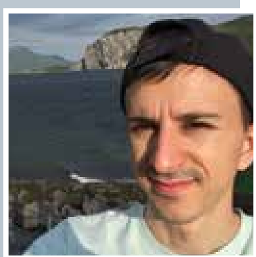
Gliding in the Labrador Sea

Brad deYoung



Nicolai von Oppeln-Bronikowski

deYoung, Oppeln-Bronikowski, Matthews, and Bachmayer develop new approaches to deploying and operating underwater ocean gliders to study ocean dynamics.

Who should read this paper?

This paper is of value to anyone with an interest in how to better observe the ocean or in new approaches to integrating autonomous ocean platforms with new sensor technology.

Why is it important?

While very flexible platforms, gliders cannot carry large sensors and have limited power to operate sensors for long periods. For the Labrador Sea, the authors' focus is on biogeochemical processes linked to air-sea gas exchange, particularly on testing CO_2 sensors on the gliders. The operation of autonomous vehicles offers much promise for ocean sampling but many challenges remain. Deployment, recovery and operation are particular challenges in this region where ice and extreme storm events are common. This work will lead to greater capabilities of integrated sampling platforms both in the sensor capabilities and the development of new approaches to operations. Understanding the potential and the challenges associated with these new platforms will help to inform those planning ocean operations or interested in developing new ocean observation systems.

About the authors

Dr. Brad deYoung is a Professor in the Department of Physical Oceanography at Memorial University. His research interests are in North Atlantic oceanography – coastal and open ocean, climate dynamics, ocean ecology and fisheries oceanography. He is currently working on the development of new sampling techniques, such as ocean gliders and autonomous surface craft, and in the coupling of biological and physical models for improving the understanding of the influence of circulation on marine organisms. He is interested in developing a long-term, sustainable approach to ocean observation and using data together with numerical models to better understand ocean dynamics and ecology.

Nicolai von Oppeln-Bronikowski is a Master of Science student in the Physical Oceanography Department at Memorial University, working with data from Labrador Sea glider deployments. With a background in ocean and naval engineering, he works with gas sensors deployed on gliders in the Labrador Sea as part of the mobile sampling team at

Memorial. His research focus is on sensor improvements and data interpretation in the context of implementing coordinated autonomous ocean observing system components.

John Brian Robin Matthews

John Brian Robin Matthews is a physical and chemical oceanographer interested in autonomous ocean observing, the marine carbon cycle, and sea surface temperature. He is currently a Science Officer at the Working Group I (Physical Science) Technical Support Unit of the Intergovernmental Panel on Climate Change (IPCC) in Paris, France. In this role, he supports all aspects of the production of IPCC assessment reports, including for the forthcoming IPCC Special Report on the Ocean and Cryosphere. Prior to this he was as a postdoctoral fellow at Memorial University where he conducted deployments of underwater gliders in the Labrador Sea and coastal Newfoundland.

Ralf Bachmayer

Dr. Ralf Bachmayer is a Professor for Marine Environmental Technology and Deep-Sea Engineering at MARUM – University of Bremen, Germany. His main research interests lie in the domain of marine robotics with a focus on unmanned marine systems. In particular he is interested in the design, control and networking of heterogeneous marine observation systems for persistent, long-term observations. He joined Memorial University in 2008 where he started the Autonomous Ocean Systems Laboratory in 2009. He joined MARUM at the University of Bremen in the summer of 2017.

GLIDER OPERATIONS IN THE LABRADOR SEA

Brad deYoung[1], Nicolai von Oppeln-Bronikowski[1], John Brian Robin Matthews[2], Ralf Bachmayer[3]

[1]*Department of Physics and Physical Oceanography, Memorial University of Newfoundland, St. John's, NL, Canada*

[2]*Université Paris Saclay, Saint-Aubin, France*

[3]*MARUM, Universität Bremen, Germany*

ABSTRACT

This paper summarizes the rationale behind developing and implementing an Autonomous Observing System for the Labrador Sea and details a recent successful glider deployment in the Labrador Sea in 2016 as part of the VITALS (Ventilation, Interactions and Transports Across the Labrador Sea) project. The glider carried a novel scientific sensor and operated using various sampling modes novel to the glider community. Some of the glider data and mission segments are shown as well as a discussion on how this effort fits in with the larger quest to implement the Canadian component of a global ocean observing system.

INTRODUCTION

The Labrador Sea is one of the most dynamic regions on the planet. There are dramatic seasonal cycles of sea-ice, icebergs moving from the Arctic and drifting southwards, severe outbreaks of cold Arctic air that result in intense air-sea heat exchanges leading to convection and the transformation of water sinking deep into the ocean. The exchanges between the atmosphere and the ocean in this region have a global influence. This region is one of the key places for the uptake of CO_2 from the atmosphere and thus plays a key role in climate change. Indeed the spreading of the anthropogenic CO_2 from this region can be traced throughout the Atlantic Ocean [Sabine et al., 2004].

