



SYMPOSIUM

Autonomous Gliders Reveal Features of the Water Column Associated with Foraging by Adélie Penguins

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Synopsis Despite their strong dependence on the pelagic environment, seabirds and other top predators in polar marine ecosystems are generally studied during their reproductive phases in terrestrial environments. As a result, a significant portion of their life history is understudied which in turn has led to limited understanding. Recent advances in autonomous underwater vehicle (AUV) technologies have allowed satellite-tagged Adélie penguins to guide AUV surveys of the marine environment at the Palmer Long-Term Ecological Research (LTER) site on the western Antarctic Peninsula. Near real-time data sent via Iridium satellites from the AUVs to a centralized control center thousands of miles away allowed scientists to adapt AUV sampling strategies to meet the changing conditions of the subsurface. Such AUV data revealed the water masses and fine-scale features associated with Adélie penguin foraging trips. During this study, the maximum concentration of chlorophyll was between 30 and 50 m deep. Encompassing this peak in the chlorophyll concentration, within the water-column, was a mixture of nutrient-laden Upper Circumpolar Deep (UCDW) and western Antarctic Peninsula winter water (WW). Together, data from the AUV survey and penguin dives reveal that 54% of foraging by Adélie penguins occurs immediately below the chlorophyll maximum. These data demonstrate how bringing together emerging technologies, such as AUVs, with established methods such as the radio-tagging of penguins can provide powerful tools for monitoring and hypothesis testing of previously inaccessible ecological processes. Ocean and atmosphere temperatures are expected to continue increasing along the western Antarctic Peninsula, which will undoubtedly affect regional marine ecosystems. New and emerging technologies such as unmanned underwater vehicles and individually mounted satellite tracking devices will provide the tools critical to documenting and understanding the widespread ecological change expected in polar regions.

Introduction

Climatic change is, and will continue, altering marine ecosystems. However, the complexity of marine food webs, combined with chronic under-sampling of the ocean, constrains efforts to predict the effects of future change. Furthermore, these limitations also restrict our capacity to suitably manage and protect marine resources. All of these problems are magnified in polar oceans because these environments are extremely difficult to observe and to study (Anisimov et al. 2007). The harsh conditions associated with low temperatures, restricted sunlight for much of

the year, high wind, sea ice, and limited logistic support often curb the widespread application of new technologies that are increasingly being deployed in temperate and tropical oceans. Fortunately, these technologies are maturing and are ready to be deployed in polar oceans. This is vital as many polar seas are experiencing changes in atmospheric/oceanic circulation (Turner et al. 2006), ocean properties (Meredith and King 2005), sea ice cover (Stammerjohn et al. 2008), and ice sheets (Steig et al. 2009). These rapid climatic changes are triggering pronounced shifts and reorganizations in

regional ecosystems and in biogeochemical cycles (Grebmeier et al. 2006). However, it remains difficult to link these changes in the ecosystem to shifts in the physical ocean–atmosphere system. Overcoming this missing link, to decipher the mechanisms of climate-driven variability in an ecosystem, is a critical step in establishing predictive skills capable of contributing to adaptation and risk reduction strategies related to climatic change.

Because of the planetary scale and localized effects of climatic change in polar regions (Kwok and Comiso 2002), sampling strategies linking the changing dynamics of ecosystems with underlying physical processes must span a wide range of temporal and spatial scales. To this end, the oceanographic community has been developing technologies and strategies intended to bridge these vast gaps in observational capacity. For example, multi-platform observatories have been able to deconstruct mechanisms of different scales to elucidate shifts in temperate coastal ecosystems (Schofield et al. 2008). Given that such interdisciplinary and multi-platform approaches have proven themselves in expedient locations, they are ready for application in remote and harsh environments. Essential to the successful application of this approach to high latitude marine ecology will be the integration of technologies that have already succeeded on their own in polar regions. To ensure efficient observing and sampling strategies of dynamic processes, key ecological indicators should be identified and utilized to adjust data collection in real-time.

Top predators, such as marine mammals and seabirds, are key components of Antarctic marine ecosystems. Life-history strategies and population dynamics of these generally long-lived predators can reflect variability occurring over large spatial and temporal scales in both the physical, and biological environment (Fraser et al. 1992). As beacons integrating the dynamics of their ecological niche over decadal time scales, these marine predators are often regarded as sensitive indicators of ecological change (Ainley 2002; Costa et al. 2010) and as important units for the conservation and management of marine resources (Turner et al. 2009). Unfortunately, much of our understanding of the ecology of Antarctic marine predators is derived from animals at terrestrial breeding areas during only a small portion of the annual cycle. Traditionally, researchers studying the ecology of Antarctic marine predators have tried to overcome this constraint by using ARGOS satellite-based tracking technologies. Yet, the scope of these satellite-based tracking technologies is limited by their size,

