Development of an Autonomous Carbon Glider to Monitor Sea-Air CO_2 Fluxes in the Chukchi Sea

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Final Report
OCS Study BOEM 2018-016
May 2018

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Abstract

The waters around Alaska are undergoing unprecedented environmental change including warming temperatures, freshening, extensive loss of sea ice, increased storm frequency and magnitude, elevated rates of coastal erosion, increased inputs of terrestrial organic matter, and ocean acidification. All of these factors could impact cycling of carbon in the Arctic. Continued development of oil and gas resources will result in increasing CO_2 emissions and additional changes in ocean carbon chemistry. Traditional ship-based observations are operationally expensive and insufficient to provide the spatial and temporal coverage of dissolved CO_2 measurements required to improve quantitative assessment and conceptual understanding of the region's carbon cycle. The goal of this project was to develop and test a carbon glider unit that could autonomously measure spatial and temporal dissolved CO_2 throughout the water column at high-resolution. The project included the design of a customized Pro-Oceanus pCO_2 sensor, integration of the sensor's physical, power, communication, and software systems with a Teledyne Webb Research (TWR) Slocum Glider, and development of glider hover missions that allowed for full sensor equilibration and the use of sensors with slower response times. As a result of this project, we developed a carbon glider and brought it to a Technology Readiness Level 6 (TRL-6 per NASA) and demonstrated a capacity for pCO_2 data collection during glider flight missions at sea.

Introduction

Contrary to physical parameters that are routinely measured from a wide range of autonomous platforms, biogeochemical properties such as pCO_2 typically require ship-based observations, which do not provide the temporal and spatial resolution needed to further our understanding of ocean productivity, carbon cycling, and ocean acidification and its impact on climate. To address this challenge, we need to integrate and deploy maturing biogeochemical sensors with autonomous sampling platforms. Carbon sensors have been successfully integrated with remotely operated platforms such as wave gliders and drifters. However, these platforms cannot measure carbon in subsurface waters where the spatial variability and vertical gradients of pCO_2 are often large and dynamic. Subsurface carbon dioxide can strongly impact surface water properties and air-sea gas exchange via physical mixing. Further, subsurface concentrations are key indicators of biological production and ocean acidification.

Our present knowledge gaps about the Chukchi Sea carbon cycle demonstrate the need for glider-based CO_2 observational capabilities. Due to inherent chemical, physical and biological processes, the Chukchi Sea is especially suited to take up atmospheric CO_2 in summer. This shallow shelf sea (<50 m) is fed with nutrient-rich waters from the Pacific Ocean (Sambrotto et al., 1984; Coachman, 1986) and exposed to sustained solar radiation during sea-ice free periods. These factors make the Chukchi Sea one of the most productive ecosystems in the world with primary production estimates in the range of ~470 g C m^2y^{-1} (Springer and McRoy, 1993). High rates of primary production in the summer drawdown CO_2 at the surface (Pipko et al., 2002; Bates, 2006; Gao et al., 2012; Mathis and Questel, 2013), support large fluxes of organic carbon to a biomass-rich benthic ecosystem (Grebmeier et al., 2006), increase levels of remineralized inorganic carbon (Pipko et al., 2002), and cause aragonite undersaturation in subsurface waters (Bates et al., 2013; Mathis and Questel, 2013). Subsequent circulation-driven export of these carbon-rich subsurface waters into the upper halocline of the Arctic Ocean (Anderson et al., 2010) is thought to support a strong continental shelf carbon pump, with an estimated CO_2 sink strength of 38 Tg C per year (Bates, 2006).

Our recent findings suggest a more complex and somewhat contradictory description of the carbon dynamics in the Chukchi Sea. Frequent autumn storms disrupt stratification and bring CO_2-rich subsurface waters to the surface, thereby decreasing the strength of the carbon sink (Hauri et al., 2013). In October 2011, wide areas of surface waters were supersaturated with CO_2 (reaching a maximum of pCO_2=604 µatm), implying substantial seasonal CO_2 outgassing to the atmosphere during windy conditions. These high surface pCO_2 values and relatively high surface salinities (>31) were observed during or right after a storm that was strong enough to homogenize the shallow water column, indicating mixing of CO_2 rich subsurface water to the surface. A low surface O_2/Ar ratio (90% of saturation ratio) was a further sign of a well-mixed water column, indicating a strong respiratory signal along with the high pCO_2 levels. Seasonality of the western Arctic and North Pacific atmospheric pressure and wind fields suggested that such

wind-induced mixing events happen on an annual basis in autumn as the water column cools and overturns prior to late fall ice formation.

Subsurface waters with high pCO_2 levels in bottom waters have been measured all across the Chukchi Sea (Pipko et al., 2002; Bates et al., 2013; Mathis and Questel, 2013). Hauri et al. (2013) hypothesized that vertically-entrained CO_2 enriched waters are a widespread pattern. However, due to the high spatial and temporal variability of pCO_2 in the region and limited data availability, a revised annual carbon budget for the Chukchi Sea and the Arctic Ocean was not proposed. These findings illustrate that the current knowledge of the carbon cycle in poorly sampled Arctic regions is strongly biased by extrapolations of temporally and spatially sparse observations. The US Coast Guard vessel *Healy* has added a continuous-underway surface pCO_2 sensor, so surface pCO_2 is now measured along transects through the Chukchi Sea approximately monthly. However, these surface transects do not give insight into the processes in the water column and at the seafloor, and they do not cover enough area to determine the carbon budget in this highly variable environment. Unfortunately, no oceanographic observation systems exist that can quantitatively collect carbon cycle data at the spatial and temporal scales necessary to accurately constrain regional carbon budgets and understand the processes that are controlling the carbon cycle. Moreover, ocean acidification and climate change are altering the chemical and physical environment in the ocean, and conventional observational techniques are not well suited to detect this change. For these reasons, the development of new autonomous methods to monitor the biogeochemical properties of the water column is a critical step in improving our understanding of carbon cycling in the oceans.

To fill this observational gap, we have developed a unique carbon glider that enables autonomous collection of pCO_2 profiles throughout the water column, thereby increasing the spatial and temporal coverage of inorganic carbon measurements. In this study, the glider has gone through intensive research and development including design of a customized Pro-Oceanus Mini-Pro pCO_2 sensor, integration of the sensor's physical, communication, power, and software systems with the Teledyne Webb Research (TWR) Slocum Glider, and development of glider hover missions that allowed for full sensor equilibration and the use of sensors with slower response times. The custom Pro-Oceanus glider Mini-Pro sensor variant went through several iterative improvements from the base unit that is currently sold by Pro-Oceanus. The sensor's response time was cut down from approximately three minutes to about one minute, which makes it suitable for glider hover missions. Power requirements were decreased by nearly 50% through hardware and mechanical changes to the sensor.

Methods

In the vertical sense, a glider is a fast-moving platform that requires sensors that can respond quickly to a changing environment, especially in areas with strong stratification. Over the last few years, there has been an explosion in the number and capabilities of pCO_2 sensors, based on a variety of technologies. The industry standard is a membrane-based sensor that allows carbon dioxide to diffuse through a membrane to the gas detector on the inside of the housing. However, for our prototype, off-the-shelf pCO_2 sensors had equilibration times that were too slow (conventional Mini-Pro CO_2, Pro-Oceanus) or the sensors were too big (HydroC, Contros). To obtain a pCO_2 sensor suitable for the glider application (i.e., fast enough equilibration time, small size, and lightweight), we partnered with the sensor manufacturer Pro-Oceanus to develop a modified version of their existing membrane-based Mini-Pro CO_2 sensor.

pCO₂ Sensor Prototypes

Prototype 1.0

The first objective for the sensor improvement was to reduce the equilibration time. Decreasing the equilibration time from three minutes (original Pro-Oceanus Mini-Pro model) to a few seconds was considered necessary to resolve the rapid changes in CO_2 that are expected as the glider moves through the water column.

The original Pro-Oceanus Mini-Pro CO_2 membrane has a surface area for gas exchange of ~12.5 cm^2 diameter. This conventional flat membrane was replaced with a hollow fiber module from Permselect (https://www.permselect.com). The hollow fiber module is a spindle of hundreds of small diameter silicon tubes leading to a surface area of one square meter, all contained in a compact form. The gas circulates inside the tubes to the infrared detector inside the main housing of the instrument. The ambient seawater that gets pumped through the hollow fiber module remains outside the tubes but is able to come to equilibrium with gas inside the tubes across a one square meter surface area. The alignment of the water outlet ports on the hollow fiber module was adjusted to a 120° angle with the gas ports (instead of 180°). This adjustment allowed for the gas ports to be closely aligned with the glider while the water outlets were still pointed vertically for gas bubbles to escape.