The realization of social and economic benefits associated with efficient, safe, and sustainable use of the ocean requires access to real and near-real time information on ocean conditions and the valued aquatic species and other marine resources upon which human society depends. In turn, this requires an observing system that informs operation and management decisions, and generates an understanding of change (e.g., in climate). The growing rate of change in the oceans, both from climate change and human development, requires a commitment from Canada to enhance its observational and monitoring capabilities. However, no single country has the capacity to undertake all the requirements of modern ocean observing, hence effective, coordinated action is required. To implement this new reality for the oceans, Canada, the EU, and the USA established the Galway Research Alliance in 2013, with the goal of creating a shared Atlantic Ocean Observing System and a closely related research agenda on changes in the climate and ecological systems of the North Atlantic Ocean. Observation systems are the foundation of this effort and will deliver information products to end-users for both scientific purposes (e.g., via understanding and projection of climate change) and operational applications for both government and industry.

What makes this region interesting, also makes it very difficult to observe. Convection and the large gas and heat exchanges with the atmosphere occur during the winter when temperatures are far below zero and storm force winds and waves abound. It has proven difficult to directly observe what is happening because ships cannot easily operate in this region during winter and indeed there is little commercial shipping in this region during the winter. In this paper, we present results from a program using autonomous underwater vehicles – ocean gliders – to study the Labrador Sea. We discuss some of the challenges associated with using such autonomous systems in the Labrador Sea and present some of our results to demonstrate the benefits of using such platforms to collect data in an extreme ocean region.

Labrador Sea and Ocean Observing

The Labrador Sea and surrounding shelves play an important role in the ecological, economic, and societal health of the Northwest Atlantic. Canada has a national investment in offshore fisheries and transportation within this basin, and a growing presence as resource exploration and exploitation moves northward and farther offshore. Eastern Canada's weather and climate are also strongly influenced

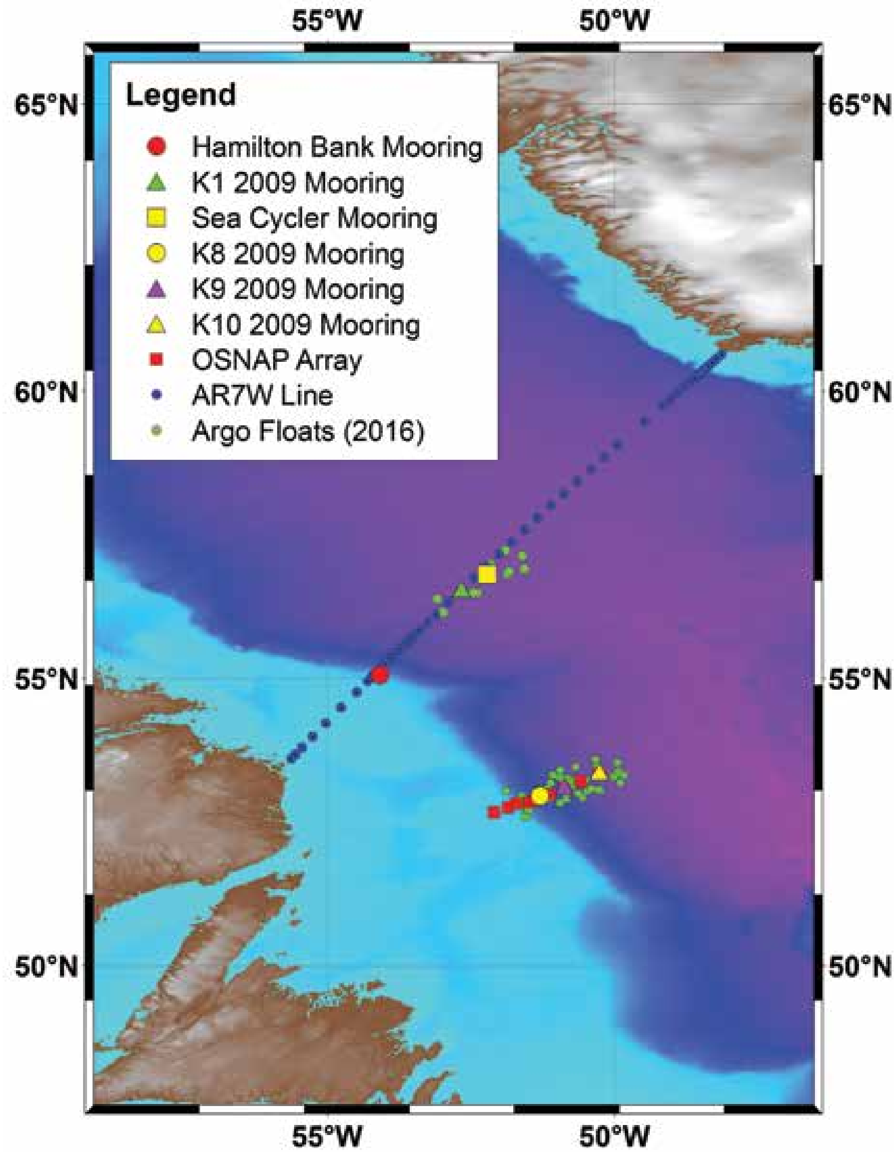


Figure 1: Labrador Sea ocean observing activities (Fall 2016). Circles plotted for Argo Floats are the locations of profiles, limited to those in vicinity of Overturning in the Subpolar North Atlantic Program (OSNAP) moorings and AR7W Line.