duration of deployment, the breeding phase of the predator, and by the predator's strategies for acquisition of prey. For example, most satellite-based tags are applied to animals at their terrestrial breeding sites during their annual breeding phase. As such, the resultant data document behavior and strategies associated only with the breeding phase of the tagged predators. Increasingly, technological advances are allowing these satellite-linked tracking tags to include meters capable of detecting environmental variables such as depth, temperature, and salinity (Charrassin et al. 2008). Despite ever more sophisticated instrumentation, the aforementioned limitations still confound researchers' ability to independently characterize the subsurface marine environment shaping the ecology of Antarctic marine top predators.

Background

Adélie penguins as integrators of Antarctic marine ecosystems

Of the world's 18 extant species of penguin (Sphenisciformes: Spheniscidae) (Baker et al. 2006), the Adélie penguin (*Pygoscelis adeliae*) is one of only two (the other is the Emperor penguin, *Aptenodytes forsteri*) true Antarctic species (Williams 1995). Circumpolar and geographically distributed at high southern latitudes, the Adélie penguin is characterized by a life-history that has evolved in close association with sea-ice in the Southern Ocean (Ainley 2002). For example, the species generally winters at the edge of the pack ice where nutrient stores are maintained during the winter months. Along the ice's edge during the early spring, Adélie penguins accumulate critical nutrient reserves required to sustain several aspects of the early-summer breeding effort. These nutrient reserves are fueled by the presence of a reliable food source that itself depends on sea-ice as a critical habitat. The Adélie penguin's primary prey are krill (*Euphausia superba* and *E. crystallographias*) and the Antarctic silverfish (*Pleuragramma antarcticum*). Specifically, the survival and cohort recruitment of juvenile krill depends on their ability to consistently forage upon sea-ice dependent algae (Daly 1990) while Antarctic silverfish forage on krill (Hubold 1985). Furthermore, by hauling out on the sea-ice, Adélie penguins reduce the demands of their maintenance metabolism. Diminished maintenance metabolism, in turn, allows individual Adélies to store more energy. By increasing their energy stores, individual penguins are better able to cope with demands such as the spring migration to terrestrial breeding

colonies, egg production by females, and defense of nesting territories by males.

As oviparous marine vertebrates, the Adélie penguin is entirely dependent on the terrestrial habitat for incubating eggs and rearing chicks. Due to the energetic demands of reproduction, predictable and reliable foraging areas must be located in close proximity to so-called “biological hotspots”. It has long been appreciated that marine “biological hotspots” are regions of high ecological significance (Steele 1976). In terrestrial and corral reef systems, the hotspots have often been defined in terms of biodiversity (Meyers 1997; Hughes et al. 2002) while in marine systems the hotspots have often been defined in terms of increased biomass in either phytoplankton (Valavanis et al. 2004) or higher organisms. Such hotspots of biological activity are driven by pelagic bio-physical interactions resulting in elevated new primary production (i.e., phytoplankton blooms driven by newly introduced rather than regenerated nutrients). These photosynthetically driven blooms result in a trophic cascade of new energy. As the physics and chemistry of the oceans varies rapidly in space and time (at the scale of minutes to days), plankton biology (and the subsequent introduction of energy into the marine food web) is extremely patchy and highly ephemeral (ranging from hours to days). In contrast, higher trophic levels (nekton, sea birds, and marine mammals) by virtue of their long life-times (years to decades) integrate over larger space and longer time scales. Consequently, mapping top-predators often identifies “biological hotspots”—or regions where such energy flows readily through the ecosystem.

The subsequent transfer of this energy, from lower trophic levels upward, is essential to the nutritional condition and reproductive performance of top predators such as Adélie penguins. Inevitably, perturbations in climatic parameters of the ocean (e.g., extent and timing of occurrence of sea ice) and in climatic anomalies have a strong affect on the propagation of this energy, ultimately modifying the availability of food for top predators. In particular, such anomalies of oceanic climate have a significant influence on seabird life history such as the timing of nest initiation and egg size (Gaston et al. 2005). Due to the energetic demands of reproduction, predictable and reliable Adélie foraging areas must be located in close proximity to biological hotspots, which represent regions with consistently high and predictable food resources. These hotspots appear to related deep sea canyons. The Adélie penguins breed in locations where deep ocean canyons exist near the land margin; these canyons provide a

possible conduit for the warm Upper Circumpolar Deep Water (UCDW) to extend to near the land margin (Klinck et al. 2004), keeping winter ice low and supporting high primary productivity rates (Prezelin et al. 2000). As a result, the life history of these seabirds, driven by sea-ice dynamics and associated food web dynamics, can spatially and temporally integrate variability in oceanic climate along the WAP. For these reasons, populations of the Adélie penguin are regarded as sensitive indicators of global climatic change (Ainley 2002).