The data output on this prototype was not comma separated, causing communication issues with the glider. The firmware was programmed for a 10-second startup and a 2-second sampling rate.

Prototype 1.1

The SBE 5M pump was upgraded to a stronger pump (SBE 5P @ 4500 rpm) to provide an adequate flow rate through the hollow fiber module (>1 L/min). The firmware was updated to support comma separated data output.

Prototype 2.0

The second iteration of the pCO_2 sensor featured the conventional, but enlarged disc membrane. The pressure housing of the Mini-Pro CO_2 was modified to accommodate a disc membrane head

with an 80 cm^2 surface area as commonly used in the Pro-Oceanus Pro-CV CO_2 sensor. Using the larger, flat membrane, prototype 2 had decreased power consumption and was less susceptible to clogging than prototype 1.1 while still maintaining a shorter equilibration time (~1 min) than the original Pro-Oceanus sensor. Furthermore, moving away from the hollow fiber module extended the depth range of the carbon glider to 200 m.

This prototype contained a new logger/controller board with firmware supporting a slower startup (>15 s) and less frequent sampling rate (4 s).

Prototype 2.1

This prototype was outfitted with a logger/controller board containing the firmware of prototype 1.1 (startup=10 s, sampling rate=2 s).

Prototype 2.2

To better accommodate the disc membrane stability during quick pressure changes, Pro-Oceanus developed a new water-pumped head with a waterside protective screen along the membrane. This new unit was installed prior to the Chukchi Sea deployment. Weeklong laboratory testing of the carbon glider showed that the sensor sporadically produced faulty data, leading to a time out of the data stream and prompt termination of the communication between the sensor and the glider, essentially aborting the mission.

Prototype 2.3

This prototype contained a new logger/controller board with a repaired pressure sensor. The firmware contained a two-second startup with an initial test data stream to prevent data stream delays and communication issues between sensor and glider.

Prototype 2.4

The membrane was backed with a silver filter to help prevent failures. A 9600 baud rate was hard-coded to prevent communication issues.

Testing Equilibration Time

The response time and stability of prototype 1.0 over a longer time period were determined with a series of laboratory experiments at the UAF laboratory facilities in Fairbanks (Figure 1). The initial experiments revealed that the SBE 5M pump recommended by Pro-Oceanus was not strong enough to provide an adequate flow rate (>1 L/min) through the hollow fiber module. The SBE 5M pump was upgraded to a stronger pump (SBE 5P @ 4500 rpm), which was subsequently tested at the Alaska SeaLife Center in Seward, Alaska (Figures 2 and 3). The sensor was run continuously for one week and pCO_2, flow rate, and pressure were closely monitored. Thirty-seven individual perturbation experiments were conducted to test the response time of the sensor in a rapidly changing environment. During each experiment, water supply to the sensor was changed from ambient to high CO_2 (~1000 to 2000 ppm) or vice versa. A response lag time was determined by noting the difference between the time that the water supply was changed and

the initial detection of a perturbation by the sensor. In addition, the response time constant was computed by fitting an asymptotic exponential curve to the pCO_2 time series.
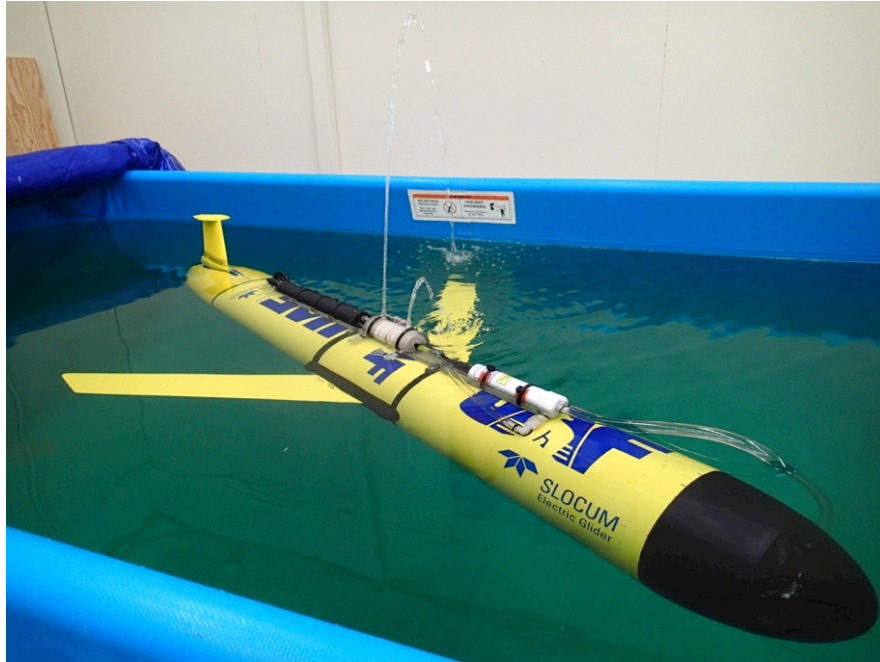
Figure 1. Carbon glider in a tank at the UAF glider facilities during ballast testing.

Figure 2. Carbon glider with prototype 1.1 (upper panel) and 2.1 (lower panel) pCO_2 sensors. The prototype 1.1 configuration (upper panel) includes an SBE 5P pump.
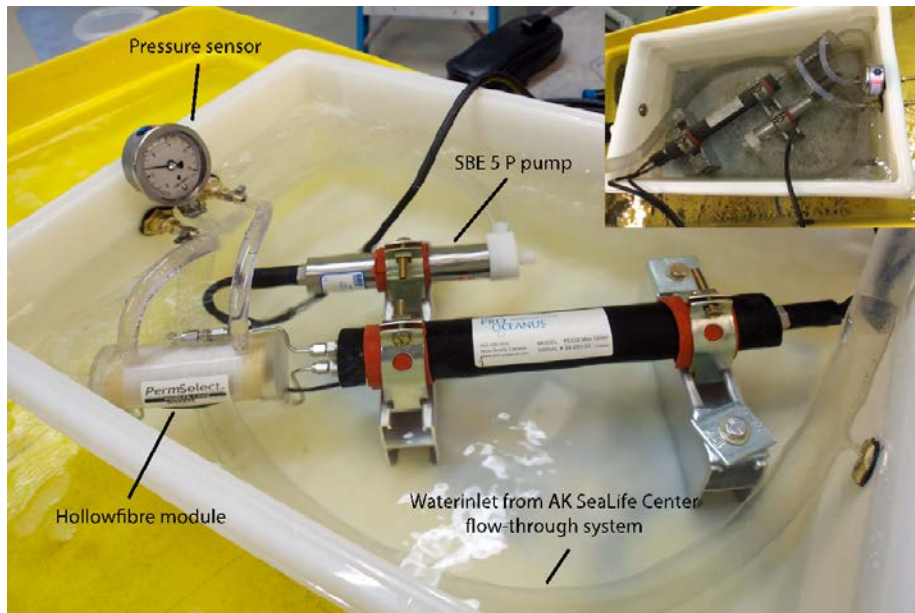
Figure 3. Laboratory setup at the Alaska SeaLife Center in Seward, Alaska. Inset: High particle concentration clogged the hollow fiber module after one week.

Glider-Sensor Integration

The mechanical and electrical aspects of the CO_2 sensor glider integration were completed in collaboration with Teledyne Webb Research (TWR) and Pro-Oceanus. The integration involved designing the mounting bracket, writing integration software to support communication and power supply between the sensor and the glider, and adding an outlet port to connect the sensor to the glider electronics. TWR integrated the sensor package (Glider Mini-Pro CO_2 prototype and SBE 5P @ 4500 rmp pump) in a nicely streamlined position conducive to glider deployment, flight, and recovery.

