor Canadian waters since 2018. It introduces the glider technology, gives an overview of glider monitoring activities in Canada, discusses the clients for these data, and lays the basis of what would be a state-of-the-art glider program in Canada (including data management, budget, staff, etc.). The document was prepared by the DFO Working Group on Ocean Gliders.

### About the authors

Dr. Frédéric Cyr is a research scientist who recently joined the Centre for Fisheries and Ecosystem Research (CFER) at the Fisheries and Marine Institute of Memorial University. His research is centred on the ocean climate and its effect on fisheries. Before joining CFER in 2025, he worked at the Northwest Atlantic Fisheries Centre (DFO Newfoundland and Labrador) for eight years. During his time at DFO, he was a lead author for the Atlantic Zone Monitoring Program (2018-2025) and chair of the DFO ocean glider working group (2019-2024).

Dr. Tetjana Ross is a research scientist at DFO in Sidney, British Columbia, who has spent her career exploring new ways to look at the ocean using innovative tools: broadband high-frequency acoustics, turbulence sensors in combination with underwater video, and autonomous platforms (floats and gliders). Over the last 10 years, she has co-developed a robust glider monitoring program in the Canadian Pacific. She leads the Deep Argo and Northeast Pacific programs for Argo Canada. She focuses on the physical oceanography of the Northeast Pacific Ocean and how it interacts with the productive continental shelf (from zooplankton to whales). She also investigates how the deep ocean is changing and how this might impact deepsea ecosystems. She is also involved with the Line P and La Perouse long-term monitoring programs.

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Dr. David Hebert is a retired research scientist from the Bedford Institute of Oceanography. Before his retirement, he was a lead author for the Atlantic Zone Monitoring Program and principal investigator of the DFO coastal glider group, using autonomous ocean gliders to sample the continental shelf and slope of Atlantic Canada (2017-2024).


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# EVALUATING SUSTAINED OCEAN MONITORING USING UNDERWATER GLIDERS IN CANADA

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ABSTRACT

Ocean monitoring carried out by governmental agencies is instrumental to understand marine ecosystems dynamics, especially in a time of rapid environmental changes. In Canada, Fisheries and Oceans Canada, the federal agency responsible for safeguarding Canada's three ocean basins, has been using ocean gliders for ocean monitoring purposes since 2018, following significant investment in new technologies starting in 2016. Ocean gliders are autonomous underwater vehicles capable of acquiring a suite of valuable environmental information, from the ocean surface down to 1,000 m depth, along standardized monitoring sections on Canada's East and West coasts. This information is used by multiple organizations to sustain both national and international programs. This paper outlines the progress and realization made at DFO regarding the glider technology and its use for monitoring the ocean in Canada. This paper includes an overview of the glider technology, the identification of clients, an overview of current glider activities, and the challenges. The requirements for data management and dissemination are also discussed as well as potential extensions to the program. Reflections are also made on the resources needed to operate a sustainable national glider program in Canada to monitor the ocean. The information contained here may serve as a baseline to plan other sustained glider monitoring programs in the world.

**Keywords:** Underwater gliders, monitoring, ocean, Canada, climate

## 1. INTRODUCTION

Societal needs for ocean observations have never been so great. Whether it is to inform the public on recreational hazards, to disentangle the impacts of overlapping commercial activity, to inform fisheries management and assess ecosystem services, or to improve weather forecast systems, observing the ocean has become an area of priority for many countries around the world. As a case in point, the United Nations (UN) recently proclaimed the UN Decade of Ocean Science for Sustainable Development (2021-2030). As part of this framework, available high-quality ocean observations form the basis for a resilient and sustainable Blue Economy [1].

Among the wide range of ocean observations methods, monitoring is a very specific type of information that becomes critical in a time of rapid environmental changes: long-term monitoring time series are the only ones capable of resolving decade-to-century scale changes in climate [2]. Environmental monitoring is usually carried out by governmental agencies that can dedicate long-term funding to such programs, and because the long-term impacts are often considered less attractive to academic researchers who generally favour short-term and high-impact research [3]. Nevertheless, environmental monitoring and long-term climate time series are so instrumental for our understanding of the Earth system that some researchers have advocated to give them a World Heritage status [4].

Ship-based hydrographic surveys have long been used to observe the ocean [5]. While those oceanographic measurements can often not be replaced (ships are needed for mooring work, water samples require manipulation on board, plankton nets, etc.), emerging new technologies such as autonomous Argo floats and underwater gliders are now contributing to ocean observation programs worldwide. These technologies also provide valuable near real-time information for operational oceanography and to improve, among other things, weather forecasts [6].

Ocean gliders are battery-powered Autonomous Underwater Vehicles (AUV) capable of cruising the ocean by adjusting their buoyancy. They can complement monitoring activity performed by traditional hydrographic surveys [7]. They can travel autonomously over hundreds to thousands of kilometres – during weeks to months at a time – while regularly sampling the ocean using onboard sensors. Gliders profile up and down the water column in sawtooth patterns and new instructions, or sampling strategies, can be communicated from land via satellite communications during their resurfacing. While the quality of the sensor data is comparable to that of ship-based surveys, the spatial resolution achieved with gliders along transects is much higher (order of ~1 km for gliders compared to ~10 km for traditional ship-based surveys). Moreover, gliders can operate in harsh oceanic conditions (e.g., storms and, in some circumstances, under ice) and sustain repeated observations over many months. They fill an important gap between the coast and the open ocean left by the Argo program that generally cannot sample waters shallower than 1,000-2,000 m.

Ocean glider technology is also highly cost-effective and environmentally friendly (they do not produce $CO_2$). For example, while a typical cost-per-profile can be more than CAD$1,000/cast for ship-based conductivity-temperature-depth (CTD) casts using a rosette (calculation based on the cost for ship operation of tens of thousands of dollars per day), gliders can realize dozens of casts per day at a rate of <$10/cast (calculation based on communications and deployment cost, battery replacement, and sensor calibrations). Gliders can also cover large geographical areas, and their real-time observations are generally assimilated into weather prediction systems. However, gliders cannot systematically collect water samples and are thus a complementary technology to ship-based operations. This document describes the current state of Fisheries and Oceans Canada (DFO) glider monitoring activities, offers lessons learned, and describes what is needed to sustain an operational glider program in Canada to monitor the ocean. We hope that the information collated here will be valuable not only for Canada, but for any other country interested in using ocean gliders to monitor its waters.