by the Labrador Sea [Dickson, 1997]. The Labrador Sea is also important strategically as the Canadian gateway to the Arctic. Indeed, Canada has made substantial contributions to scientific understanding of this region of global climatic importance, including recognition of the variability in Labrador Sea Water formation [Dagmar and Yashayaev, 2015], along with the first process-oriented and tracer studies of deep convection [Gascard and Clarke, 1983a] and ocean acidification [Azetsu-Scott et al., 2010]. However, Canada's open ocean scientific capabilities in the Labrador Sea have declined over the past few decades. The Department of Fisheries and Oceans (DFO) has traditionally maintained a presence in the basin through Atlantic Zone Monitoring Program (AZMP) cruises, conducting Expendable Bathythermograph (XBT) and CTD surveys and launching Argo Floats along the AR7W Line (Figure 1). However, 2017 marked the first year since the early 1990s when the

AR7W line (Figure 1) was not sampled by a Canadian vessel. While other research programs have helped to fill these gaps (e.g., the German K-mooring program and the joint USA-UK-Canada OSNAP [Overturning in the Subpolar North Atlantic Program] initiative), few maintain a permanent presence, often being tied to short term research projects (less than five years).

Observing efforts encounter difficulties pertaining to the special meteorological characteristics of the Labrador Sea. Beyond the ubiquitous open ocean observing challenges of water pressure, corrosive seawater and distance from shore, the Labrador Sea experiences extreme weather conditions including high winds, large wind waves and swell, and extreme cold generating ice and icing conditions. While challenging from a measurement perspective, these extreme conditions also make the Labrador Sea one of the most oceanographically interesting regions [Talley and McCartney, 1982]. Moreover, while the Southern Ocean offers similarly important and critical ocean processes to be studied, it is more remote and has similarly challenging environmental conditions [Killworth, 1983]. The Labrador Sea thus provides a good balance between broad oceanographic relevance and ease of reach. Despite this, winter conditions are such that few ships can safely operate there, arguably the most important period in the Labrador Sea's oceanographic calendar has received the least attention. Autonomous vehicles (e.g., gliders) offer one solution to this challenge since they can either operate in these conditions or avoid them by submerging.

Ocean Gliders

Underwater gliders (e.g., Teledyne Webb Research Slocum electric gliders) are autonomous underwater vehicles (AUV) that use small changes in their buoyancy in conjunction with wings to convert vertical into horizontal motion, and thereby propel themselves forward with very low power consumption [Rudnick et al., 2004]. This significantly increases their range and endurance compared to vehicles propelled by electric motor-driven propellers, from hours to weeks or months, and to thousands of kilometres of range. A bi-directional satellite data-communications link allows for real-time data access, mission monitoring and control. Gliders can be deployed and recovered from small vessels and carry an array of sensors.

While offering many advantages, many trade-offs remain, particularly between sampling (e.g., spatial, temporal, parameters), financial cost and power requirements/battery life. Indeed battery life requires a constant balancing act. It is desirable to leave the glider in the ocean for as long as possible, and thus use as much of the battery capacity as possible (batteries being expensive and gliders time-consuming to deploy and recover). Even more critically, running out of power would very likely mean losing the glider. While we have a general sense of battery consumption and thus of the power remaining, there is variation in individual batteries. Available power from the batteries also depends on external factors such as temperature. Finally, it can take several days to recover a glider waiting for a weather window, especially in the stormy Labrador Sea. Thus sufficient battery reserve must be made available for such end-of-mission eventualities.

One of the facets of glider battery life is that most oceanographic instruments deployed from ships use far more power than a glider could provide. For gas sensors, which are of particular interest in the Labrador Sea, traditional sensors are both too large and too “power hungry” to be used. To overcome this, Aanderaa Data Instruments has developed optode sensors based on the Lifetime Principle [Tengberg et al., 2006] to measure in-situ gas concentration, which are ideal for low-power situations. The O_2 version of this sensor has been widely used on gliders, with confidence in its measurements being high, as validated by many studies [Uchida et al., 2008; Ratsimandresy et al., 2014; Pizarro et al., 2016].

Memorial University’s Autonomous Observing Systems Laboratory (AOSL) owns and operates a small fleet of Slocum gliders manufactured by Teledyne Webb Research Corp., USA. In 2016, a deep (1,000 m) Slocum G2 glider named Unit 473 was modified to carry out open ocean observing in the Labrador Sea. A deployment was then conducted in the fall 2016 as part of a wider program, Ventilation, Interactions and Transports Across the Labrador Sea (VITALS); a national, interdisciplinary program to study how the deep ocean exchanges carbon dioxide, oxygen and heat with the atmosphere in the Labrador Sea. The glider component of this combined observational and modelling program supported other observations from both moorings deployed over the winter and ship surveys conducted in May of each year of the program (Figure 1). The fall 2016 glider deployment spanned over 2,000 km of track length and ran from September to December.