Climatically, the WAP is among our planet’s fastest warming regions with an increase in average air temperature of 6°C during the winter months over the last half century (Ducklow et al. 2007). This rapid warming has resulted in a reduction in the extent and duration of annual sea-ice formation (Vaughan et al. 2003). Proximate causes of regional warming and sea-ice decline involve the impact of climatic phases such as El Niño-Southern Oscillation, and the Southern Annular Mode on the atmosphere-ocean systems (Kwok and Comiso 2002). The interactions within these atmosphere-ocean systems can result in an increase of the cross-shelf transport of relatively warm water derived from the Antarctic Circumpolar Current (ACC). Such cross-continental-shelf intrusions of the ACC are possible because the WAP is the only place where the ACC encounters the Antarctic continent. Furthermore, submarine canyons present on the WAP funnel the warmer ACC deep water across the continental shelf to the near-shore sea surface. In addition to being warmer than the locally formed Antarctic water masses, the ACC’s deepwater is nutrient-laden, and when brought to the sea surface may drive persistent upwelling that is localized at the head of each cross-shelf canyon (Ducklow et al. 2007).

As a result, the WAP is susceptible to the increase in oceanic heat transport across the continental shelf that appears to have intensified over the last 30 years (Martinson et al. 2008). In response, along the Palmer Archipelago near Anvers Island (64°46’S, 64°03’W, Fig. 1), *Pygoscelis* community composition has shifted over the last 30 years (see Forcada and Trathan 2009 for review). Most dramatically, the population of breeding adults has declined from ~15,000 in the mid-1970s to presently <4000 (Ducklow et al. 2007). Concurrent community shifts are evident in rising populations and the expanding of the sea-ice intolerant chinstrap (*P. antarctica*) and gentoo (*P. papua*) penguins. Population growth and range expansion are occurring at chinstrap and gentoo nesting colonies, respectively established in 1976 and 1994, on islands in close proximity to the declining

Adélie colonies near Palmer Station (Ducklow *et al.* 2007, Fig. 2). Understanding why one species is declining while others are increasing remains an open question. The differences likely reflect distinct foraging strategies among the penguin species and the dependence of such strategies on the variability of sea ice along the WAP.

These broad shifts in top predator community structure point to significant and fundamental changes at the base of the WAP marine ecosystem (Schofield *et al.* 2010). Indeed, such shifts in the

basic composition of the pelagic marine environment are manifest in variability in foraging strategies by top predators at the decadal-scale (Ainley *et al.* 2005). However, sampling of the pelagic marine environment at spatial and temporal scales contemporaneous to top predator foraging behavior will be required to develop an understanding of the mechanisms and processes underlying variability in the WAP marine ecosystem.

Diet sampling of seabirds, traditionally conducted from the terrestrial environment, provides an

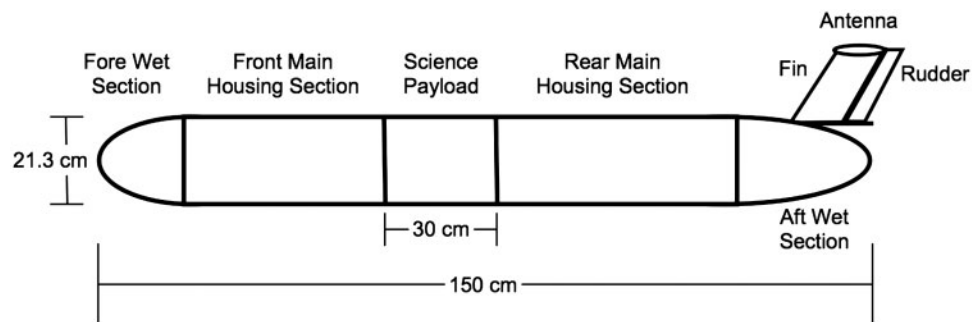


Fig. 1 Diagram of Teledyne-Webb Corporation's Slocum Glider (coastal model). The Front Main Housing Section glider's ballast, and consequently its flight, is controlled by moving water into or out of the Fore Wet Section. The Front Main Section contains battery packs supplying power to both the ballast regulator and the Science Payload. The Science Payload can be modified to contain a wide variety of instrumentation including an externally mounted (port side) SBE CTD. The Rear Main Housing Section holds more battery packs and all of the glider's electronic hardware. While at the sea surface, a bladder is inflated in the Aft Wet Section to increase the fin-mounted antenna's clearance above the water. The rudder is controlled by the onboard computer (in the Rear Main Housing Section). Depending on the year of manufacture, the wings may be mounted on either the Science Payload or the Rear Main Housing Section.