## 2. OVERVIEW OF CURRENT GLIDER MONITORING ACTIVITIES

Ocean gliders were acquired by DFO in 2017 and 2018 to supplement existing ocean monitoring and support the department's mandate of safeguarding Canada's waters. Given the vastness of Canada's coasts, the different requirements between the regions, and to spread the expertise, the decision was made to have two separate fleets. One fleet is hosted on the East Coast at the Bedford Institute of Oceanography (BIO), and another one on the West Coast at the Institute of Ocean Sciences. It was also decided that gliders would be mainly used for monitoring purposes. In this section, we give an overview of the current glider activities at DFO.

### 2.1 West Coast Activities

On the West Coast, the historical monitoring of Line P, a hydrographic section regularly monitored since 1959 [8], was the initial section targeted. Given the distance to be travelled for Line P (1,400 km one-way), two non-rechargeable Slocum gliders were initially purchased for this monitoring in 2017, one of which was lost. Later, when more investment was made in the West Coast Glider Program through the start of the Canadian-Pacific Robotic Ocean Observing Facility (C-PROOF) collaboration between DFO, University of Victoria (UVic), University of British Columbia, and Hakai Institute, two coastal sections (Calvert and Southern lines) were added (Figure 1). Over the following years, several new gliders were added to the fleet: 2018, one rechargeable coastal SeaExplorer glider (DFO funding); 2019, one non-rechargeable Slocum and one rechargeable SeaExplorer (UVic, C-PROOF/DFO funding); 2022, five extended-rechargeable Slocum gliders (C-PROOF funding); 2023, two Slocums, one for monitoring, one with specialized sensor (C-PROOF funding). Including two other external gliders obtained through collaborations, the group now operates eight Slocums and two SeaExplorer gliders for monitoring purposes. The additional three gliders are kept for special process studies.

### 2.2 East Coast Activities

On the East Coast, four gliders were initially purchased to monitor the historical Halifax

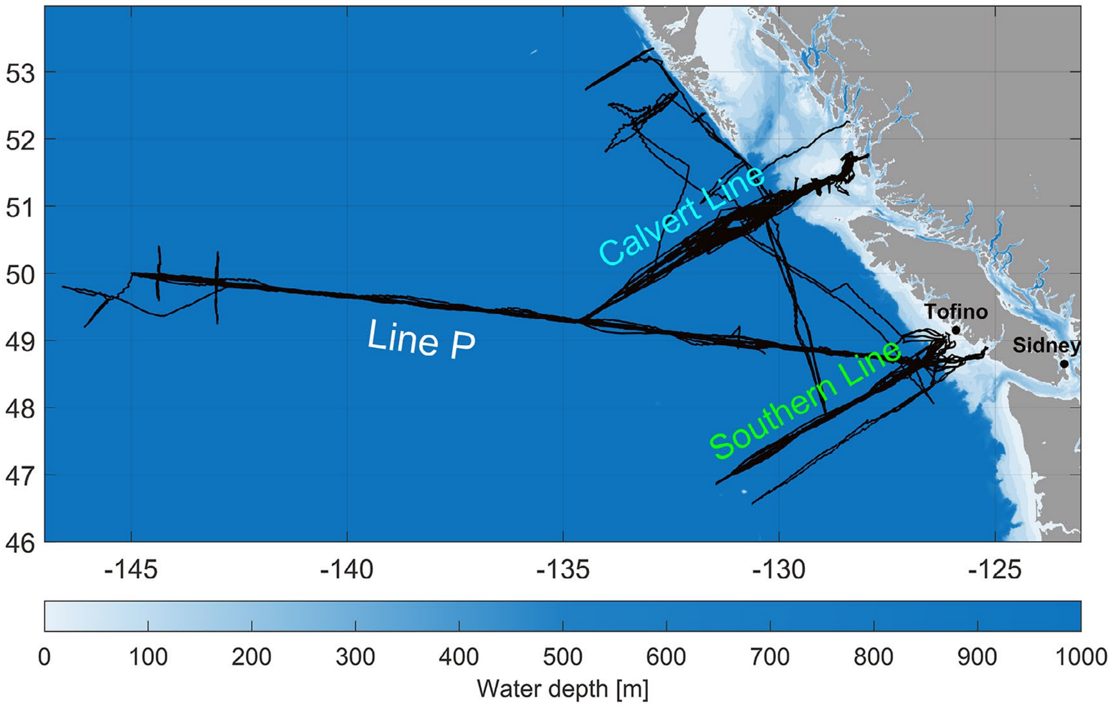


Figure 1: Three sections are monitored on the West Coast. From North to South: Calvert Line, Line P, and Southern Line. For more information, see https://cproof.uvic.ca/.

Line on the Scotian Shelf. This section was first targeted because of previous glider occupations made as part of a DFO-academia collaboration between 2011 and 2016 [9]. DFO operations on the Halifax Line began in 2018. In November 2018, the Bonavista Bay monitoring section on the Newfoundland Shelf was added as one of the core monitoring sections after a successful proposal process overseen by DFO's Ocean Science Observation and Monitoring subgroup (Figure 2). A fifth glider and a passive acoustic payload were purchased in 2018 to use on the East Coast SeaExplorer gliders, which has been used to run missions related to marine mammals.

**2.3 Whale Acoustics Slocum Glider Program**

The Whale Acoustics Slocum Program was funded externally to DFO by the Nature Legacy Fund. In 2022, four Slocum gliders with rechargeable batteries were purchased. While these activities are done in collaboration with the East Coast glider group, they are not considered part of the core monitoring program targeted in this document. However, because the oceanographic data (e.g., CTD) acquired through the Whale Acoustics Program is managed as if coming from regular glider deployments, this program is considered an extension of the proposed work and is worth mentioning here.