GLIDER MISSION 2016

Mission Overview

Several modifications were made to the glider prior to deployment. A thruster, developed at Memorial University, was added so that it could operate in horizontal flight mode, as well as the more typical saw-tooth profiles of underwater gliders [Claus et al., 2010]. Such thrusters are routinely deployed on underwater gliders which are then sometimes referred to as hybrid gliders. Two gas sensors were mounted, one for O_2 and another for CO_2. The CO_2 optode, while based on a similar principle to the O_2 sensor, is a recent development [Atamanchuk et al., 2014] and remains in prototype-testing stage. Most other CO_2 sensors are either too large or consume too much power to be deployed on an underwater glider or on a float such as an Argo float. Indeed, we were among the first to deploy a glider with a CO_2 sensor on a mission.

Test flights were carried out in Trinity Bay, Newfoundland, where the water depths exceed 500 m, allowing testing of both the glider and CO_2 sensor with a planned maximum mission depth (1,000 m). Trinity Bay was also near our St. John’s glider operations base, and had readily available small boats for deployment and recovery. Unfortunately, testing ran into problems and so we were late in deploying in the Labrador Sea. We had intended to deploy from a research vessel in September, requiring us to have testing completed by August. This would have allowed us to deploy directly in the Labrador Sea. Because we missed that opportunity, we were forced to deploy from the coast of southern Labrador.

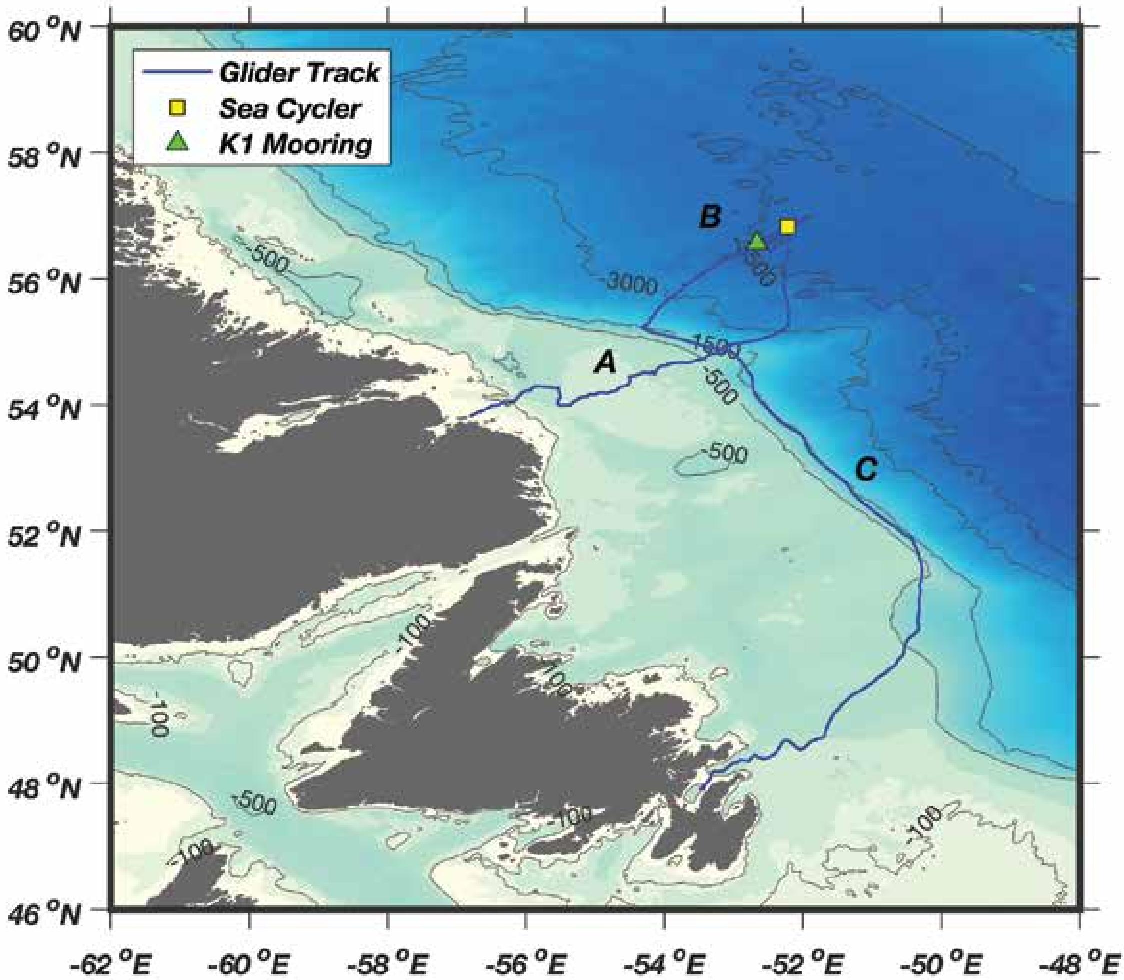


Figure 2: Glider track for the Labrador Sea deployment of fall 2016. The locations of the SeaCycler and K1 moorings are indicated.