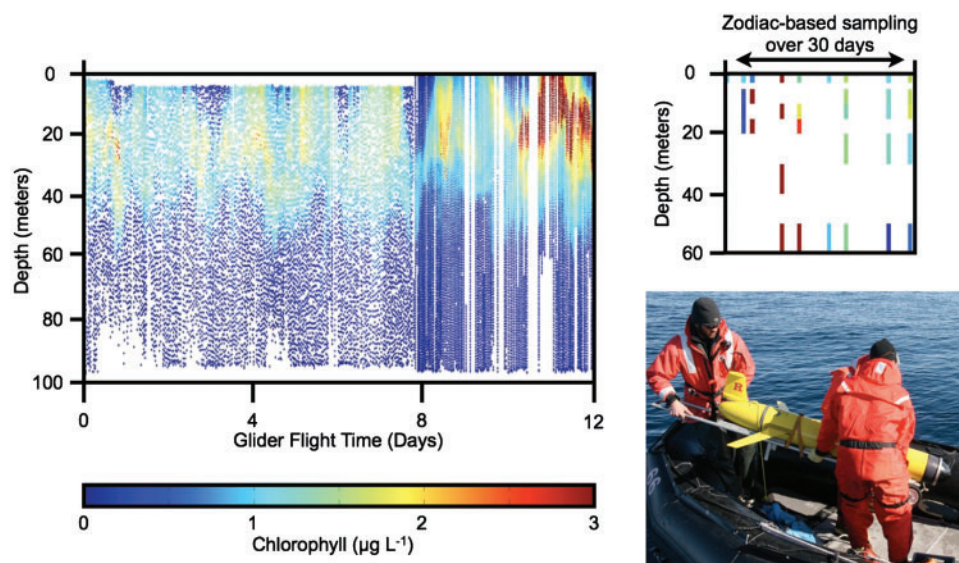


Fig. 2 Comparison of chlorophyll concentration at the Palmer LTER collected by the Slocum glider (12 days) and by hand via zodiac (30 days). The glider chlorophyll data also show the ability to change the sampling rate of the fluorometer (increased beginning on Day 8) without disrupting the glider flight. The image in the lower right depicts the deployment of the Slocum glider by hand over the side of a zodiac at the Palmer LTER.

integrated signal of the ecology of the foraging region. However, traditional diet sampling techniques do not provide insight into *in situ* foraging strategies and their constraining bio-physical factors. Indeed, some polar pelagic marine environments have been sampled (e.g., salinity and temperature with depth) with satellite-tracking tags on marine mammals (Boehme et al. 2008). However, the data derived from these tags are biased by the behavior of the tagged animal. Consequently, it has been difficult to illustrate a broad-scale picture of the hydrography driving the lower trophic levels in Antarctic marine ecosystems. Additionally, tagged marine animals only provide snapshots of the pelagic marine environment when conditions are ideal for the predator (e.g., during feeding or transit). Ideally, satellite-tagged animal data should be complimented by both contemporaneous and temporally extraneous high-resolution regional sampling of the oceanographic factors shaping these marine environments. For a robust definition of the factors, data focusing on both the biology and physics of these polar pelagic marine environments should be collected for sustained periods of time.

Integrating autonomous underwater vehicles into a long-term ecological study

Due to its remote location and harsh conditions, it is exceedingly difficult and expensive to observe polar marine ecosystems at the appropriate time and space scales. By necessity, observing and sampling of such systems must be highly efficient both in terms of logistics and costs. Inevitably highly efficient methods of observation in polar regions must be “scalable” to the process of interest (Rudnick and Perry 2003). Mobile platforms are undergoing exponential development and are transitioning into observational tools (Rudnick and Perry 2003). One autonomous platform that is rapidly becoming indispensable in temperate marine research is the buoyancy-driven underwater glider. Buoyancy-driven gliders, as currently configured, were first detailed in Doug Webb’s lab book in February 1986 as a novel instrument approach. Gliders were widely publicized in 1989 by Henry Stommel’s view of a futuristic smart fleet of instruments (Stommel 1989). During the time it has taken to bring these concepts to reality, gliders have earned their reputation as a high-endurance sensor platform. More importantly, this class of long-range and relatively low-cost autonomous underwater vehicle (AUV) is making affordable

adaptive sampling networks a reality (Rudnick et al. 2004).