3. CLIENTS

Monitoring data acquired by gliders can respond to several societal needs. For example, in the United States, ocean gliders have been used to monitor the California Current System in support of the California Cooperative Oceanic Fisheries Investigations (one of the longest running boundary current observational programs in the world) [10], to support

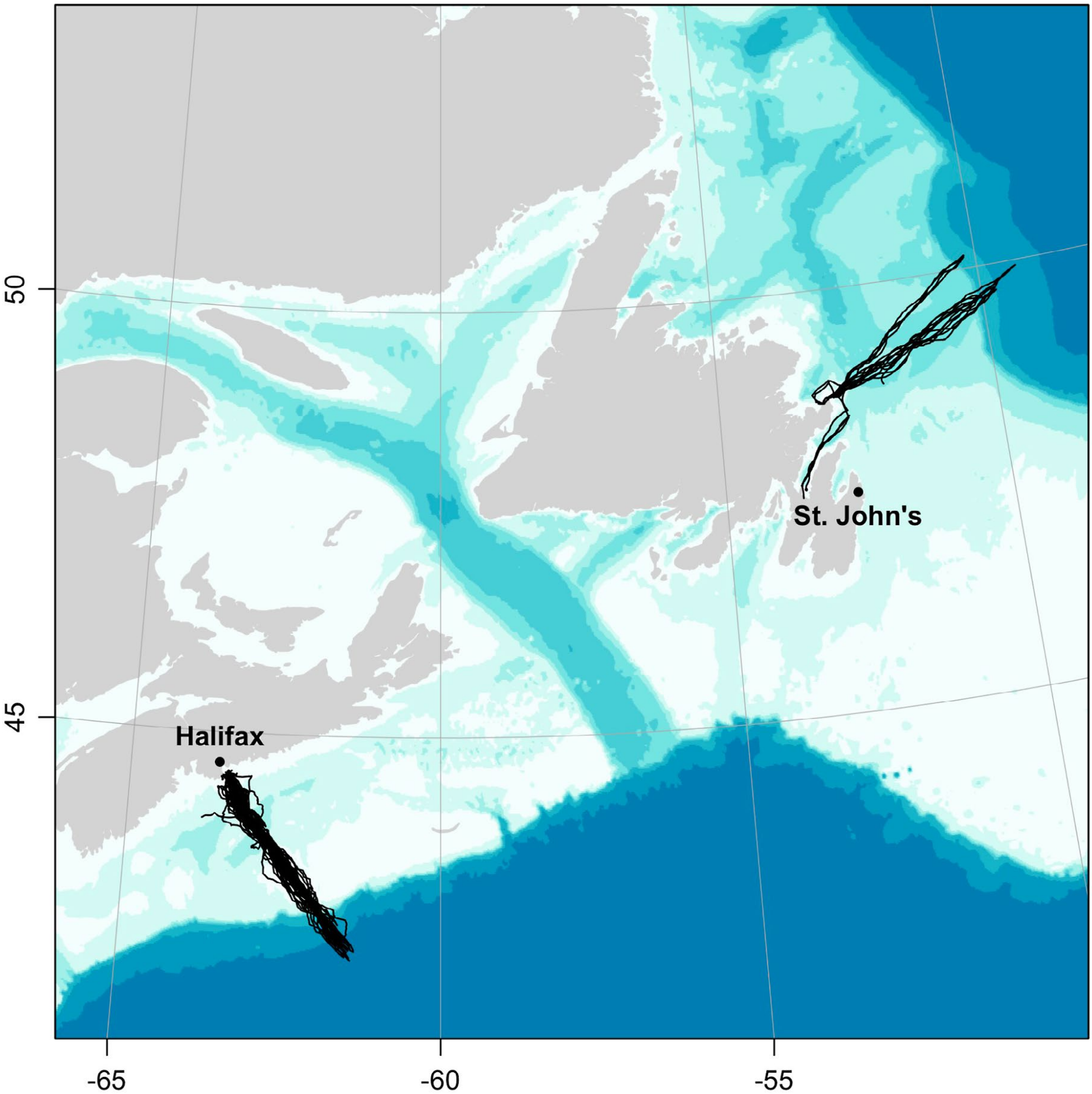

Figure 2: Two sections are monitored on the East Coast. From North to South: Bonavista Bay in Newfoundland and Halifax Line in Nova Scotia.

hurricane forecasting and research [11], and to report the presence of marine mammals in the ocean [12]. In Canada, gliders have been used to support monitoring programs and their use to plan and monitor Marine Protected Areas (MPAs) has been demonstrated [13].

Two distinct categories of data are routinely acquired by gliders: near real-time and delayed-mode. There are numerous clients that benefit from one or the other category of data. In this section, we review some of the societal needs that can be filled with ocean gliders in Canada.

**3.1 Near Real-Time Data**

When gliders connect to shore-based servers via satellite communications while on a mission, they not only receive adjustments to their onboard navigational programming but also can transmit science data. Typically, these data are sub-sampled to reduce transmission time. This is because transmission time is not only costly, but it is also only possible when the glider is at surface where the risk of biofouling and collisions with ships is greater. These real-time data are highly valuable both to the pilots (e.g., confirming sensor functionality) and, due to their timeliness, for assimilation into ocean forecasting models. Typically, the near real-time hydrographic data from DFO gliders are made widely available on the Global Telecommunication System (GTS) within 24 to 48 hours, i.e., the timeliness necessary to be assimilated in short-term weather forecast models. Once on the GTS, these data can also be assimilated by international weather and climate forecasting groups. Clients include the Canadian Operational Network of Coupled Environmental Prediction Systems (a joint program between DFO, Environment and Climate Change Canada, and the Department of National Defence), the European Centre for Medium-Range Weather Forecasts [14], and the US National Oceanic and Atmospheric Administration's National Weather Service.

Because the path the gliders take can be adjusted at every surfacing, another use case for the near real-time glider data is to explore events as they occur. There are two examples of this to date from the West Coast program. The first example is when the glider passes through a Haida Eddy while traversing the Line P monitoring line [13]. Haida Eddies are highly relevant to the Tang.g̱wan – ḥačxwiqak – Tsigis MPA, the Deep Sea Ecology Program, and Line P Monitoring Program. The real-time observation of the Haida Eddy allowed adaptation of both the glider and subsequent Line P cruise sampling plans to quantify the biogeochemical impacts of this eddy in the NE Pacific.

The second example of adaptive sampling enabled by near real-time data is when a glider was used to determine the end of the widespread deoxygenation event on the West Coast of Vancouver Island [13]. During the summer of 2021, a deoxygenation event that occurred west of Vancouver Island was deemed highly relevant to marine conservation, the Ocean Protection Plan, La Perouse, and aquaculture programs. Thanks to near real-time glider data from the Southern Line, where monitoring continued in the fall after the end of traditional fall sampling cruises in the region, scientists were able to determine the end date of the low oxygen event over a wide range of locations [15].