The mission consisted of three main sections, which we have labelled A, B and C (Figure 2). These segments overlap with three physical regions: (A) the Labrador Shelf; (B) Interior Labrador Sea; and (C) Labrador Shelf Break. The glider was deployed from a small fishing vessel near the entrance of the inlet to Cartwright, Labrador, and used its thruster to cross the shelf in a direct, horizontal manner without having to glide up and down (i.e., yo). The intention was to minimize the time the glider would spend on the shelf and to also avoid strong surface currents. The glider moved across the shelf in a nearly straight line over the first several days, averaging 0.3 m/s in the horizontal. But after a week or so, it began to move directly southwards caught, in a strong southward flowing surface current. After a modification of the waypoints and flight characteristics via satellite, we got the glider back on track across the shelf. This happens quite frequently with glider missions. Oceanographic conditions change and piloting adjustments are required to keep the vehicle moving in the right direct and sampling that was intended.

The glider was directed to the Labrador Sea to survey around two moorings deployed there. SeaCycler [Send et al., 2013] was deployed by

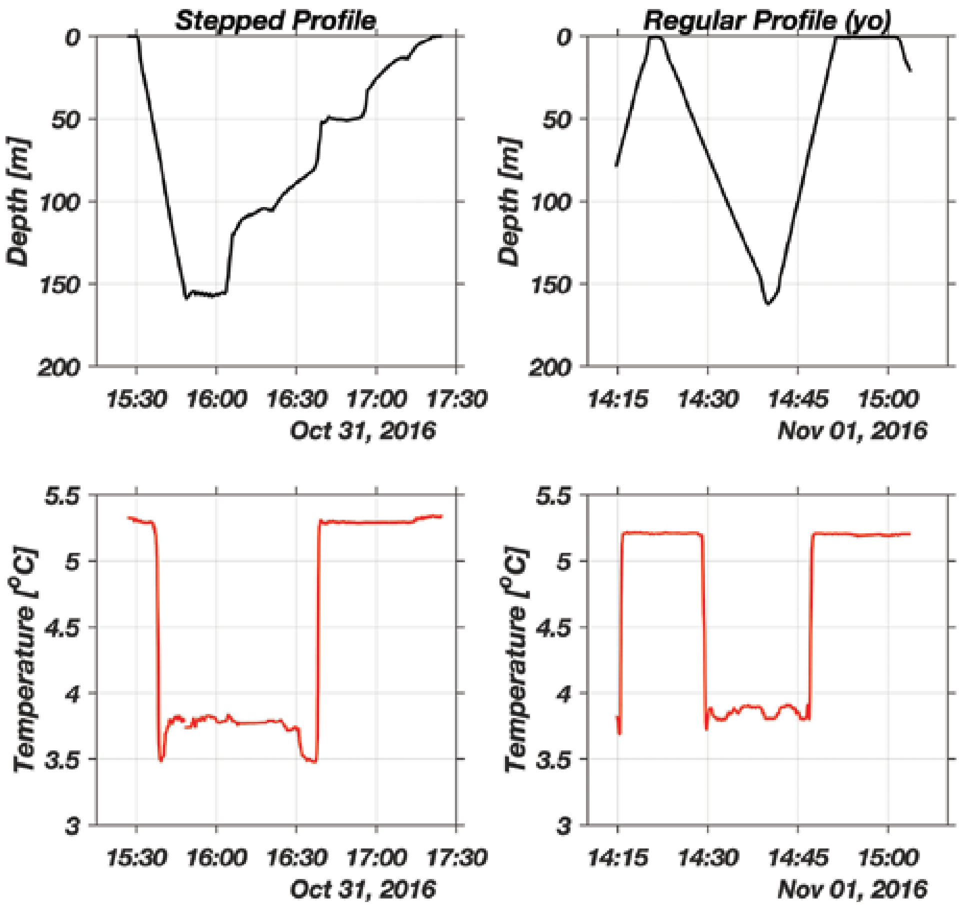


Figure 3: Comparison of yos and stepped profiles during the repeat sampling within section B.

Dalhousie University as part of VITALS and a long-term mooring K1 deployed and maintained [Zantopp et al., 2017] by GEOMAR in Germany (Figure 2). As the glider approached and passed over the shelf break, it was flown in yo mode, capturing physical and chemical properties down to 1,000 metres. Reaching the SeaCycler and K1 moorings in the central Labrador Sea, it began a repeat transect along a track length of about 100 km (section B), which continued from October to November. Subsequently the glider was flown "homeward," back towards the shelf-break and then south along the 1,500 m isobath, taking advantage of the strong current there [Colbourne et al., 1997]. The latter current contributed around 20 cm/s to glider speed-over-ground, equating to an extra 20 km/day or 600 km over 30 days. Finally, the glider was piloted back across the Labrador shelf into Trinity Bay, Newfoundland. Piloting challenges continued until mission's end with strong currents in the bay necessitating active piloting to avoid shoals. Recovery took place off Heart's Content on December 31, 2016.