Results and Discussion

Equilibration Experiments

Laboratory tests suggested that the equilibration time of the prototype 1.1 pCO_2 sensor was short enough to be suitable for the glider application. Response times typically ranged from 10–20 s at flow rates greater than 1.5 L/min and increased to ~30 s for flow rates less than 1 L/min (Figure 4). However, over the course of the response time experiments, the high suspended sediment concentration in the flow-through seawater sourced from just offshore the Alaska SeaLife Center reduced the flow rate through the hollow fiber module (Figure 3 inset). Over the first five days of testing, the flow rate dropped slowly from 5.5 L/min to 2.16 L/min, which suggested that use of the 1.1 sensor prototype would limit carbon glider mission durations to about one week to avoid the effects of the obstruction of the hollow fiber module by suspended sediments.
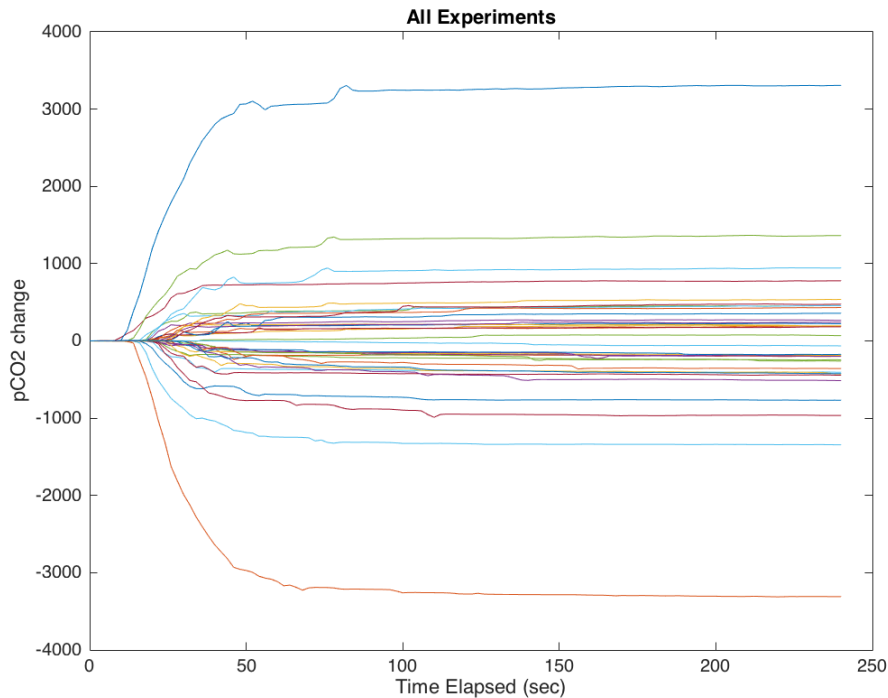
Figure 4: Data from equilibration-time experiments at the Alaska SeaLife Center in Seward. Each line represents a separate test.

Glider-Sensor Integration

The power supply from the glider to the pump and pCO_2 sensor worked well, water flow through the hollow fiber module was strong, and the glider was well ballasted. However, an infrequent parsing error interrupted the communication between the pCO_2 sensor and glider. This problem was eliminated by updating the sensors firmware to support comma separated data output (prototype 1.1).

Early Field Trials

Initial field testing of the carbon glider showed that the integration of the Teledyne Webb Slocum Glider, the Pro-Oceanus Mini-Pro pCO_2 sensor (prototype 1.1), and a Seabird 5P submersible pump (Figure 2, upper panel) was successful. The glider operated as expected during several dive and climb cycles, and the components successfully communicated with each other to record pressure, temperature, salinity, backscatter, Chlorophyll-*a*, CDOM concentrations, and the partial pressure of carbon dioxide (pCO_2) data throughout the water column (Figure 5). We were able to verify that the addition of the pCO_2 sensor and pump, which directed seawater through the hollow fiber module, did not significantly alter the flight characteristics of the glider.
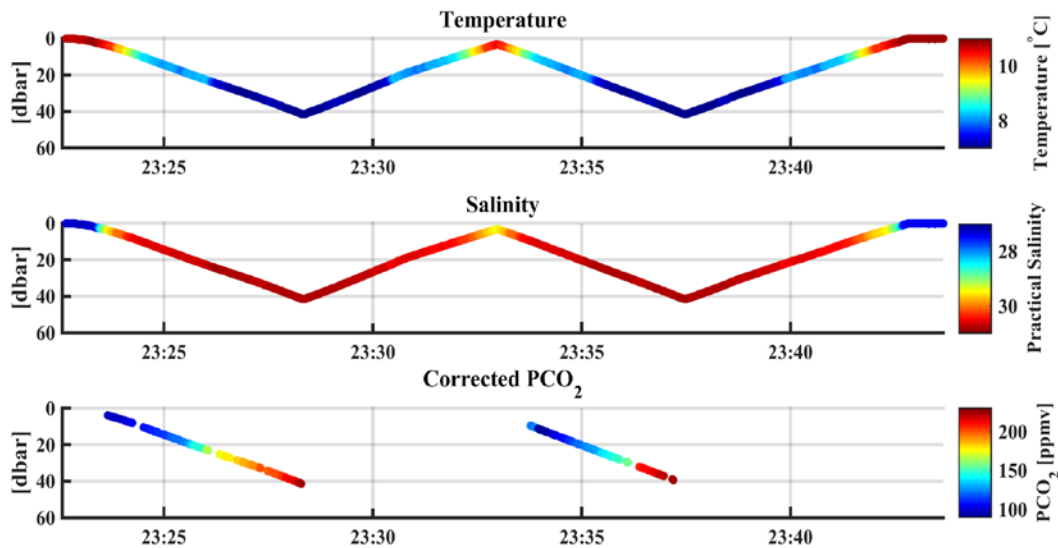

Figure 5: Time series of temperature, salinity, and pCO_2 from initial field testing (backscatter, CDOM, and Chlorophyll-*a* are not shown). The initial dives to 40 m sampled temperature, salinity, backscatter, CDOM, and Chlorophyll-*a* continuously throughout the water column; whereas, the Mini-pro pCO_2 sensor was set to sample only during the downcast in order to conserve battery power for the Chukchi Sea missions.

During the first sea trials, we encountered a leakage issue with the hollow fiber module that was added to the Mini-Pro to accelerate its equilibration time. Data suggested that the hollow fiber module failed on the second mission at pressures within our intended working depths. This issue, combined with findings from our laboratory testing that indicated the hollow fiber module was susceptible to clogging and required a high-powered pump (both of which shorten mission duration), helped us determine that the hollow fiber module was not suitable for the intended glider application.

Development of Glider Hover Missions

We constructed glider flight control missions to accommodate a pCO_2 sensor with a longer equilibration time. During these missions, the glider hovered at various prescribed depths for a preset time (Figure 6). The testing and refinement of the hover missions was, in itself, a success.

Hover missions for gliders are uncommon and had to develop and refine the technique and create mission program files for the glider to execute. The ability to hover a glider is a powerful new tool for use with sensors that require an equilibration period.
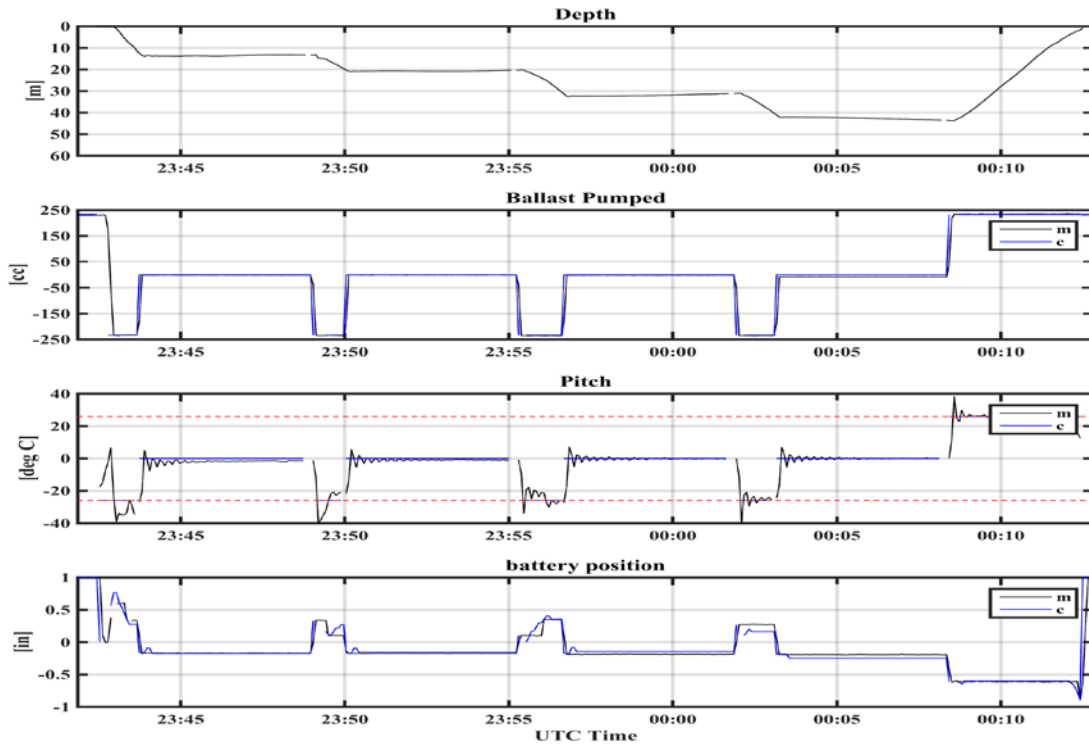

Figure 6: Glider flight data showing the first successful glider hover mission on May 23, 2016, with controlled hover at the prescribed flight depths. Depth (top), ballast pumped (second from top), pitch (third from top) and glider battery position (bottom) are plotted as a function of time. Black lines ("m") designate measured values, and blue lines ("c") designate commanded value.