**3.2 Delayed-Mode Data**

Once gliders have completed their missions and are recovered, the high-resolution delayed-mode data are downloaded and made available. Typically, these data are quality controlled by software, supervised by a scientist with knowledge of the region, and compared to reference data collected as part of ship-based monitoring programs. This can take several months or longer depending on staff availability and volume of data, but the resulting data are highly valuable for a wide variety of scientific and forecasting applications. These data are useful for any client that needs high quality ocean observations.

Glider data are useful for exploring the boundary between the coast and the open ocean, a region usually not covered by the

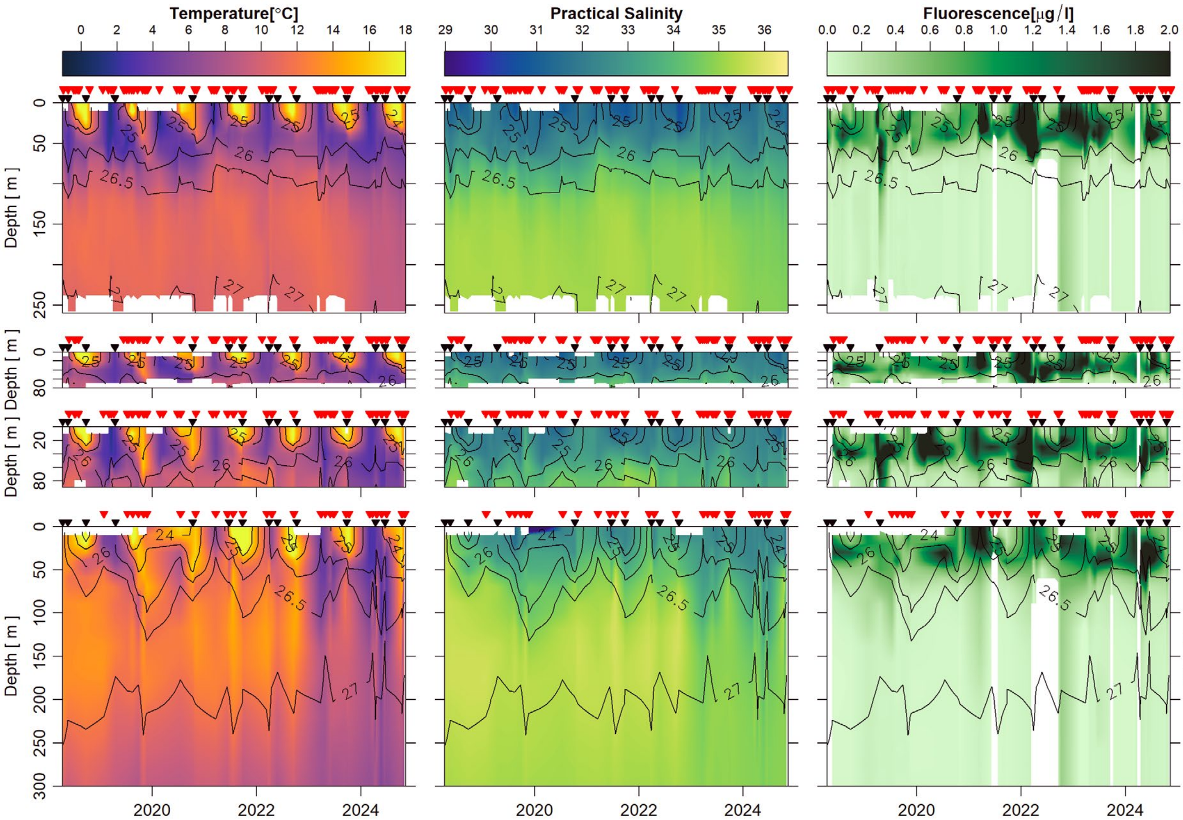


Figure 3: Time/depth sections of temperature, salinity, and chlorophyll fluorescence for 2018-2024. Triangles show the ship-based (black triangles) and glider-based (red triangles) measurements across the shelf of the Halifax Line stations from Emerald Basin (HL_03) to the shelfbreak (HL_06). White contours show the isopycnal depths over the period.

Argo Program, which focuses on the deep (>2,000 m) ocean [16]. Gliders are suited to characterize the interface between human activities (recreational or commercial, such as navigation, fishing, aquaculture, and transportation) and the open ocean environment. These regions are generally very dynamic (presence of tides, strong currents, fronts, etc.) and play a key role in both chemical and biological processes. As such, DFO is part of the OceanGliders Boundary Ocean Observing Network (BOON; www.oceangliders.org/taskteams/boundary-current). The data provided by underwater gliders also match the resolution of regional and coastal ocean models, and progress over the last decade has proven the efficacy of gliders as a key component of an observing/modelling system [17], [18]. Clients for glider data are thus numerous, but here we name a few with special significance for the Government of Canada.

### *3.2.1 Governmental Monitoring Programs*

Governmental monitoring programs such as the Atlantic Zone Monitoring Program (AZMP) on the East Coast or La Perouse and aquaculture programs on the West Coast are already benefiting from glider observations. Such glider observations have been reported in the State of the Pacific Ocean [19], [20], [21], [22], [23] and in the annual review of the Physical

Oceanographic Conditions on the Scotian Shelf [24], [25], [26]. As an example, glider observations on the Halifax Line increase the spatial resolution (not shown) and the temporal resolution (Figure 3) of the two to three ship-based CTD surveys per year. The increased sampling frequency allows for the seasonal cycle to be resolved along this section.

In addition, ocean gliders can also be equipped with biogeochemical sensors that can be used to monitor a suite of environmental metrics such as spring blooms and net community production [27], hypoxia [28], and ocean acidification [29]. In conjunction with regular ship-based monitoring (for example, to calibrate the glider data), glider data acquisition can enhance and reduce the cost of the biogeochemical data collection of a monitoring program (the ship-based collection of discrete biogeochemical samples is usually more time consuming and costly than physical data collection such as temperature and salinity).

*3.2.2 Ocean Protection Plan*

Real-time glider data can be used to monitor regions as part of the Ocean Protection Plan (OPP). For example, gliders can be used to track ocean currents (e.g., for drift prediction) or, when equipped with proper sensors, patrolling for oil spills [30] or detecting whales [31].