Sampling Strategy

During the missions, a novel way of flying gliders was employed, combining thrustering and yo flight to create "stepped profiles" (Figure 3). These were implemented to

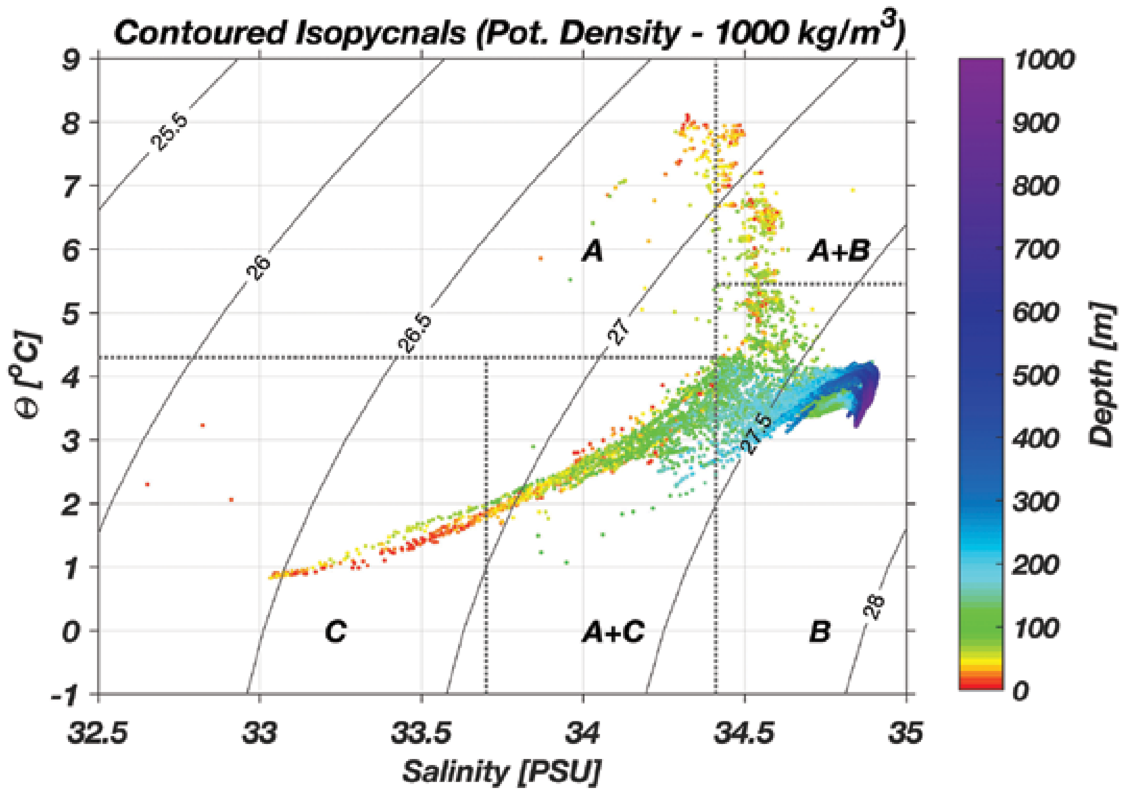


Figure 4: Temperature-Salinity diagram for the fall 2016 glider mission grouped by water masses consistent with the different sampling regions, with isopycnals shown from 25.5 to 28.0. Colour shading is depth and centred around mixed layer depth (average is 100 m).

(a) reduce lag effects for the glider's CTD and gas sensors and (b) allow measuring in synchronization with fixed depth repeated measurements from the moorings. While much faster to equilibrate than traditional membrane-enclosed CO_2 sensors (with passive equilibration), which have response times of tens of minutes, sensor response time still runs several minutes. Profiling in the normal manner (yos) through a gradient would have posed problems in interpreting the sensor data, so we developed a new approach in which the glider would remain at a fixed depth for sufficient time to obtain a stable measurement. Sampling was periodically adjusted via satellite communication, with changes made to the number of steps in the profiles and/or their depths.

Glider Data

A Temperature Salinity diagram (Figure 4) reveals that most of the CTD data lies in a relatively narrow band of temperatures (3 to 4ºC) and salinities from 34 to 35 PSU (Practical Salinity Units). The small range in magnitude is unsurprising given that most of the data collected comes from a narrow strip of the interior deep Labrador Sea sampled over two months within section B. About the shelf and shelf-break (sections A and C), we see extremes in salinity and temperature. The lowest salinities and temperatures recorded are from to the return flight to Newfoundland (section C) in the relatively fresh and cold Labrador current in late November and December. The initial crossing of the shelf (section