Prototype 2 Field Trials and Improvements

In close collaboration with the pCO_2 sensor manufacturer, Pro-Oceanus, we modified our sensor configuration to work without the hollow fiber module (see prototype 2.0 section above). Testing the carbon glider with prototype 2.0 (Figure 2, lower panel) produced reasonable pCO_2 data strings in the laboratory; however, a subsequent glider mission at sea produced zeros and error readings. Troubleshooting showed prototype 2.0 required a longer startup time than the glider software allowed, leading to communication issues. This problem, caused by small changes Pro-Oceanus made to the logger/controller board, was resolved by installing a new logger/controller board (prototype 2.1) containing the firmware of prototype 1.1. The new board was tested in the laboratory in combination with the glider. During these tests, the glider actively logged the data (rather than simply live streaming to the computer), which ensured that the laboratory tests were representative of a true glider mission at sea.

The field trials to test sensor prototype 2.1 took place in August 2016. Conditions in Resurrection Bay were not favorable for glider missions. Unexpectedly low surface salinities of

18 salinity units led to a density gradient twice as large as the glider could handle in the upper 40 m of the water column at our regular field test sites. The glider was deployed in the Gulf of Alaska, about 25 nm offshore from Seward, at surface salinities of 26 and a manageable density gradient of 6 sigma units. The deployment site was in the Alaska Coastal Current, which exposed the glider and boat to a large swell and strong drift. These difficult oceanographic conditions caused a delay in the glider operations and limited the number of deployments we were able to accomplish. However, we were able to conduct the necessary tethered glider safety missions (making sure the glider can operate in the conditions), two saw-tooth dives (Figure 7), and one hovering mission (Figure 8). The glider successfully logged pCO_2 data from prototype 2.1 during these missions.

The first double sawtooth mission (to 40 m) demonstrated that the glider was able to dive and climb at a steady rate while maintaining course and logging pCO_2 data and other ancillary data (Figure 7). The pCO_2 profile shows the low to high gradient expected with low salinity and high primary production measured at the surface, and less freshwater and primary production and more respiration of organic matter at 40 m depth. As expected from the response time of the pCO_2 instrument, there was some hysteresis observed in the profiles, with the maximum pCO_2 values observed 67 seconds after the maximum depths were reached.
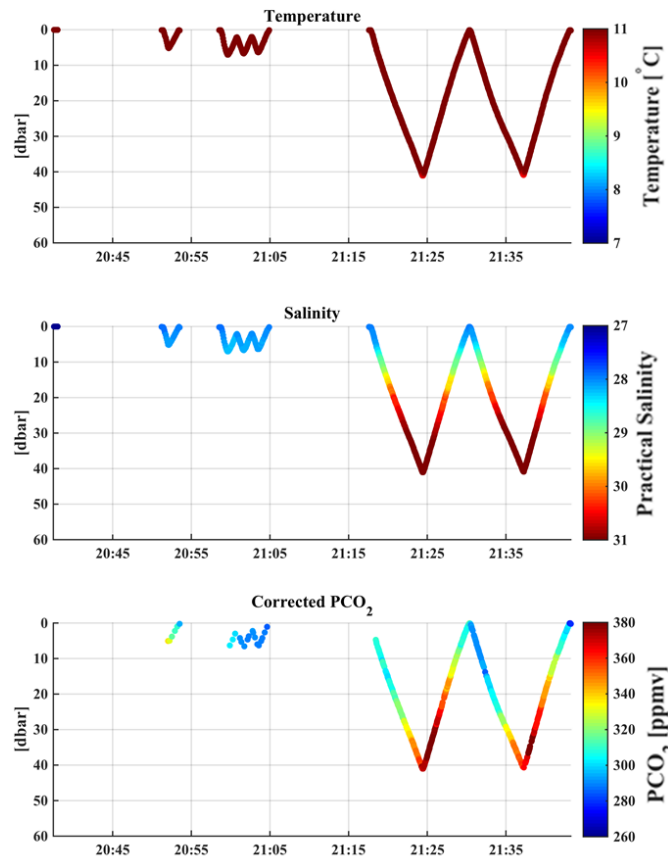

Figure 7: Profiles of temperature (upper panel), salinity (mid panel), and pCO_2 (lower panel) from the saw-tooth carbon glider prototype 2.1 mission during the August sea trials.

The hover mission was conducted with programmed hover depths every 5 m between 5 and 30 m and at 40 m (Figure 8). The glider executed this hovering by dynamically adjusting the battery position such that the glider maintained a level pitch. Meanwhile, the buoyancy was dynamically adjusted to bring the glider to the desired depth. At the 15 and 20 m hover depths, the glider was essentially neutrally buoyant and required very little buoyancy adjustment. At other depths, significant buoyancy adjustments were required to reach the desired depths. These difficult conditions pointed out the need to improve the glider's hovering capabilities by refining the flight control in response to the local conditions. pCO_2 stabilized within a few ppm during the hover missions, which demonstrates that short hover missions can achieve equilibration of the sensor and construction of pCO_2 profiles in the water column, a first for an autonomous glider.
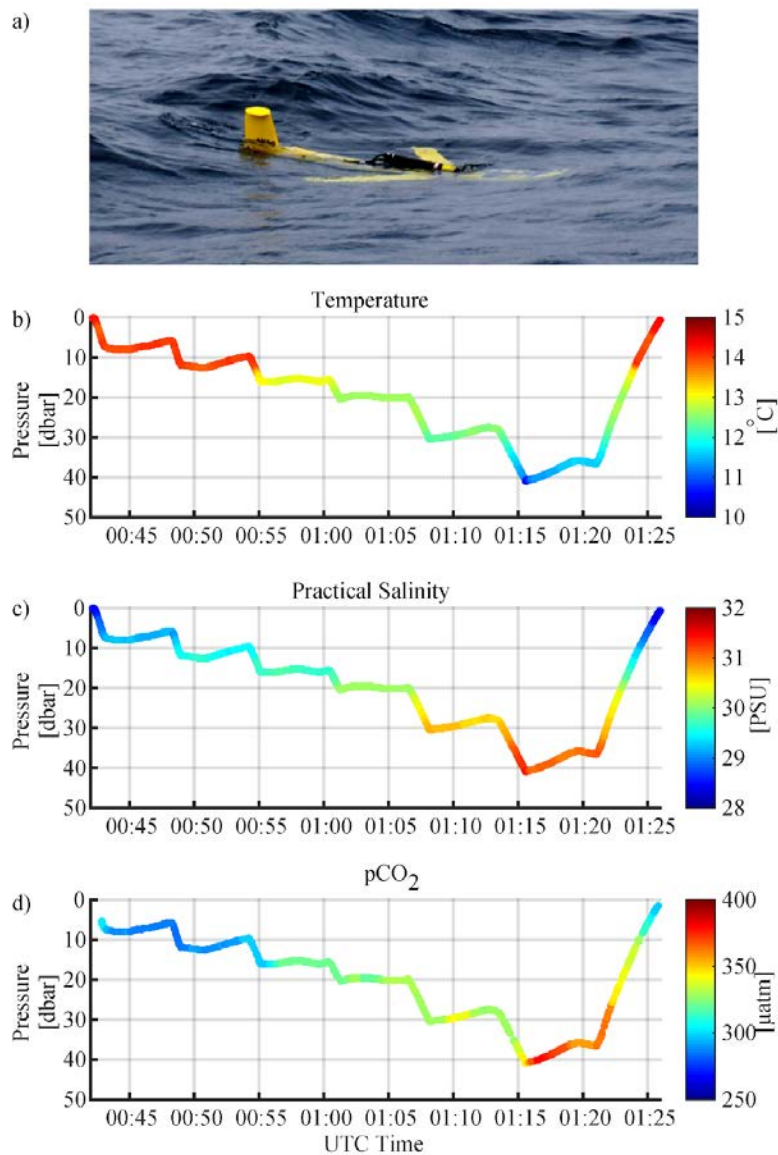

Figure 8: Image of the carbon glider prototype 2.1 at the surface during the August 2016 sea trials (a) with profiles of temperature (b), salinity (c), and pCO_2 (d) from a hovering mission. Hover stops were programmed every 5 m between 5 and 30 m and at 40 m.