*3.2.3 Marine Conservation Targets (MCT)*

Together with several maritime nations around the world, Canada is advocating for the protection of 30% of the world's ocean by 2030 [32]. This commitment comes with monitoring support of existing protected areas, which is considered an important step toward conservation and management. Because they offer the possibility of performing some measurements in a very cost-effective fashion (where autonomous sensor measurements suffice), gliders can be used as a tool to plan and monitor MPAs or other closures and refuges [13] when frequent occupation of a region is necessary.

As an extension to the core program, the DFO glider program could easily include repeated sections crossing protected areas [13]. For example, the Calvert monitoring line samples just outside the Southern Reef portion of the Hecate Strait/Queen Charlotte Sound Glass Sponge Reefs MPA monthly. The Laurentian Channel MPA and St. Anns Bank MPA are also located at a short distance from Newfoundland and Nova Scotia, respectively.

*3.2.4 Environment and Climate Change Canada*

High resolution delayed-mode data can be assimilated into reanalysis products or used to validate long-term model simulations. These can be useful to assess climate change and its impact on ocean properties, circulation, and ecosystems.

*3.2.5 Universities*

Many universities in Canada operate ocean gliders or have their own glider fleet. However, glider operations from academia usually target specific research projects or questions and rarely serve monitoring purposes. Governmental monitoring data, from gliders or other means, can sustain multiple university projects such as students and faculty research projects targeting, for example, climate change [33], [34]. Numerous government-academia collaborations already exist (e.g., C-PROOF, in which DFO, universities, and non-governmental organizations – NGOs – jointly operate the West Coast fleet, or in terms of collaborations between DFO and Dalhousie University and/or Memorial University on the East Coast). Universities are currently the main external client of the DFO glider program delayed-mode data.

*3.2.6 Non-Governmental Organizations*
Like academia, NGOs are potential clients for DFO glider data. For example, the Hakai Institute is a key partner in the West Coast Glider Program. Other scientific NGOs can also benefit from openly accessible glider data.

*3.2.7 Industry*
Glider data can be used by various industries to establish a baseline for environmental impact assessment or to feed into numerical simulations such as of oil spills. Gliders can also be potentially useful to monitor for threats that are facing the aquaculture industry (e.g., marine heat waves, low oxygen events, super chills, etc.). Industrial clients also include, for example, sensor developers who can benefit from a glider deployment to test their instruments. Examples of the latter are the C-PROOF collaboration with Rockland Scientific, a Victoria-based ocean technology company using C-PROOF gliders to collaboratively refine its ocean microstructure sensors, and collaborations between the East Coast Glider Program and Ottawa-based RBR Ltd., which has developed a low power consumption unpumped CTD for gliders and AUVs.

*3.2.8 Intergovernmental Groups*
Glider data are also a valuable contribution to data products or catalogues and training experiences developed by intergovernmental groups, such as the International Council for the Exploration of the Sea and the North Pacific Marine Science Organization (PICES). Glider data are regularly reported on in the PICES Technical Committee on Monitoring. Additionally, glider data from both Canada and the US were central to the 2022 PICES Virtual Summer School (theme: Ocean Big Data). Data provision by gliders on near real-time ocean conditions and on ocean climate also contribute to international initiatives such as the Global Ocean Observing System (GOOS) and the United Nations Framework Convention on Climate Change.

**3.3 Monitoring Sections**
Based on the Canadian experience to date, we think that the current number of monitoring sections occupied (three on the West Coast and two on the East Coast as described in Section 2) is a minimal requirement to effectively monitor the spatial ocean variability on the country's East and West coasts. However, the program currently suffers from a lack of temporal coverage on some of these sections. In an ideal setup, the program would consolidate the current number of sections to achieve an initial target of 200 glider-days per section, with a mid-term goal of reaching a near 100% annual coverage where logistically possible (e.g., in regions without sea ice, for example). To do so, we calculate that at least 2.5 gliders per section are required (to swap gliders and not lose at-sea time, plus provisions for glider downtime). With the current size of the fleet, this target is achievable provided that the fleet is kept operational.

These sections are designed in such a way that the gliders patrol from inshore to offshore and are separated by latitudinal gradient to cover as much of the Canadian continental shelf as possible within a range of relatively easily accessible locations. The gliders provide year-round information about the ocean in chronically under sampled locations, e.g., Calvert Line where there was previously no wintertime data in most locations. They also complement the BOON network, helping to make North America's boundary ocean basins the best observed in the world. In the eventual extension of the program (see Section 5), an extension of the coverage with northern sections would be a valuable addition.

### 3.4 Physical Infrastructure

Following several rounds of investment, DFO's effective glider monitoring fleet has grown to 15 units (excluding the Whale Acoustics Slocum Program and gliders reserved for process studies). This number is sufficient to reach the goal of the glider monitoring program described in the previous sub-section, but these units will need replacement after a life expectancy of about seven to 10 years (see Section 3.8 on rust out).

DFO is also currently equipped with glider facilities on each coast (including workshop and ballasting tanks) to perform mission preparation duties (glider sensor preparation, ballasting, compass calibration, etc.). These facilities are sufficient for the current size of the fleet, but other facilities may be needed to operate gliders in more remote areas of the country. For example, there is currently no DFO glider facilities in Newfoundland and Labrador and one glider is shipped to St. John's every year from BIO at the beginning of the season and it is shipped back at the end of the season.

### 3.5 Staff

Staffing is often overlooked when purchasing gliders to sustain a monitoring program. Not only do gliders need to be piloted when at sea, they also need dedicated personnel for mission preparation, glider piloting, calibration, management, and data curation (including retrieving the data, ensuring their quality, and making them available for the public). As such, the lack of dedicated and trained staff is often one of the main reasons for the failure of a glider program (e.g., gliders purchased but not being used, or gliders being used but quality-controlled data not made available).

Glider operators around the world agree on a general guideline of 1:1.5 as an appropriate ratio between the personnel and the number of gliders (one full time equivalent staff – FTE – per 1.5 glider) to achieve a successful program. With 15 gliders at the national level (not counting the Whale Acoustic Slocum Glider Program and gliders reserved for process studies), this would lead to a requirement of 10 FTEs. Currently, DFO has only one FTE dedicated to the program on each coast, and 0.5 FTE is dedicated to the data management in the National Capital Region. In addition, each glider group is currently leveraging the equivalent of one FTE from C-PROOF (West Coast) and Hakai (West Coast) and 0.5 FTE from AZMP (East Coast).