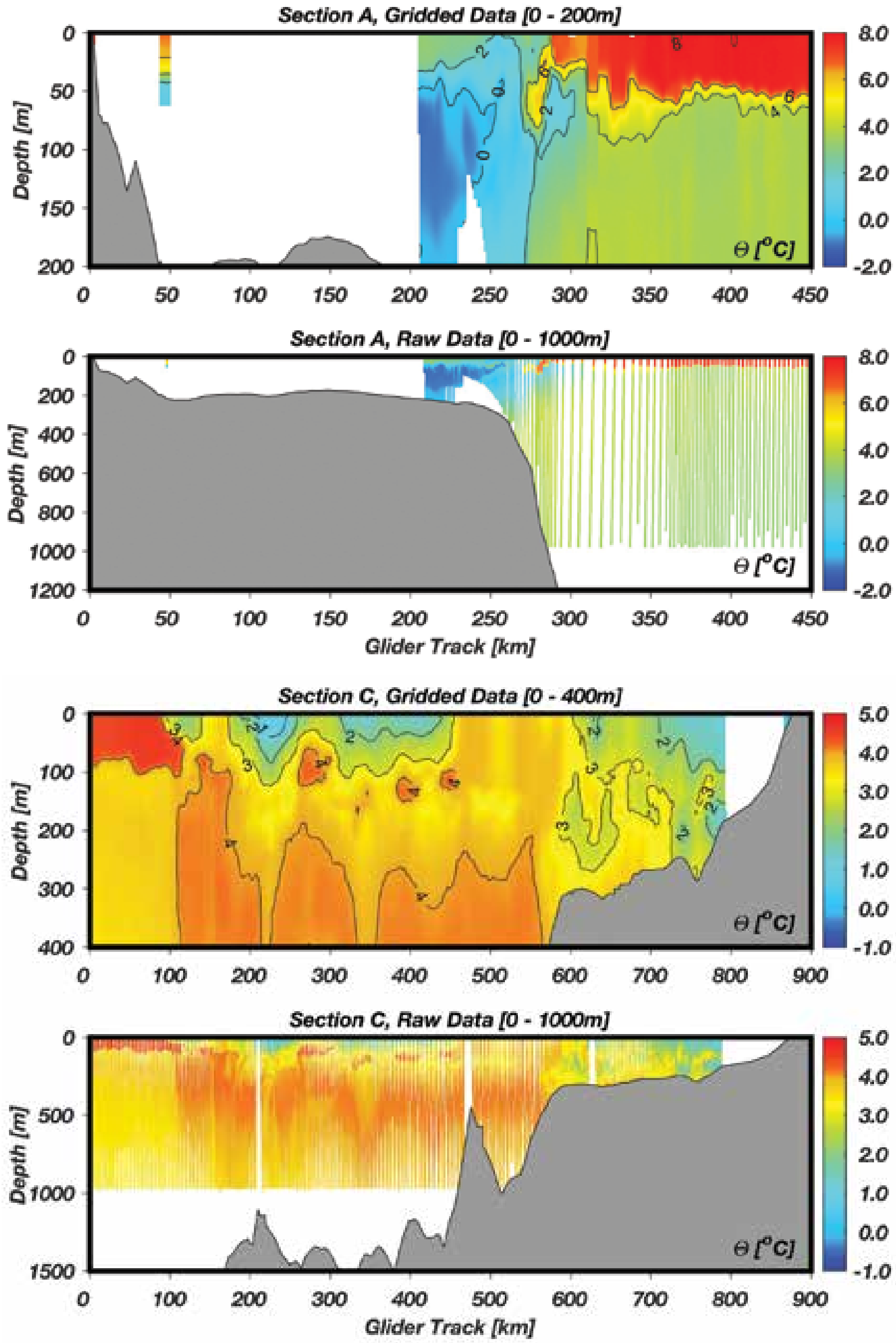


Figure 5: Potential temperature along section A (top) and C (bottom). Plots show the raw data with bathymetry patch. Gridded data shown for the top 200 and 400 m, respectively.

A) in September found water that was similarly fresh in the shallow coastal zone, but warmer than the shelf-break in section C during December since the water depth was shallower initially.

Another way to visualize glider-observed ocean properties is to plot along-track sections (e.g., Temperature, Salinity, Density), colour-shaded according to magnitude. Doing so for section A (upper two panels of Figure 5) reveals that