The August sea trials also demonstrated that the water-pumped head, designed by Pro-Oceanus for our second generation Mini-Pro pCO_2 sensor, had the potential to damage the flat semi-permeable membrane. The semi-permeable membrane is used as an interface for the equilibration of headspace gas with the surrounding water and is the only barrier preventing water from penetrating the sensor housing and electronics. The repeated pressure cycling during dives and climbs pushed the membrane against the water-pumped head, slightly wrinkling it and potentially flooding the sensor (Figure 9).

Figure 9: Picture of the wrinkled membrane from prototype 2.1 following successful sawtooth and hover missions during the August 2016 sea trials.

Arctic deployment

Prototype 2.3 was deployed and recovered twice during the 2016 September cruise of the *R/V Sikuliaq* (Figure 10). The first deployment attempt on September 11 was aborted after a failure in the glider's science bay. Following an initial dive to 5 m, the glider began aborting the mission because it lost communication with its science computer, having blown a fuse on the science board. The second deployment was on September 20 at 71.61°N, 163.77°W. Before this second deployment, the glider was sitting outside for over 12 hours in 0°C weather. On-deck tests the night before and an hour before deployment reported pCO_2 values ranging from -2000 to 0 ppm. The glider was checked out following the standard deployment procedure and sent on an extra check-out mission to dive to 20 m with 2-minute safety stops at 5 m at the start and end. On this initial hover mission, the glider sank through the water column during its attempt to hover at 5 m. The poor hover behavior was attributed to the glider being ballasted too heavy for the surface density of 1022.7 kg/m^3.

Figure 10: The carbon glider deployed near the *R/V Sikuliaq* in the Chukchi Sea in September 2016.

The glider was sent on its next mission after reviewing the science and engineering data files from the test dives. Due to the response time of prototype 2.3, we developed novel missions to allow the glider to hover at various depths through the water column in order to get accurate pCO_2 data. Since the glider can only make headway during its standard "yo" or "sawtooth" missions, we had to develop a secondary mission that would allow us to make forward movement as well as perform the required safety stops. The intended mission had the glider do a safety stop, perform ten dives to 35 m, do another safety stop, then surface after approximately two hours.

The glider began its mission September 20th at 21:45 UTC and did not resurface until September 21st at 03:37 UTC, 5.86 hours after diving. The sensor must have been partially flooded at mission start because the glider was not able to do the safety stop or yo properly (Figure 11). During each of the ten dives, the glider attempted to climb but would complete early and sink back to 37 m. The safety stop was the last behavior the glider was supposed to run in the mission; instead, it sank to the seafloor at a depth of 42.3 m. The glider aborted after 30 minutes because it was not able to change depth. After four hours of attempting to surface while sitting on the seafloor, the glider began its emergency procedure to drop a 1 kg weight and within nine minutes of dropping the weight surfaced.
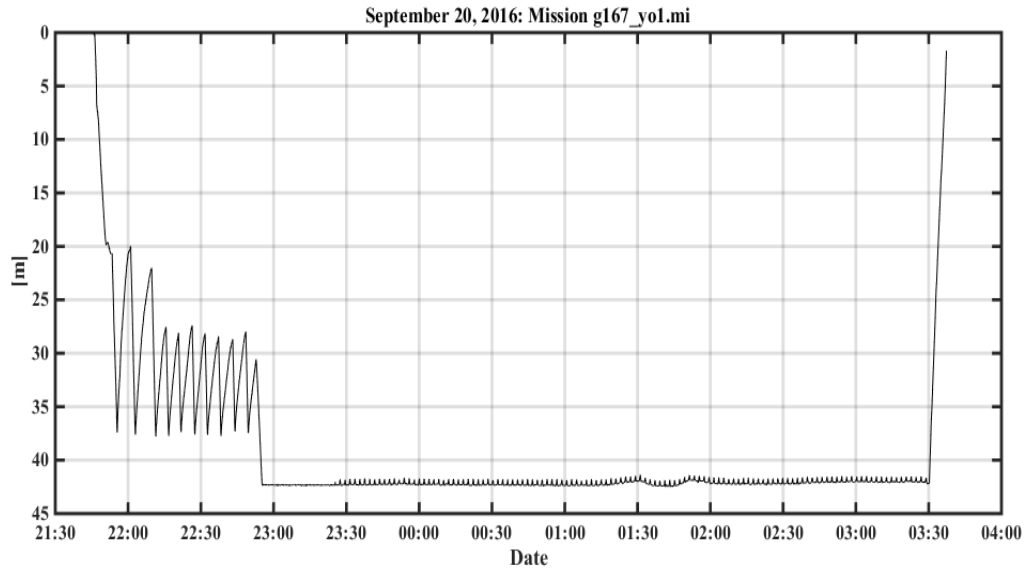
Figure 11. The carbon glider depth profile from a September 2016 mission.

Science data were not collected during the mission because the Mini-Pro pCO$_2$ sensor caused a fatal error at the start of the mission. After removing the water-pumped head, small indentations were visible on the semi-permeable membrane. Inspection of the pCO$_2$ sensor by Pro-Oceanus confirmed that the sensor flooded as a result of the perforated membrane (Figure 12). The failure was due to a missing O-ring between the membrane and mesh in the pressure head, which may have come loose during shipment.
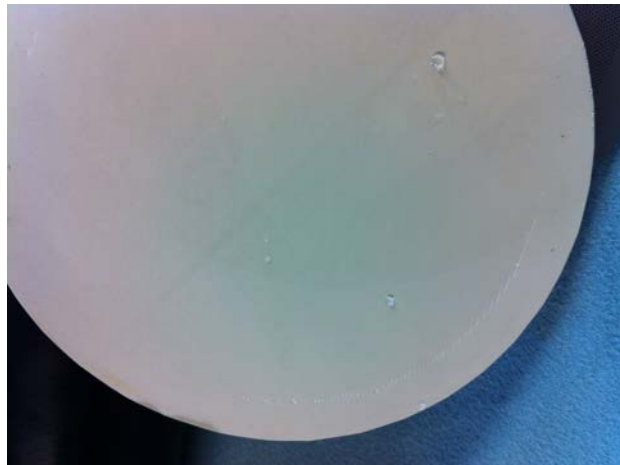

Figure 12: Image of the perforated membrane from the flooded pCO$_2$ sensor after deployment in the Chukchi Sea.

Final sea trials

Final sea trials took place in May 2017, just south of Caines Head in Resurrection Bay. Deployments were made from the small vessel *Dora* . The goals for these trials were to fly the glider for consecutive days, ground-truth the pCO_2, salinity, and temperature data with CTD casts, and proof the overall concept of the newly developed unit.

The carbon glider experienced another blow out of the F2 fuse on the science board during laboratory tests between field trials. Since this also happened during the Chukchi Sea deployment, it appears an infrequent high-power demand by the pCO_2 sensor causes this failure. Additional bench top tests also showed that the sensor suddenly changed baud rate from 9600 to 19200, causing communication issues with the glider. The carbon glider was run in the laboratory tank for nearly 20 hours without re-occurrence of these issues before being deployed for final sea trials.

When the glider first deployed into the water for the sea trial, the sensor baud rate switched back to 19200 after checking out fine minutes before. After this initial problem, the deployment, recovery, and mission executions were very smooth. The data from these missions showed that the glider stayed +/- 2.5 m of the set point while hovering. While the glider was able to stabilize its pitch, it had a hard time maintaining buoyancy (Figures 13 and 15). The pCO_2 profiles suggest that either the 7-minute long hovers were too short for the sensor to equilibrate or the glider went in and out of different water masses while hovering (Figures 14 and 16). Note that salinity data is not corrected for sensor lag or thermal lag effects. This glider has an unpumped CTD and relied on forward motion to increase response times. It would take significant time to redo processing scripts to account for these hover missions, which is outside the scope of this project.

Figure 13: Glider flight data showing a hover mission during the sea trials in May 2017 with controlled hover at the prescribed flight depths. Depth (top), ballast pumped (second from top), pitch (third from top) and glider battery position (bottom) are plotted as a function of time. Legend "m" designates measured value, whereas "c" designates commanded value.