Here we argue that with the number of monitoring sections projected in the Canadian context, a successful glider program would need eight FTEs distributed as follows: one

Table 1: Example of staffing scheme to sustain a national glider program dedicated to monitoring the East and West coasts of Canada distributed over DFO administrative regions.

| Region | Type of position |
| --- | --- |
| Pacific | 1 Glider Science Lead<br>2 Technicians |
| Maritimes | 1 Glider Science Lead<br>2 Technicians |
| Newfoundland and Labrador | 1 Science Staff |
| Any region | 1 Data Manager |

glider science lead (glider chief scientist) and two technical staff for each coast and one data manager responsible for both regions. Since the East Coast glider group is distributed over two DFO administrative regions (Maritimes and Newfoundland and Labrador), another science staff would be required to sustain the glider operations on the Bonavista section in Newfoundland. All technical and science staff would need to be trained as pilots on both glider models so they can help or take turns piloting. The two science leads on each coast would also oversee the program at the national and international levels (e.g., data products, new developments, collaborations, etc.). An example of what the staff requirement could look like is provided in Table 1.

It is important to note, however, that two different modes of operation exist between the West and East coasts, which may be interpreted as an imbalance in the staff table. On the West Coast, the glider program is part of a multi-institutional group (C-PROOF) that shares resources (people, gliders, and other logistics). Many logistical aspects of the program are thus provided by the partners and not by DFO. On the East Coast, DFO alone is responsible for the glider operations and logistics. In addition, the East Coast program is separated into two administrative regions (Maritimes and NL). In the NL region, the deployment site is also a four-hour drive from St. John's, adding logistical complexity to the operations. The staff requirement provided in Table 1 already reflects this situation by providing more resources to the East Coast in proportion to the number of sections monitored and the number of gliders in operation. It is important to note that when the C-PROOF program ends, the number of staff for the West Coast may need to be revised. It would also be an asset that the East Coast group develops a mode of operation in collaboration with partners such as the one on the West Coast.

### 3.6 Access to Boats

Deploying and recovering gliders can be done nearshore from small boats, so deployment costs are kept at minimum. On the West Coast, no dedicated vessel is maintained because all deployments and recoveries are done in collaboration with either the Canadian Coast Guard (CCG; Tofino coast guard station; DFO Science pays fuel costs only) or the Hakai Institute (both vessel costs and personnel covered by Hakai). This keeps deployment costs very low for this group (mostly just transportation costs to the often remote, offsite locations), but leads to a precarious situation, with a dependence on the continued goodwill of both the Coast Guard and Hakai.

In the Maritimes Region, the team relies on a small Canadian Coast Guard Ship (CCGS *Sigma-t*) that supports several programs in the region. This includes weekly sampling in Bedford Basin and monthly/bi-monthly sampling at Station 2 on the Halifax Line as part of AZMP. This vessel is used for deployments and recoveries of the gliders at the mouth of Halifax Harbour near the traffic lanes.

For the Maritimes Region, chartering commercial vessels for glider operations must be done by Public Services and Procurement Canada independent of the cost. In addition, selected vessels must have a Transport Canada certificate that allows them to carry passengers. Not only does this eliminate potential fishing vessels, but the procurement procedure can also take months, which is unrealistic for an emergency recovery, for example. It is thus best to have an approved list of service providers throughout the region. For example, DFO recently created a standing offer with a local company to provide support when the *Sigma-t* is not available (e.g., due to annual refit or during emergency conditions).

In NL, deployment and recovery are generally done in collaboration with DFO's Conservation and Protection (C&P) officers based in the town of Bonavista. This collaboration has grown over the years and has worked well. However, glider operations are highly dependent on the availability of C&P staff and this situation may cause mission planning difficulties. Because the team responsible for the glider deployments does not own a boat, emergency missions or deployment/recovery using alternate locations (e.g., inner bays for more protection) are challenging.

One important aspect to consider as part of any program is the emergency recoveries. An emergency recovery occurs when a glider can no longer travel under its own power or is under circumstances putting it at high risk of being damaged or lost (dying battery, incoming storm, stuck in high ocean currents or in shallow depths, etc.) and needs to be recovered in a timely manner. This can require the use of much larger and more expensive vessels if the glider is offshore, or to charter a local boat near the location of the glider if close to shore. Examples of such emergency recovery, together with the reasons and the associated costs, are provided in Table 2. Until now, thanks to good relationships with the CCG, C&P, and NGOs (e.g., Hakai), very little direct costs have been engaged toward emergency recoveries. However, in-kind costs to other research programs (e.g., loss of day of sampling due to diversion to recover glider) can be substantial. It is worth considering whether the absence of contingency funds set aside for emergency recovery could impact the long-term sustainability of the glider program. A mechanism to easily spend funds toward a charter without a bidding process is also crucial to allow glider operators to rapidly subcontract a boat when a glider is in danger of being lost.

**3.7 Operational Budget**

The budget of a glider fleet (not including staff) comprises mission related costs (overtime, travel, deploying, and communication) and maintenance costs (batteries, sensor calibration, and glider regular maintenance, upgrade, or replacement). Based on the experience acquired to date, we provide a table of approximate costs to operate a glider fleet. We separated the costs categories in terms

Table 2: Examples of emergency recoveries and their associated costs for East and West glider fleets since their inception.

**East Coast Glider Program (2018-2024)**

| Type of recovery | Number of occasions | Direct Cost to programs ($) | Type of boat used |
|---|---|---|---|
| Drop weight loss and other malfunction | 3 | $2,500 | CCGS, C&P, Charter |
| Battery life combined with bad weather | 3 | 0 | |
| Trapped in strong currents / bad weather | 1 | 0 | |
| Damage from shark attack | 1 | 0 | |
| Other (pandemic shutdown) | 1 | $1,200 | |

**West Coast Glider Program (2019-2023)**

| Type of recovery | Number of occasions | Direct Cost to programs ($) | Type of boat used |
|---|---|---|---|
| Drop weight loss and other malfunction | 6 | 0 | CCGS, NGOs (Hakai), Charter |
| Battery life combined with bad weather | 1 | $2,500 | |
| Trapped in strong currents / bad weather | 1 | 0 | |