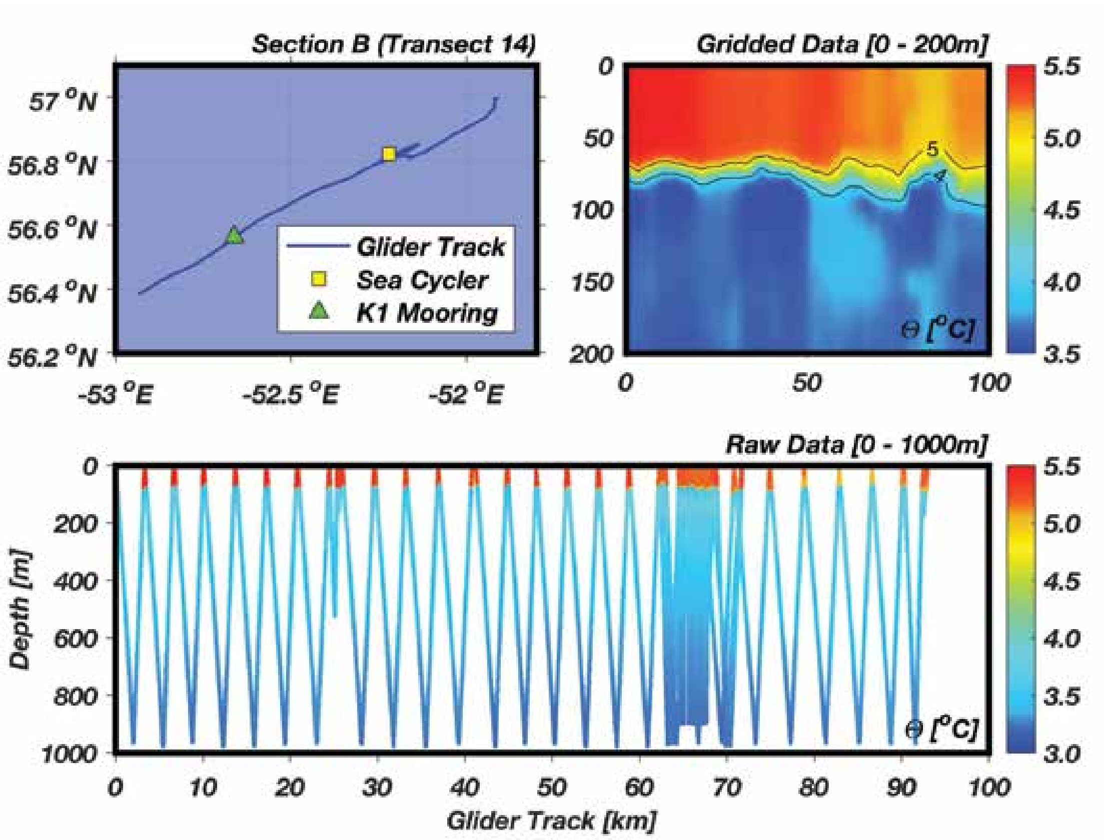


Figure 6: Typical transect in section B between K1 and SeaCycler. Note extra loop flown around SeaCycler mooring and increased data density at the mooring.

temperature in the shelf-break jet, the strong flow of the Labrador Current centred over the shelf-break between the 400 m and 1,000 m isobaths, encounters a strong boundary and is strongly mixed in the vertical with warmer interior waters [Lazier and Wright, 1993]. This was well captured in the glider data with the warm tongue of water overlain by colder waters from the shelf-break jet.

On the mission's homeward-bound shelf-break leg (800 km long, lower two panels in Figure 5), traversed by the glider in two weeks, strong meanders, possibly from eddies, are visible in the temperature data.

The glider continued to its sampling area in section B doing repeat transects between two moorings, K1 and SeaCycler. These moorings measure temperature and salinity as well as gas properties (SeaCycler: O_2 and CO_2, K1: only O_2). The glider sampled in two modes – yo and staircase profiling – and completed 18 transects, of which 10 were 40 km long and took around one to two days. The remaining longer transects (100 km) took three days and covered an extra 30 km beyond each mooring. The glider transects were operated along the line between the two moorings. The water properties are fairly consistent throughout the sampling period with a strong thermocline at about 50-80 m and fairly homogenous temperatures down to 1,000 m (around 3.5ºC). This "two layer" fluid property is characteristic of the Labrador Sea deep convection zone [Gascard and Clarke, 1983b].

In the particular transect shown (Figure 6) the glider flew an extra loop around the SeaCycler mooring to collect additional CO_2 profiles.

CONCLUSIONS

Transiting over 2,000 km of ocean, this glider mission demonstrated various strategies for operating gliders in the central Labrador Sea. It showed how the southern Labrador coast and Trinity Bay, Newfoundland, can be used as deployment and recovery locations, thus avoiding transporting gliders to the central Labrador Sea for deployment. It also illustrated how a mounted thruster could be used to traverse the 200 km-wide Labrador shelf.

The mission yielded valuable data on the Labrador Sea, particularly with the deployment of a novel gas CO_2 sensor and flying repeat sections about other types of autonomous platforms (namely SeaCycler and K1) to collect a joint data set. Such multi-plaftorm observing remains novel in remote areas such as the Labrador Sea, and the mission demonstrated a viable method to address gaps in ocean observing in an ocean region of key scientific and government interest. Finally, the mission also employed novel sampling strategies, including stepped profiles. Future papers will evaluate their utility with respect to synchronized multi-platform data collection (e.g., SeaCycler).

In the future, we intend to operate gliders in the Labrador Sea during the period of convection and restratification. We have plans to deploy other underwater gliders in combination with a Surface Wave Glider [Manley and Willcox, 2010], and thus to make both oceanographic and atmospheric measurements at the same time. It is well known that the atmospheric conditions, both the gas concentration and the wind speed, strongly influence the rate of air-sea gas exchange. While there remain great challenges to long-term glider deployments, there are also great opportunities.

ACKNOWLEDGMENTS

We thank Mark Downey and Mingxi Zhou for technical support and the Natural Sciences and Engineering Research Council for financial support through the Climate Change and Atmospheric Research (CCAR) program.

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