Slocum gliders

All of Rutgers University’s Slocum gliders are controlled and monitored from a centralized control center located on Rutgers Campus in New Jersey (USA). The control center is called the Coastal Ocean Observation Lab (RU COOL) at the University’s Institute of Marine and Coastal Sciences. For almost two decades RU COOL has posted freely available real-time data to the world-wide-web. RU COOL maintains control of a fleet of more than 24 gliders that are routinely deployed around the world. Taking advantage of rapidly expanding telecommunications technologies has allowed the centralized function of the COOL room to also be accessed remotely, continually increasing the flexibility of glider operations. However, glider operations in the Antarctic are unique from deployments and recoveries elsewhere because of the remoteness, unique hazards such as sea ice, and lack of reliable access to ships should a malfunction occur. High winds, heavy seas, or thick ice conditions also frequently hamper these deployments and recoveries.

The glider used for this study is the Webb Slocum Coastal Glider (Figs. 1 and 2). Coastal gliders such as the one deployed in this study have a hull diameter of 21.3 cm and an overall length of 1.5 m (Fig. 1). The 56 kg glider is rated to dive depths of 100 m and has a horizontal average speed of 0.4 m/s. The glider propels itself through the water column by changing its buoyancy. Consequently the glider’s path of travel resembles a continuously advancing saw-tooth pattern between the surface and 100 m depth.

While at the surface, an internal air bladder thrusts the glider’s tail above water allowing satellite communications. The glider can receive commands and send data via line-of-sight radio frequency modem, or satellite telephone link (i.e., Iridium Satellite phone). Each glider in our fleet uses its Iridium connection to call into the COOL room to upload scientific and engineering flight (each underwater Glider deployment is termed as an underwater flight) data. These data are generally archived for subsequent analysis and are also posted to the web in “real-time” to allow sampling strategies to be adapted in real-time based on the most recent information (“adaptive sampling”). Conversely, data transfer between the glider and the COOL room is bi-directional such that the Glider may also download new navigation or sampling command files

from the COOL room. A glider can only transmit data or receive commands while at the surface of the ocean as all communications are transmitted via antennas located in the tail fin. Also contained within the tail is an ARGOS emergency beacon and a GPS. The glider uses the GPS to navigate between waypoints uploaded in a “mission” text file. Because the glider dead reckons between waypoints while underwater, upon surfacing any deviation from the intended path of travel is compensated for on the next dive by virtue of a rudder in the tail fin. During these “surfacing”, flight parameters such as; duration until next surfacing, the list of upcoming GPS waypoints, and instrument sampling rate can be modified by the operator.

All Slocum gliders come with an external CTD and a modular science payload. The science payload module can be adapted to hold a wide variety of instruments. In this deployment, the glider had a fluorometer and two backscatter meters. Other scientific payloads include a photosynthetically available radiation sensor and a variable fluorescence detector. The factors limiting the type of scientific instrument onboard the glider are the size of the payload section (length = 30 cm, diameter = 21.3 cm, maximum weight = 4 kg) and power consumption of the scientific instrument. Depending on the science payload the duration of a glider deployment on one pack of batteries may last as long as one month. However, the duration of the deployment is subject to a wide variety of variables such as environmental temperature, scientific payload power requirements, and dive depth (i.e., shallower water requires more cycles of ballasting and unballasting seawater thus requiring more use of the pumps).

Glider personnel monitor the polar ocean deployments carefully because of the high risk of encountering objective hazards such as icebergs, sea ice, and uncharted seamounts. Conducting most glider flights during the peak of Austral summer has minimized risks associated with sea ice. Additionally, because objective ice hazards exist year-round but are primarily at or near the surface, keeping the glider away from the surface as much as possible further minimizes the risk of such encounters occurring. We also reduce the risk of colliding with various forms of ice in the marine environment by receiving annotated images from the National Oceanographic and Atmospheric Administration’s National/Naval Ice Center. The combination of flying the gliders during the three months of annual ice minimum and using satellite ice images to avoid flying in ice-dense waters have both helped to increase the viability of operating gliders in polar regions.

Expanding the Palmer long-term ecological research

Spatial and scientific expansion at the Palmer long-term ecological research site

Since its inception in the early 1990s, the bulk of the work at the Palmer long-term ecological research (LTER) site has been focused on collecting and maintaining time series data to study systemic shifts in polar environments due to climatic change. Historically, oceanographic measurements at the Palmer LTER have consisted of zodiac-based collection of *in situ* physical and optical parameters and acquisition of water samples for subsequent analysis. Such labor-intensive *in situ* measurements have been complimented by satellite remote sensing which opened the doors to quantifying ice-dependent ecosystem shifts along the WAP (Stammerjohn and Smith 1996). This sampling regime of combining *in situ* investigations with remotely sensed observations has been highly effective at capturing the seasonal variations and the decadal trends in primary production. However, the data required to resolve the dynamics linking primary production to top-predators have not been acquired because of spatial and temporal constraints associated with traditional Zodiac sampling techniques. Principally, the glider is able to survey the head of the adjacent submarine canyon, an area that has been outside the scope of operations of the traditional LTER sampling regime. This is especially crucial as the head of this canyon is increasingly being recognized as an area of elevated primary production responsible for supporting the large populations of breeding penguins (i.e., a “biological hotspot”) nearby Palmer Station. In addition to expanding the spatial reach of the Palmer LTER scientists, underwater gliders are also increasing the temporal resolution of the data. While traditional sampling techniques may yield several hundred water column profiles of temperature, salinity, and other properties over the course of a summer season, the glider provides several hundred water column profiles in a matter of days (Fig. 2). By merging data from satellite-tagged penguins with data from an underwater glider, the monitoring and hypothesis testing capacity of the Palmer LTER site has been expanded.

