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Letting Penguins Lead: Dynamic Modeling of Penguin Locations Guides Autonomous Robotic Sampling

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The southwest coast of Anvers Island harbors one of five major populations of Adélie penguins in the West Antarctic Peninsula (WAP; Fraser and Trivelpiece, 1996). This "hotspot" is colocated with a submarine canyon that provides a conduit for warm, nutrient-rich Upper Circumpolar Deep Water to stimulate primary production and support a productive ecosystem (Prézelin et al., 2004). Paleoecological evidence shows Adélie penguins (*Pygoscelis adeliae*) have used this location for hundreds of years (Emslie et al., 1998). Since the mid- to late twentieth century, the Southern Ocean near the WAP has warmed significantly (Gille, 2002) and has lost significant sea ice (Stammerjohn et al., 2008). The maritime climate of the northern WAP has shifted poleward, replacing the cold continental Antarctic climate in the Anvers Island region. During this time period, there has been an 80% decrease in the sea ice dependent Adélie penguin populations and an introduction and increase of Gentoo penguins (*P. papua*; Ducklow et al., 2007). Sympatry of Adélie and Gentoo penguins during the breeding season is new to this coast, and it not known if these species will continue to coexist or if the Gentoos will supplant the Adélies. The stability of this new species interaction depends on how well each species is able to exploit the coastal ecosystem. It may be that while submarine canyons offer predictable prey populations, different foraging strategies may allow Gentoos better access to existing prey (krill and fish) populations relative to Adélies. This situation is difficult to assess because penguins are dynamic predators that rapidly forage for krill and fish across a heterogeneous and complex coastal ocean.

In January 2011, we implemented a nested and flexible sampling network to measure the physical and biological features of penguin foraging locations. We coupled 13 satellite-tagged Adélie and seven satellite-tagged Gentoo penguins with multiple deployments of a buoyancy-driven Slocum glider and a propeller-driven REMUS-100 (Figure 1A). When tags, autonomous underwater vehicles (AUVs), and global communications are combined, it is possible to sample the polar ocean as the penguins experience it. However, these robotic assets still require guidance for coordinated sampling strategies (Kahl et al., 2010). In a novel approach, we fused AUVs with satellite-tagged penguins, thus providing a means for seabird top predators to provide the ecological guidance needed to optimize sampling of robotic networks.

The core Adélie and Gentoo penguin foraging regions from Humble Island and Biscoe Point are near the submarine canyon (Figure 1a). We sampled historic penguin foraging locations according to AUV capabilities. The Slocum glider can maintain continued in-water presence for 30 days (Schofield et al., 2007). Therefore, we used the Slocum glider to map larger-scale oceanographic features over the canyon and to gather multiday time series of currents, temperature, salinity, oxygen, and optics. The REMUS-100 mimics the endurance (8–12 hrs), speed (~ 2.5 m s^{-1}), and depth range (0–75 m) of the foraging penguins, and was therefore used to sample temperature, salinity, optics, and acoustic krill densities in the shallow area of the core penguin foraging regions (Figure 1a).

The main feature of our sampling design is that it allowed us to react quickly to new penguin foraging locations. The new locations were relayed via the Argos satellite system to our team in Palmer Station. We then implemented a time-resolved utilization distribution kernel (Keating and Cherry, 2009) with bandwidths corresponding to the location errors of our Argos penguin positions to map likely foraging habitats at hourly resolution. The result was a multispecies dynamic probability map of penguin foraging locations that could be opportunistically targeted by both the Slocum glider and the REMUS-100 AUVs (Figure 1b). The dynamic foraging map enabled creation of a real-time adaptive sampling plan for the penguin foraging locations. Our team of seabird ecologists and oceanographers could change the mission of the AUVs to intersect the penguin foraging locations in order to sample them at high resolution. The fusion of seabird tracking and AUV guidance through the modeling of near-real-time distributions allows researchers to target critical sampling assets to understand the complex interactions between these species and to provide insight on how penguins access their environment in a changing climate.