Table 3: Example of costs encountered when managing a glider fleet. Fixed costs are independent of the number of missions while the operational costs depend on the number and length of missions. These numbers are used to derive the annual glider fleet operational budget shown in Table 4. These numbers are based on the dollar value from 2022 and may become rapidly outdated because of inflation.

| | Type of Expense | Cost | Details |
|---|---|---|---|
| **Fixed Costs** | **Data Management** | $5,000/yr | Data storage on the cloud ($5,000/yr) |
| | **Maintenance SeaExplorer** | $12,000/glider/yr | $60,000 every five years for SeaExplorer (including battery upgrade) |
| | **Maintenance Slocum** | $10,000/glider/yr | $20,000 every two years for Slocum (not including battery upgrade) |
| | **Sensor Replacement** | $20,000/sensor | On average, one sensor needs to be replaced every year for a fleet of five gliders |
| | **Sensor Calibration** | $2,000/sensor | Sensors are calibrated every year |
| **Operational Costs** | **Communication** | $50/day/glider | Approximate cost for Iridium communications during surfacing |
| | **Travel** | $1,000/mission | Cost related to glider technician travel to deployment/recovery sites |
| | **Mission Cost** | $1,000/mission | Average costs for shipping a glider by road (applies when the mission is far from the fleet base) |
| | **Boat Rental** | $2,500/mission | Approximate cost to charter a boat. Not always needed at DFO (see Table 2) |
| | **Slocum Non-rechargeable Battery** | $30,000/mission | Non-rechargeable Slocum gliders have a longer autonomy (used at DFO for Line P) |

of fixed costs ($/glider/year) and operational costs ($/mission and $/glider/day of operation). These costs are provided in Table 3.

We also perform a cost-analysis simulation of a glider program that would occupy five monitoring sections (like the current DFO program) 200 days per year. To do so, we calculate that at least 2.5 gliders per section are required (to swap gliders and not lose at-sea time, plus provisions for glider downtime). This would require a fleet size of 12 to 13 units. Not accounting for staff salaries, facilities maintenance (workshop, ballasting tanks, etc.), and rust out (see Section 3.8), we provide below an estimation of an annual operational budget. Such a budget of a glider fleet comprises mission related costs (overtime,

Table 4: Annual operational budget for a fleet of 12 gliders sustaining five monitoring sections. This budget takes the fixed and operational costs from Table 3 and sums them based on the assumption of 200 days of occupation on each monitoring section using similar expense categories.

| Expense Categories | Costs | Details |
|---|---|---|
| **Operations** | $90,000 | Operational budget (shipping, boat rental, staff overtime, travel, etc.) |
| **Communications** | $50,000 | Iridium communications calculated at a rate of $50/day/glider. Here the calculation is based on five sections occupied 200 days a year |
| **Data Storage** | $5,000 | Cloud data storage at $5,000/year |
| **Maintenance** | $180,000 | Regular maintenance by the manufacturer: approx. $15,000/glider/year (not including battery replacement in the case of non-rechargeable Slocum gliders) |
| **Sensors** | $75,000 | Sensor calibration: ~$35,000 per year<br>Sensor replacement: ~$30,000 (approx. 1.5 sensor per year) |
| **Batteries** | $60,000 | Two non-rechargeable batteries |
| **Total** | **$460,000** | |

travel, deploying, and communication) and maintenance costs (batteries, sensor calibration, and glider regular maintenance, upgrade, or replacement). Assuming the description made above (five monitoring sections and 200 days of occupation), we estimate that an annual budget of $460,000 is required (Table 4). This gives a rough budget for Canada, or any other country interested in establishing a similar national glider monitoring program, to sustain the occupational coverage described above.

### 3.8 Rust Out Plan

There are inherent risks in deploying electronic instrumentation in the ocean (e.g., one Slocum glider was lost on the West Coast in 2018, and a SeaExplorer was damaged after a shark attack on the East Coast in 2024). Gliders are especially at risk of collision with a ship or vehicle failure – such as the loss of a wing, sea water infiltration, or other electronic malfunction – that may cause the glider to be left adrift in remote areas that are not easily accessible. The components of gliders that are constantly in contact with sea water are also exposed to corrosion and an aging fleet is more prone to malfunction. Finally, the technology itself is constantly improving, which makes newer glider models ever more efficient than older ones (e.g., battery endurance, depth ratings, software compatibility, etc.).

Based on this and on expert knowledge, a glider lifetime can be estimated to range within seven to 10 years. Any country interested in investing in a glider program should establish a strategy (i.e., a rust out plan) to sustain the necessary assets to the program. In the Canadian context, this would require the purchase of approximately one unit per year, on average, to maintain the current fleet size. A new glider costs on average $300,000 (approximate cost per unit in 2024).

## 4. DATA MANAGEMENT

Data management is crucial to ensure the success of a glider program dedicated to ocean monitoring to benefit from both real-time and delayed-mode data acquired by this technology. In the Canadian context, the data management objectives of the DFO glider program follow the DFO data strategy and

Everyone's Gliding Observatories (EGO) data management strategy. DFO also plans to follow the OceanGliders metadata format as soon as it is formalized. This strategy promotes a systematic and collaborative approach for glider collection, processing, quality control, and dissemination of physical and biogeochemical data. It is applied to both DFO and Canadian universities' glider fleets.

The emphasis of the glider data management plan is on rapid and easy discoverability and shareability and is used appropriately, effectively, and ethically to deliver on DFO's core responsibilities and achieve results for Canadians as well as contributing to the GOOS [18]. This requires close collaboration and cooperation between the data managers and scientists on regional and national levels.

We propose here a model to build on existing infrastructure for data management of physical and chemical data, and to develop new infrastructure, where it is required, to improve glider data management in Canada.

**4.1 Data Management Objectives**

The glider data management objectives are:

- To ensure that all physical and chemical data are collected, processed, quality controlled, and documented to international data management standards.
- To ensure that data includes metadata, that products and derived information generated by the program are accessible via internet websites to meet client needs, and that near real-time physical data are accessible to modeller communities via the GTS.
- To ensure the safekeeping and long-term multiple re-use of the data and information collected and generated by the monitoring program.
- To facilitate data and information exchange between Canada's glider program(s) and other countries within GOOS.

**4.2 Data Quality and Information Standards**

It is the responsibility of the glider science leads to ensure the quality and integrity of the data collected under the glider program. The near real-time data will be processed, quality controlled, disseminated, and archived according to the guidelines and standards recommended by EGO's data management task team. At DFO, the Marine Environmental Data Section (MEDS) is responsible for the near real-time data acquisition and dissemination while delayed-mode data quality control will take place in the regions.