As part of the Palmer LTER study, pelagic top-predators such as Adélie penguins have been used to integrate ecological shifts in the ecosystem. However it has been difficult to acquire environmental constraints that reside in the pelagic environment in which the Adélies forage. Indeed, relevant water-column characteristics such as salinity, temperature,

chlorophyll-a, and mixed layer depth can now be measured using gliders. Adélie penguin diving behavior, which spans much of the euphotic zone, can be tracked using satellite-tagging techniques. Data from satellite-tagged penguins have shown that 90% of foraging by Adélies occurs over the region of deep water adjacent to the Palmer LTER site (Fraser WR, unpublished). Prior to incorporating gliders into the Palmer LTER, the water-column (i.e., vertical) characteristics of this “biological hotspot”, have not been studied at relevant ecological time and spatial scales because this area is outside the safe boating limits of scientists working at the Palmer LTER site.

Results from penguin-driven adaptive sampling by gliders

Penguin tracking data from 2006 to 2008 were analyzed to determine the extent of the foraging region for the Adélie populations near Palmer Station. These historical data were then used to develop the flight plan for the Slocum underwater glider. The glider, RU05, was deployed and recovered from the Palmer LTER site in December 2008 and continuously surveyed the Palmer Basin “biological hotspot” during a 12 day deployment (Fig. 3). The glider was tasked with flying a box-like pattern around the penguin foraging zone and then conducting a series of cross-canyon transects within the same box. The data collected during the survey include; salinity, temperature, pressure, depth-averaged current, optical backscatter (470 nm, 532 nm, 660 nm), colored dissolved

organic matter fluorescence, and chlorophyll fluorescence. RU05’s flight path was adapted to cope with the currents and winds present during the mission by scientists in the COOL room at Rutgers University in New Jersey. This was enabled by the real-time data, which also allowed for adaptive sampling of changing conditions at the Palmer Basin “biological hotspot”.

The Slocum glider transects of the Palmer Basin “biological hotspot” revealed a phytoplankton bloom, indicated by an elevated chlorophyll fluorescence signal, that lessened yet persisted over a six-day period (Fig. 4). The chlorophyll fluorescence signal of the phytoplankton bloom was more than an order of magnitude greater than the signal in the adjacent non-bloom waters. During the glider’s survey of the “biological hotspot” the phytoplankton bloom predominated between 10 and 30 m below the sea surface. Accordingly, the temperature data show an intensification of nearly half a degree in the water being upwelled from below 100 m over the same period (Fig. 4). The intensification of the bloom likely comes from increased mixing of warmer, nutrient rich upper-circumpolar deep water (UCDW) and western Antarctic WW which are characterized by temperature and salinity (Martinson, Stammerjohn et al. 2008) relative to Antarctic Surface Water (AASW) (Fig. 5). While UCDW is nutrient-rich its relatively warm temperature often prevents mixing with significantly colder AASWs. However, if UCDW is mixed during