Figure 14: Temperature, salinity, and pCO₂ data from mixed sawtooth/hover mission 1. The upper left panel shows temperature (blue), salinity (red), and density (black) as a function of pressure. pCO₂ is shown as a function of time (middle left panel) and as a function of pressure and time (lower left panel). The right figures show temperature (upper), salinity (middle), and density (lower) as a function of time and pressure.
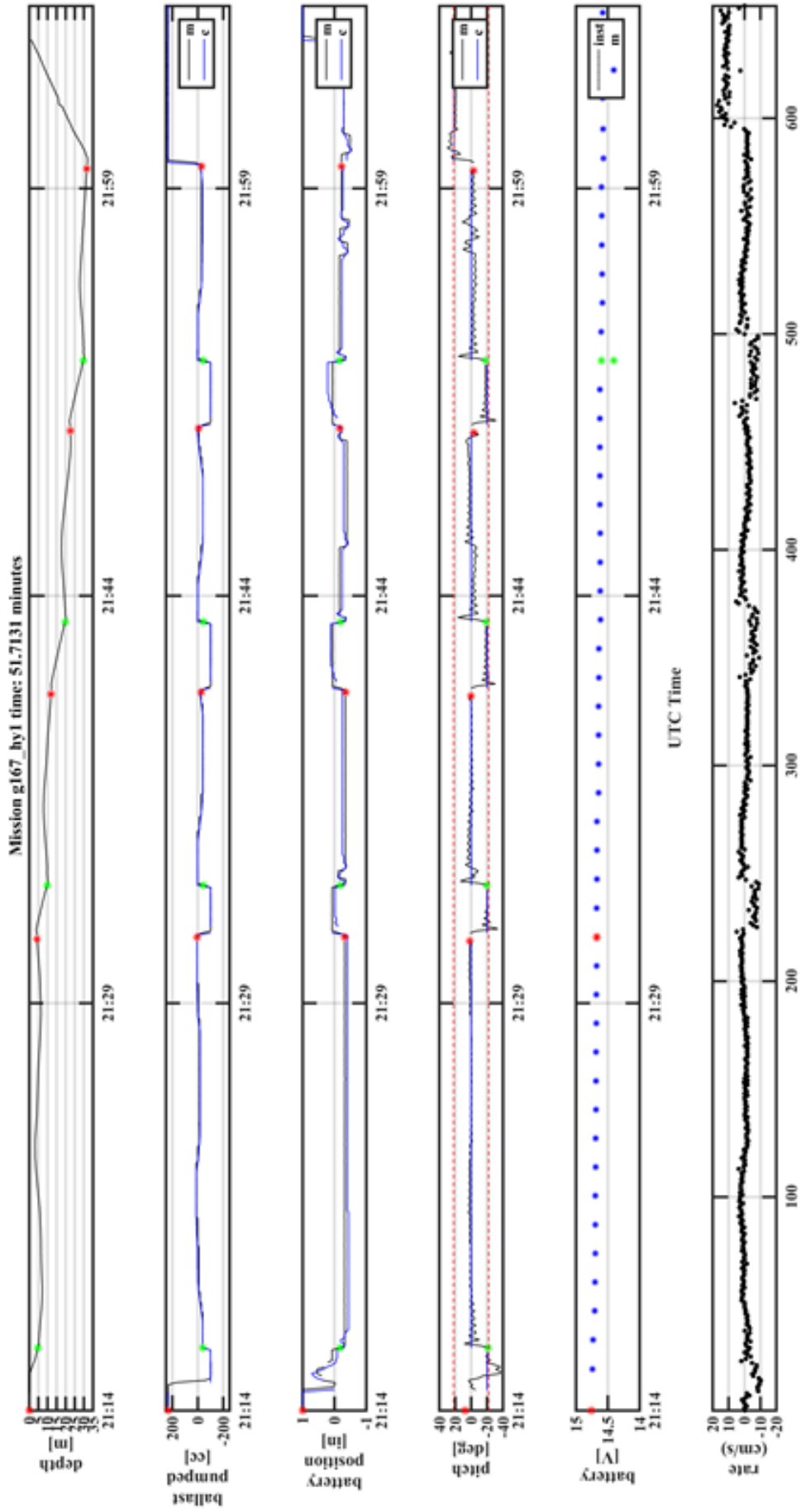
Figure 15: Glider flight data showing a hover mission during the sea trials in May 2017 with controlled hover at the prescribed flight depths. Depth (top), ballast pumped (second from top), pitch (third from top) and glider battery position (bottom) are plotted as a function of time. Legend "m" designates measured value, whereas "c" designates commanded value.
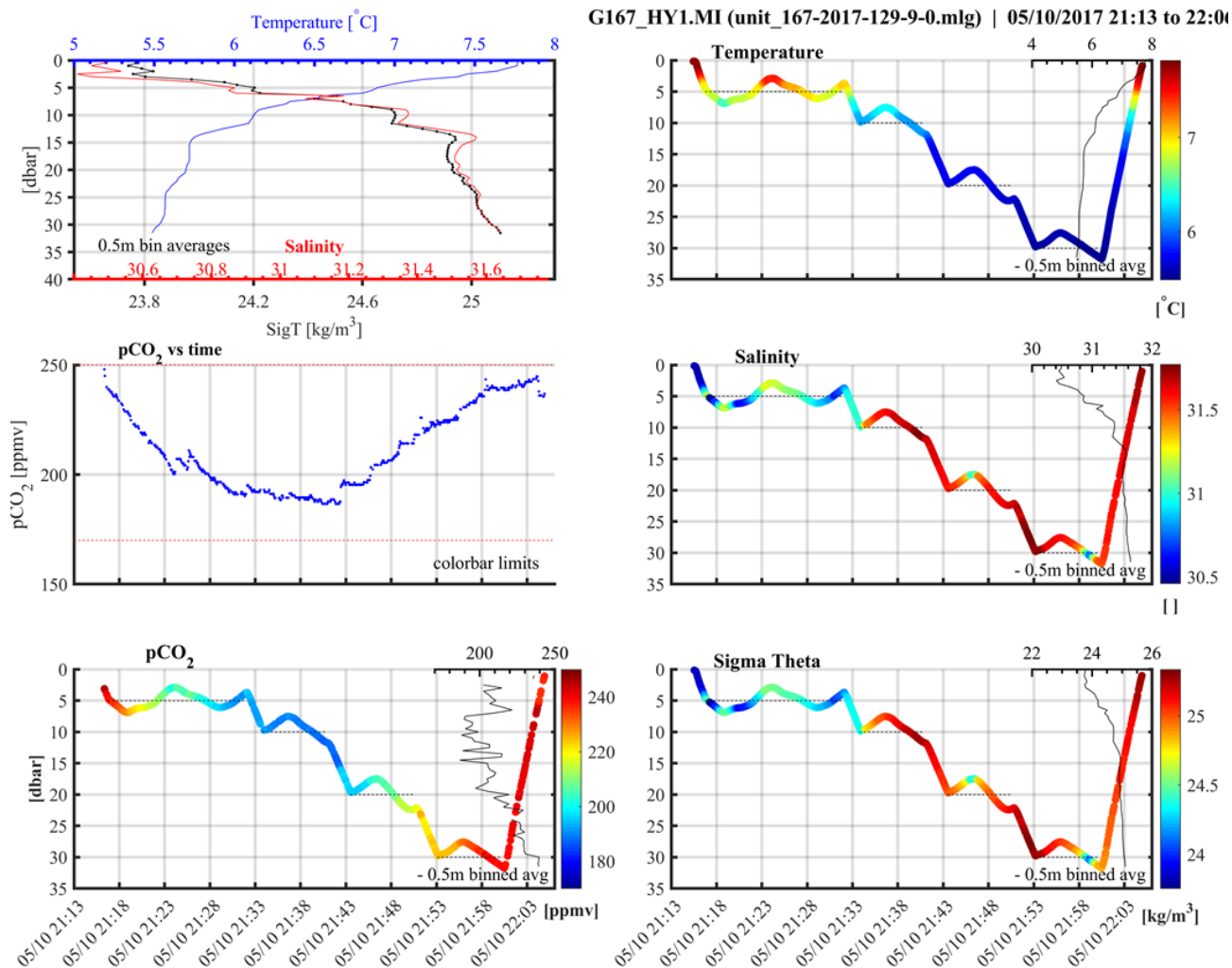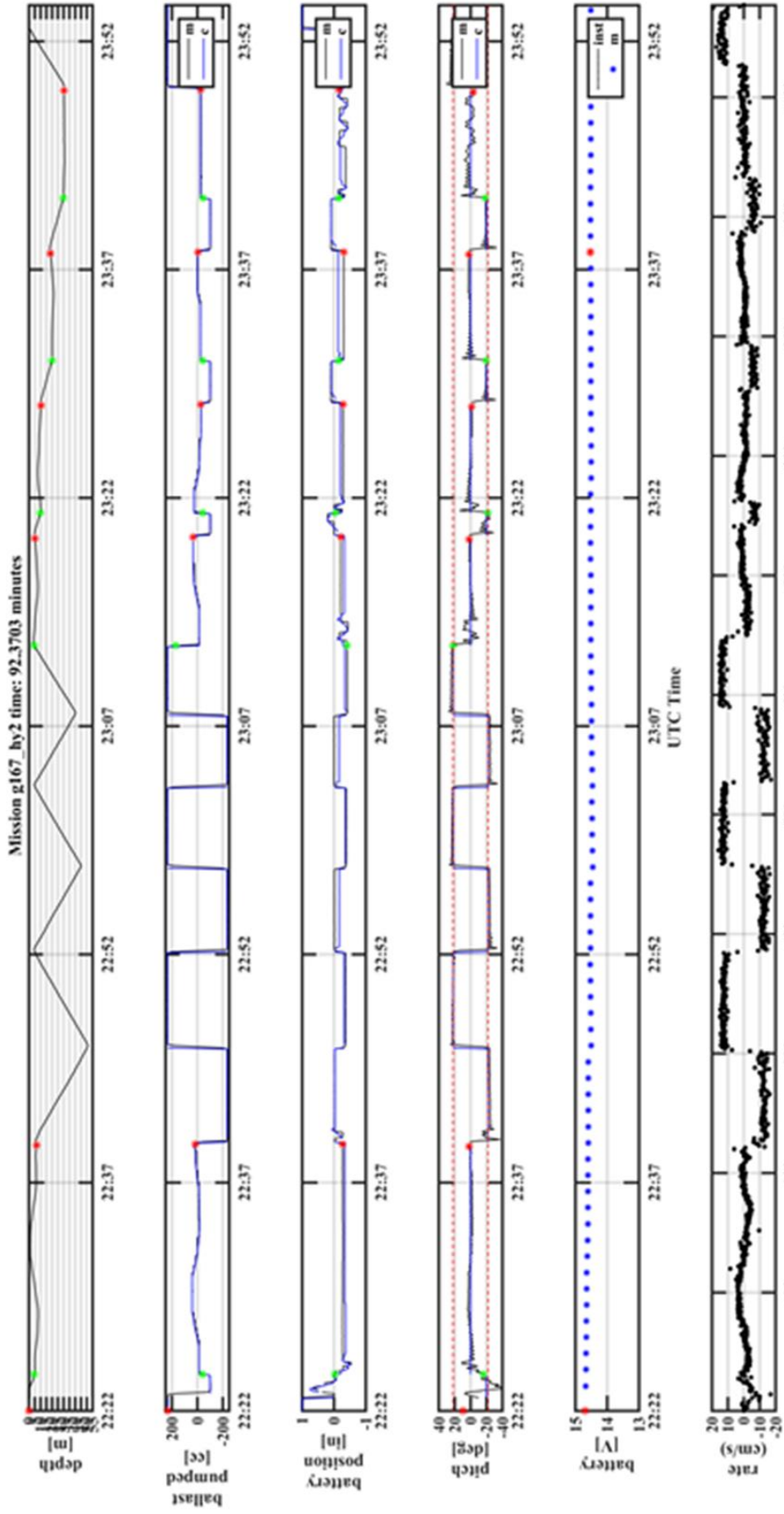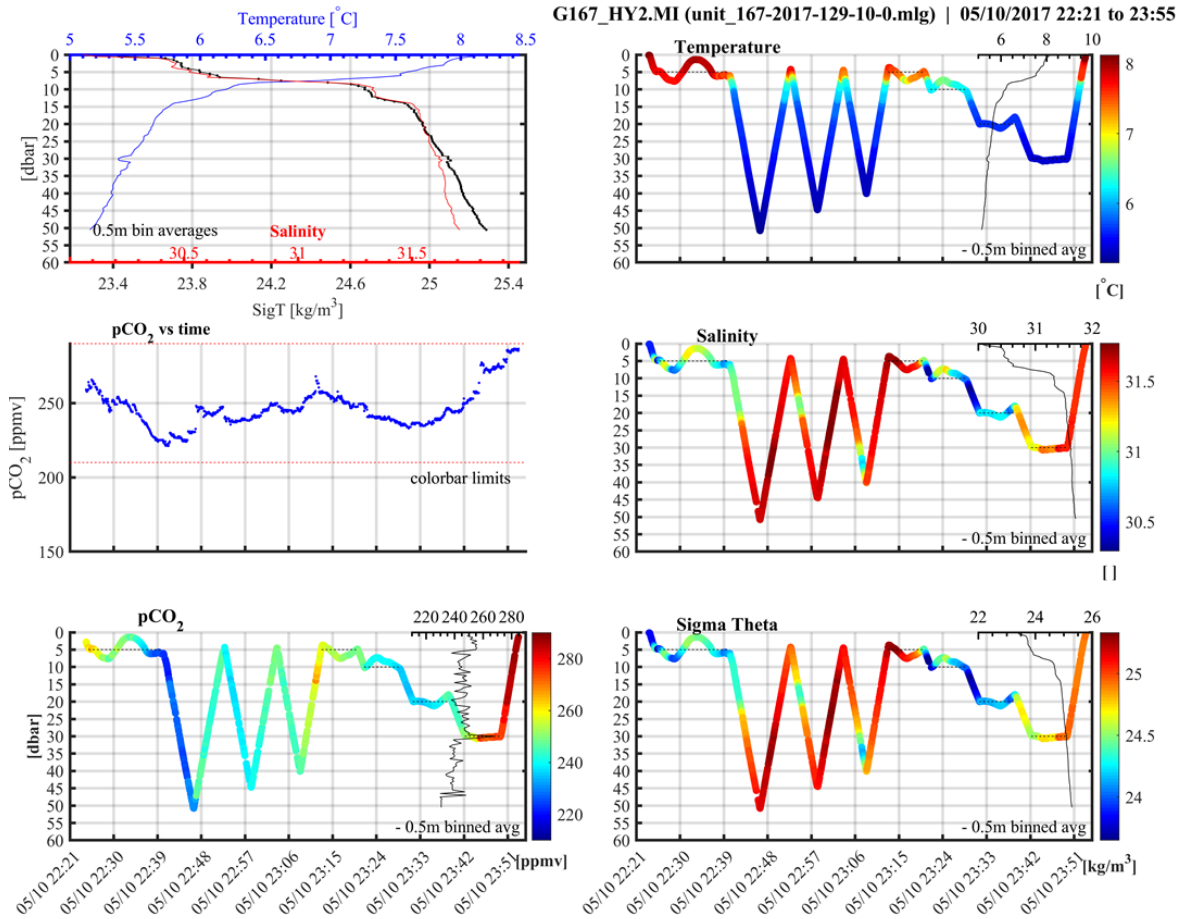
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Figure 16: Temperature, salinity, and pCO_2 data from a mixed sawtooth/hover mission 2. The upper left panel shows temperature (blue), salinity (red), and density (black) as a function of pressure. pCO_2 is shown as a function of time (middle left panel) and as a function of pressure and time (lower left panel). The right figures show temperature (upper), salinity (middle), and density (lower) as a function of time and pressure.