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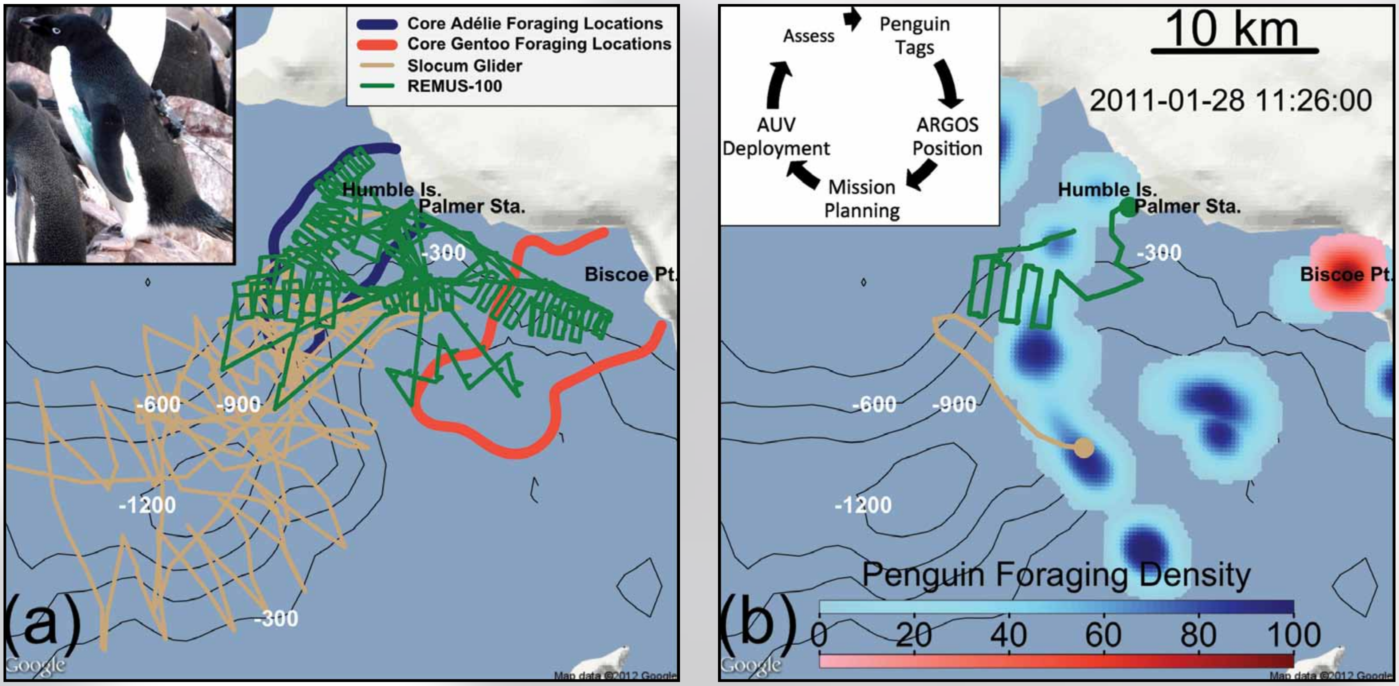

Figure 1. Adélie and Gentoo penguin colonies are located at Humble Island and Biscoe Point near Palmer Station on the south coast of Anvers Island. (a) The thick contours show the historic foraging locations of tagged Adélie (blue) and Gentoo (red) penguins. The inset is an Adélie penguin carrying a satellite tag. The regions around these contours were continually sampled by Slocum glider (tan) and REMUS-100 (green) autonomous underwater vehicles (AUVs). (b) During our experiment, real-time, species-specific foraging density maps based on penguin locations allowed us to intersect our AUVs with these foraging regions. On January 28 at 11:26:00 GMT, the Slocum glider and REMUS-100 intersected an Adélie penguin foraging location (blue). Tagged Gentoo penguins (red) are close to their colony on Biscoe Point at this time.

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