**4.3 Data and Data Product Distribution**

Most near real-time data and metadata are available to everyone in NetCDF data format (i.e., Network Common Data Form). While a glider is at sea, the data are also available to users via the GTS. For delayed-mode data, there will be a delay in data accessibility due to the nature of scientific quality control procedures and the fact that the data can only be downloaded from the glider after it is retrieved from its mission.

The summary of glider activities within Canada will be hosted at Ocean Gliders Canada (www.oceangliderscanada.ca) where users can find additional information about various glider missions and links to other glider programs within Canada.

Furthermore, most of the data collected under this program will be freely accessible to the public via File Transfer Protocol (FTP) servers on MEDS and EGO websites. The websites and FTP sites will help fulfil national and international commitments to other programs (e.g., GOOS, EGO, Canadian Integrated Ocean Observing System, OpenData).

### 4.4 Data Exchange and Safekeeping

The derived analysis products and data collected from the program will be maintained regionally and nationally. MEDS will coordinate the data exchange with international partners and other data programs.

To ensure safekeeping of glider datasets, the archival responsibilities will be divided between MEDS and regions unless there are other pre-agreement arrangements. MEDS will be responsible for archival of near real-time data collected, and regions will be responsible for data downloaded after the gliders have completed their missions, and for glider metadata. The entire raw dataset for each mission will need to be archived for the possibility of future data reprocessing due to recalibration of sensors.

## 5. EXTENSIONS TO THE PROGRAM

Plans for the extension of the program may include the support of different DFO initiatives mentioned above such as the OPP or MCT programs. Extensions of the program in remote and less accessible areas (e.g., in the northern part of the shelves or in the Arctic Ocean where currently DFO does not monitor using gliders), or to sustain Indigenous research initiatives (e.g., lines near Haida Gwaii) have also sparked some interest by different science or stakeholder groups, although no concrete plans have been developed. Currently, the Whale Acoustics Slocum Glider Program (see Section 2.3) is also considered an extension to the core glider program and part of its data (e.g., temperature and salinity) will be processed in real time by the data management team.

A sustainable glider program with a dedicated source of funding enables additional monitoring sections to be added to core monitoring activities. We provide here examples of potential extensions to the current Canadian glider monitoring program. On the East Coast, the AZMP sections Louisbourg (Scotian Shelf) and Seal Island (Labrador Shelf) are first on the list because of their long-term history of measurements (see location Figure 4). This would, however, have a significant impact on the operational budget since qualified vessels would have to be chartered and travel costs would increase. Cabot Strait is another natural section located just at the border between the Scotian Shelf, the Newfoundland Shelf, and the Gulf of St. Lawrence. Sections in the Gulf of St. Lawrence, such as the Bonne Bay section – located in the inflow from Belle Isle Strait and in a region where deep waters experience hypoxia – are also possible. On the West Coast, a section north of the current network (e.g., north end of the current Calvert Line and near Haida Gwaii) would be a natural extension. These potential extensions should be evaluated on a case-by-case basis by teams in the respective regions.

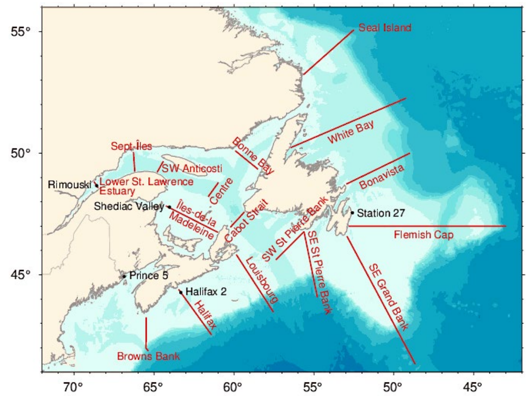


Figure 4: Atlantic Zone Monitoring Program (AZMP) sections (in red). High frequency monitoring stations are also highlighted in black. (Source: www.dfo-mpo.gc.ca/science/data-donnees/azmp-pmza/index-eng.html)

## 6. CONCLUSION

Ocean gliders were acquired by DFO in 2017 and 2018 as part of the *Science 2016* initiative and are used currently to monitor hydrographic sections on Canada's West and East coasts. In the West, DFO's investment was leveraged with academic institutions and NGOs to create C-PROOF, which expanded the Pacific monitoring glider fleet to 10 units, with three monitoring lines done collaboratively: the 1,400-km historical Line P, Calvert, and Southern lines. In the East, five DFO gliders monitor the AZMP Halifax Line (Maritimes) and Bonavista Bay (Newfoundland and Labrador) sections. Near real-time glider data are managed by MEDS at DFO.

DFO glider data are used by multiple external and internal clients; ocean forecasters, GTS, the State of the Pacific Ocean reporting, and AZMP. The glider program has significantly contributed to ocean science; however, challenges remain, including understanding the program needs to ensure it is resourced appropriately and sustainably. The present paper is the result of reflections from a group of glider experts who have been running Canada's glider monitoring program since 2018. It represents a review of the current activities and a vision for a state-of-the-art glider program in Canada. The working group identified three main challenges:

1. **Piloting.** Allocation of staff resources is important to sustain permanent glider operations because pilots need to be on call 24/7.
2. **Data Management.** While some glider data are made available and posted in real time on the GTS, many delayed-mode data are still not yet accessible. Moreover, both real-time and delayed-mode pipelines are fragile and require new developments.
3. **Funding.** A need to establish recurrent and predictable permanent dedicated funding is required to achieve the long-term sustainability of a program.

The authors of this report identified tangible solutions to ensure the long-term sustainability of DFO's glider program. These are discussed here together with requirements for data management and dissemination as potential extensions to the program and recommendation for permanent management and coordination. An example of an operational budget to sustain a program with the current number of glider sections and to increase their sampling frequency to near year-round occupations is also discussed.

Being surrounded by three ocean basins, Canada is in an enviable position to become a world leader in the use of ocean gliders to monitor its coastal and offshore zones. Building on experience acquired since 2018, we reflect on the realizations made, the lessons learned, and the potential consideration for improvements to the use of ocean gliders for monitoring. We hope that the information provided here will be useful not only for Canada, but for any other country interested in investing in a glider program to monitor its waters.

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