After two days of successful hover and yo missions, the carbon glider was checked out for its first overnight mission. The pCO_2 sensor switched baud rates mid/end of its first 2-hour mission. Since the baud rate cannot be changed over iridium, the sensor was switched off, and the carbon glider continued with its missions without collecting pCO_2 data. Upon recovery of the carbon glider, the pCO_2 sensor was found partially flooded (<118 ml of seawater). The sensor was gutted and outfitted with a new board, new O-rings, and new membrane. The new board was outfitted with a code to fix the baud rate issue. The carbon glider was redeployed and collected pCO2 data for another few hours. Then, all missions produced "delayed ERROR (558)" errors, without causing aborts. In addition, science sensors and pressure cut out randomly after the last mission with pCO_2 data. Examination of the sensor showed that an impulse connection failure was the reason for these issues. A pCO_2 profile collected by the carbon glider before the complete failure shows very long response times (Figure 17), suggesting that the pump failed due to the defect impulse connector not supplying the sensor with adequate through-flow to decrease its equilibration time.
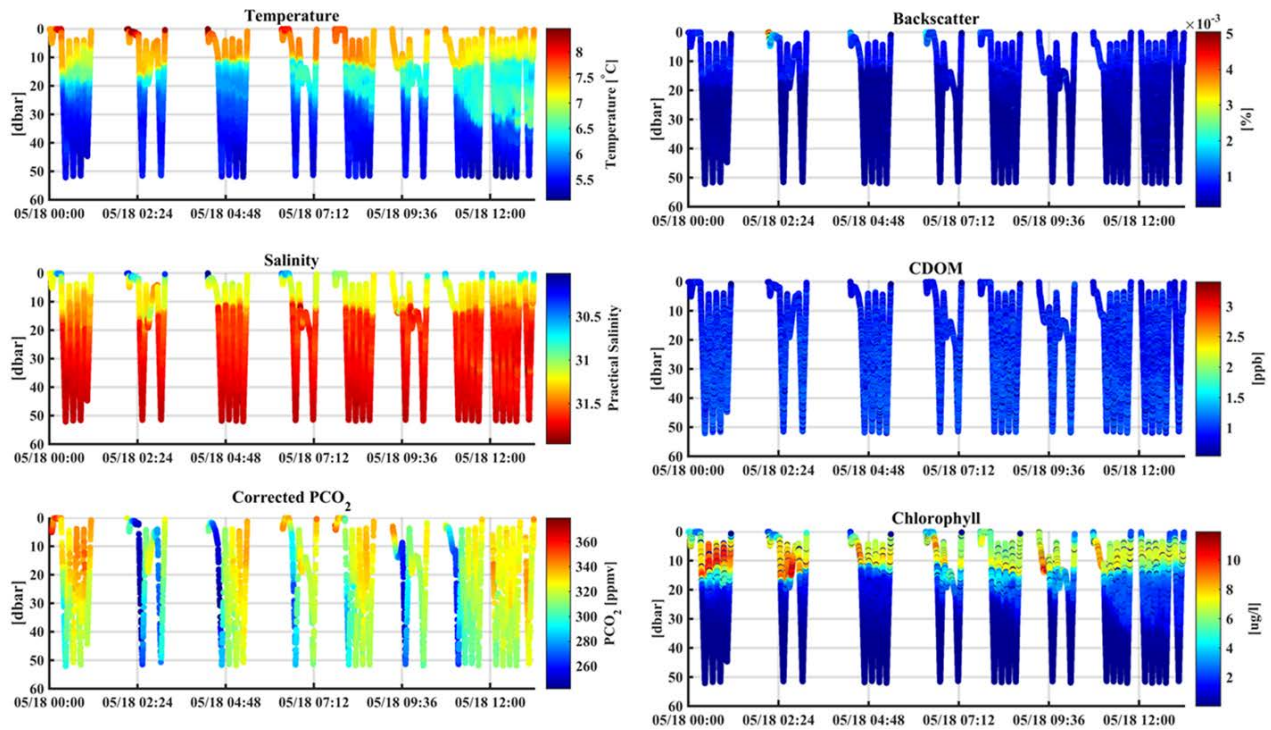
Figure 17: Temperature (upper left), salinity (middle left), pCO$_2$ (lower left), backscatter (upper right), CDOM (middle right), and Chlorophyll-*a* (lower right) data from glider missions after the pCO$_2$ sensor was flooded.