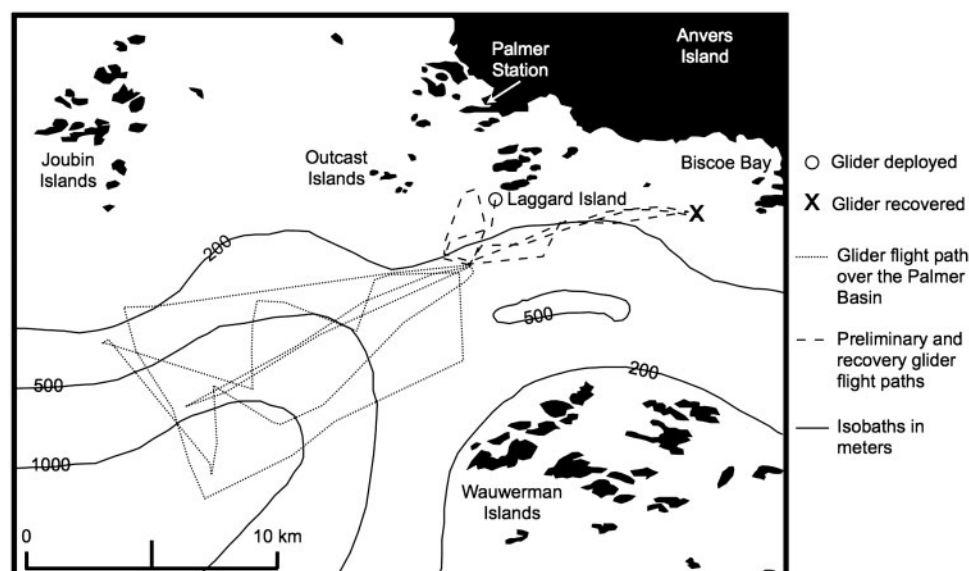


Fig. 3 Map of the Palmer Basin adjacent to Anvers Island on the western Antarctic Peninsula. Palmer Station is located at $64^{\circ}46'S$, $64^{\circ}03'W$. The Slocum glider was deployed for twelve days, six of which were spent over the Basin surveying the Adélie penguin foraging area.

cross-shelf transport and upwelling with WW, then the combined UCDW/WW water mass can more readily mix nutrients into locally formed AASW. The mixture of the nutrient-laden UCDW and WW with AASW provides an ideal environment for a phytoplankton bloom. Frequently, such phytoplankton blooms occur along the slope of the Palmer

Basin closest to Anvers Island where the radio-tagged Adélie penguins preferentially forage.

The radio-tag information provides data on the location in the water column where the penguins forage. The radio-tagged data suggest that more than half (54%) of penguin foraging occurred at depths ranging from 30–50 m. Within the 90% foraging

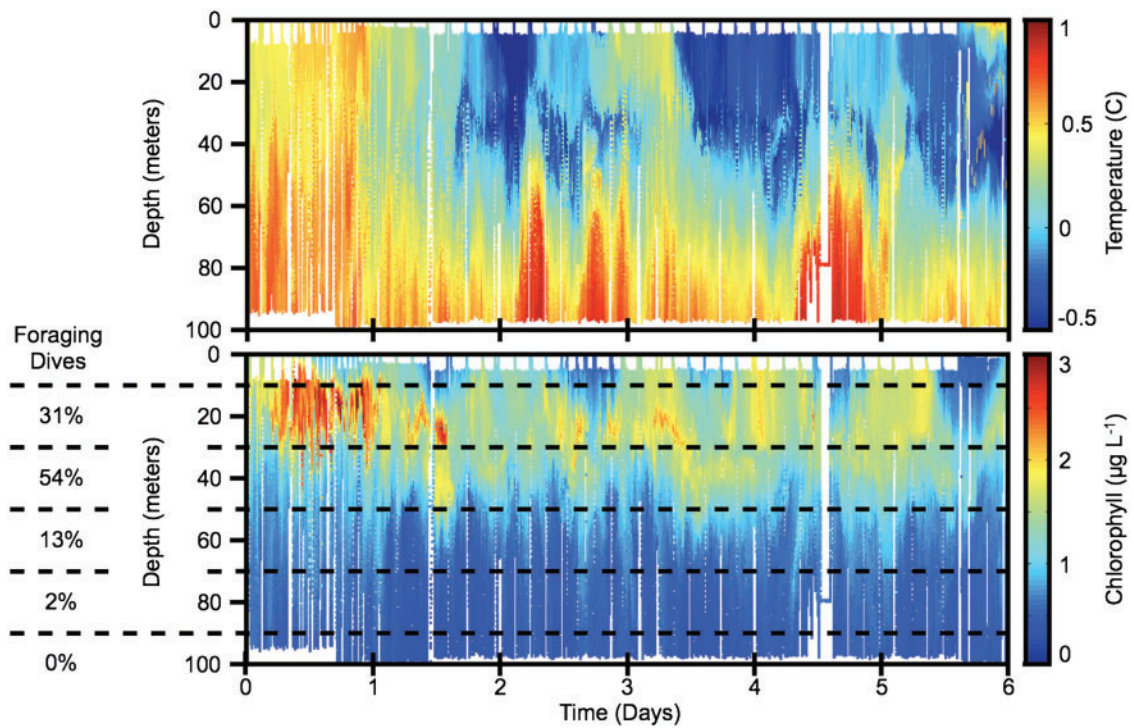


Fig. 4 Temperature (top) and chlorophyll concentration (bottom) measured by the Slocum glider within the Adélie penguin 90% foraging kernel over the Palmer Basin. Within the 90% foraging kernel, the percent of Adélie penguin foraging dives to five depth bins is aligned with the chlorophyll data.