Problems identified through the final sea trials included both glider and sensor issues. The hovers were not very good, in large part because the glider software will have to be updated to account for tight station-keeping requirements. Hover time was increased by several minutes over the August 2016 trials, which added to the problem of the glider holding position. Mini-Pro related problems included a partially flooded sensor, slower response time than in previous versions, a defective impulse connector, and ongoing issues with blown fuses (has happened twice with carbon glider, but uncommon for other glider operations)

Conclusions

The main goal of this project was the development of a carbon glider to autonomously acquire high-resolution spatial and temporal data of dissolved CO_2 concentrations throughout the water column. Initially, we aimed to reduce the equilibration time of the Mini-Pro pCO_2 sensor to accommodate measurements of fast pCO_2 changes as the glider moves through the water column. However, since we were not able to reduce the equilibration time to <1 minute, we developed glider hover missions. We have made significant advancements with the hover flight profiles, but more work is required to reduce the need for dynamic adjustments to the glider buoyancy, a change that would save energy and further extend the mission duration. While the membrane set-up of the pCO_2 sensor went through several iterations, it is currently still not strong enough to withstand the rapid pressure changes that the sensor experiences during glider missions. Once this issue is resolved, the performance of the carbon glider needs to be thoroughly evaluated with *in situ* pCO_2 sampling. Furthermore, longer test missions need to be conducted in order to understand the power budget. However, due to the high power consumption of the pCO_2 sensor and the SBE 5P pump, mission longevity is estimated to about one week. Upgrade to a lithium powered glider would increase the mission length and, therefore, the safety of the carbon glider substantially.

As a result of this project, we developed a carbon glider and brought it to a Technology Readiness Level 6 (TRL-6 per NASA), with demonstrated capacity of pCO_2 data collection during glider flight missions at sea. However, as discussed above, issues remain to be solved before the carbon glider can be advanced to a fully operational level.

Acknowledgments

We are very grateful to the Seward Marine Center and the Alaska SeaLife Center for accommodating our experiments, bench top testing, and pre-cruise preparation work. Many thanks also go to *Dora* Captains Mike and John. We would also like to thank Alutiiq Pride Shellfish Hatchery for letting us test the carbon glider in their tank and for sharing 'Burkulator' data with us.

Study Products

Results from this study were presented at the Alaska Marine Science Symposium in 2017 and annual Coastal Marine Institute meetings. The raw data from the carbon glider missions was archived at the National Oceanic and Atmospheric Administration's National Centers for Environmental Information (NOAA NCEI). Information on this project can be found at http://mather.sfos.uaf.edu/artlab/projects/CarbonGlider/.

References

Anderson, L. G., T. Tanhua, G. Björk, S. Hjalmarsson, E. P. Jones, S. Jutterström, B. Rudels, J. H. Swift, and I. Wåhlstöm (2010), Arctic ocean shelf–basin interaction: An active continental shelf CO_2 pump and its impact on the degree of calcium carbonate solubility. Deep Sea Res. Part I Oceanogr. Res. Pap., 57(7), 869–879. doi:10.1016/j.dsr.2010.03.012.

Bates, N. R. (2006), Air-sea CO_2 fluxes and the continental shelf pump of carbon in the Chukchi Sea adjacent to the Arctic Ocean. J. Geophys. Res., 111(C10), 1–21.

Bates, N. R., M. I. Orchowska, R. Garley, and J. T. Mathis (2013), Summertime calcium carbonate undersaturation in shelf waters of the western Arctic Ocean – how biological processes exacerbate the impact of ocean acidification. Biogeosciences, 10(8), 5281–5309. doi:10.5194/bg-10-5281-2013.

Coachman, L. K. (1986), Circulation, water masses, and fluxes on the southeastern Bering Sea shelf. Cont. Shelf Res., 5(1), 23–108.

Gao, Z., L. Chen, H. Sun, B. Chen, and W.-J. Cai (2012), Distributions and air-sea fluxes of carbon dioxide in the Western Arctic Ocean. Deep Sea Res. Part II Top. Stud. Oceanogr. (81–84), 46–52. doi:10.1016/j.dsr2.2012.08.021.

Grebmeier, J. M., L. W. Cooper, H. M. Feder, and B. I. Sirenko (2006), Ecosystem dynamics of the Pacific-influenced Northern Bering and Chukchi Seas in the Amerasian Arctic. Prog. Oceanogr., 71(2–4), 331–361.

Hauri, C., P. Winsor, L. W. Juranek, A. M. P. McDonnell, T. Takahashi, and J. T. Mathis (2013), Wind-driven mixing causes a reduction in the strength of the continental shelf carbon pump in the Chukchi Sea. Geophys. Res. Lett., 40, 5932–5936, doi:10.1002/2013GL058267.

Mathis, J. T., and J. M. Questel (2013), Assessing seasonal changes in carbonate parameters across small spatial gradients in the Northeastern Chukchi Sea. Cont. Shelf Res., 1–10. doi:10.1016/j.csr.2013.04.041.

Pipko, I. I., I. P. Semiletov, P. Y. Tishenko, S. P. Pugach, and J. P. Christensen (2002), Carbonate chemistry dynamics in Bering Strait and the Chukchi Sea. Prog. Oceanogr., 55, 77–94. doi:10.1016/S0079-6611(02)00071-X.

Sambrotto, R. N., J. J. Goering, and C. McRoy (1984), Large yearly production of phytoplankton in the western Bering Strait. Science, 225(4667), 1147–1150. doi: 10.1126/science.225.4667.1147.

Springer, A., and C. McRoy (1993), The paradox of pelagic food webs in the northern Bering Sea-III. Patterns of primary production. Cont. Shelf Res., 13(5/6), 575–599. doi:10.1016/0278-4343(93)90095-F.

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