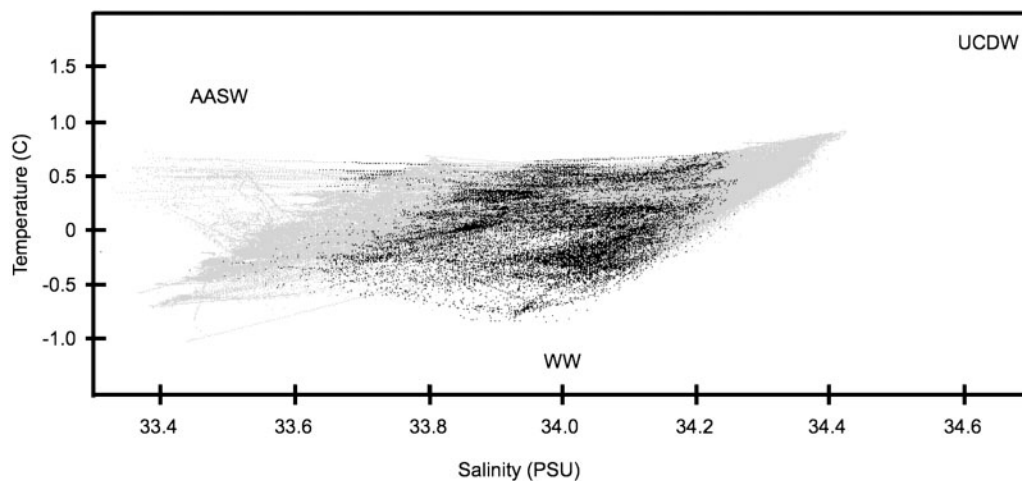


Fig. 5 Temperature versus salinity plot of water sampled by the Slocum glider. Black dots are samples collected from the primary foraging depth bin (30–50 m depth) of Adélie penguins in the Palmer Basin. The primary oceanic water masses, as defined by their temperature and salinity, in the region are: UCDW from the core of the Antarctic Circumpolar Current, western Antarctic Peninsula WW formed during the winter, and AASW formed during the summer along the coast of the western Antarctic Peninsula.

kernel, the maximum chlorophyll concentration was immediately above the 30–50 m penguin foraging dive depths. Comparatively, only 31% of foraging dives occurred at depths shallower than the depth of the chlorophyll concentration maximum. Because foraging dives originate at the surface, random feeding behavior would result in the highest number of dives occurring near the surface. However, in the Palmer Basin “biological hotspot”, Adélie penguins appear to be targeting specific regions within the euphotic zone. In this study, the region being foraged was immediately below the most productive part of the water column. This foraging behavior suggests that the Adelies are preying on krill who are grazing on the phytoplankton cells at the base of the chlorophyll maximum. Krill undergo vertical migration (Morris et al. 1984; Godlewska and Klusek 1987) to graze in the high phytoplankton biomass regions in the surface waters at night, and have then been observed to migrate below the chlorophyll maximum during daylight hours (Morris et al. 1984) when Adélie penguin forage. Future studies will focus on this by deploying gliders outfitted with acoustic sensors to provide maps of the zooplankton biomass. These future efforts will combine swarms of gliders that measure the physical properties (temperature and salinity), phytoplankton biomass (chlorophyll fluorescence), and zooplankton (acoustic measurements). Further study is necessary to link krill at the bottom of the chlorophyll maximum to targeted Adélie foraging. Furthermore, because the depth of the mixed layer drives the location of the chlorophyll maximum in the water-column, variability of the mixed layer depth may have direct effects on the energetic balance for a foraging seabird. Bringing together satellite tagged birds and gliders to highlight linkages such as these will be critical towards expanding our knowledge of the role of environmental variability in Antarctic “biological hotspots”.

Conclusion

While the traditional LTER needs to be maintained, modern ocean time series and ecosystem monitoring programs will increase the scientific questions that might be addressed (Ducklow et al. 2009). To this end, the subsurface-sustained- and high-resolution glider data will provide a critical tool. Not only do these low-cost emerging technologies expand scientific capabilities, they also have the potential to expand scientific collaboration. Indeed, these new technologies may provide a gateway for emerging earth science programs to enter polar research.

For example, through collaborative purchasing of batteries or renting flight time on a glider, scientists working at institutions without a traditional capacity for polar research may be able to contribute to research that has traditionally been the province of well-established research entities. By focusing on innovative means of collaborating, low-cost, emerging technologies can lower the barrier of entry for many potential polar researchers. Increasing the capacity of scientists from around the world to help understand the climatically linked mechanisms already occurring in polar marine environments may have the added benefit of helping to prepare these same scientists to address similar responses to climatic change in marine ecosystems closer to home.

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