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Autonomous Underwater Vehicle Exploration of the Ocean Cavity Beneath an Antarctic Ice Shelf

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In recent years, mass loss from the Antarctic Ice Sheet has contributed nearly 0.5 mm yr^{-1} to global mean sea level rise, about one-sixth of the current rate (Church et al., 2011). Around half of that contribution has come from accelerated draining of outlet glaciers into the southeast Amundsen Sea (Rignot et al., 2008), where the flow speed of Pine Island Glacier (PIG; Figure 1) in particular has increased by over 70%, to around 4 km yr^{-1}, since the first observations in the early 1970s (Rignot, 2008; Joughin et al., 2010). The accelerations have been accompanied by rapid thinning of the glaciers extending inland from the floating ice shelves that form the glacier termini (Shepherd et al., 2002, 2004). One implication of these observed patterns of change is that the mass loss has probably been driven by changes in the rate of submarine melting of the floating ice shelves. The ubiquitous presence of warm Circumpolar Deep Water (CDW) on the Amundsen Sea continental shelf, at temperatures 3–4°C above the pressure freezing point, was first revealed during a 1994 cruise of RVIB *Nathaniel B Palmer* (Jacobs et al., 1996). Repeat observations at the Pine Island Ice Front made from the *Palmer* in 2009 showed that submarine melting of PIG had increased by 50% over the intervening 15 years despite a modest rise in the temperature of CDW of only about 0.1°C (Jacobs et al., 2011). While ice front observations were able to document those changes, the reason for the dramatic increase in submarine melting would have remained speculative while the ocean cavity beneath the approximately 65 x 35 km, fast-flowing, central part of the ice shelf remained a black box.

During the 2009 cruise, the *Palmer* carried *Autosub3*, an autonomous underwater vehicle (AUV) capable of accessing and observing the sub-ice cavity (McPhail et al., 2009). Launched over the stern of the *Palmer* (Figure 2) from a containerized workshop, the vehicle is capable of diving to 1,600 m depth and has an endurance of about 400 km. In the Amundsen Sea, it carried a CTD system with dual conductivity and temperature sensors, a dissolved oxygen sensor, transmissometer, upward- and downward-looking acoustic Doppler current profilers (ADCPs), and a multibeam echosounder. *Austosub3* navigates below the ice using a combination of an inertial navigation system (INS) and ground- or ice-track velocity readings from the ADCPs; GPS provides positional updates when it is at the surface.

During the PIG campaign, *Autosub3* was launched eight times, including twice for test runs in open water. It covered a total of 510 km in 94 hours beneath the ice shelf (Figure 3a). Each run beneath the ice included an initial five hours in open water, where progress could be monitored and an "abort" signal sent if problems were detected. Once the sub was

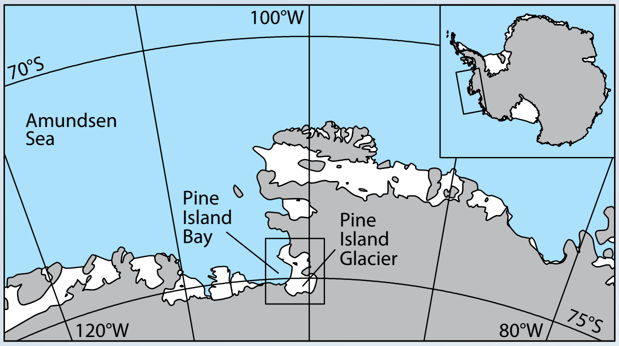

Figure 1. Map of Antarctica (inset) and enlargement of the eastern Amundsen Sea coastline showing grounded ice (grey) and floating ice shelves (white). The box outlining Pine Island Bay indicates the area shown in Figure 3.

Figure 2. Launch (upper panels) and recovery (lower panels) of *Autosub3* during the January 2009 operations in Pine Island Bay. The sub is 7 m long, 0.9 m in diameter, and powered by 5,000 alkaline D cells. A VHF link between ship and sub enables remote download of data and upload of mission scripts, so that recovery is only necessary for adjustment of sensors or replacement of batteries.

farther than 5 km beneath the ice, all contact was lost, and the *Palmer* departed to undertake work elsewhere before returning to the recovery waypoint at the programmed end time. Atypical open water and calm seas (Figure 2) in late January 2009 contributed toward smooth operations, the only untoward incident being when *Autosub3* collided with the ice shelf base. This occurred within a large basal crevasse about 55 km from the open water and resulted in minor damage. The AUV successfully extricated itself from the crevasse and cavity, was quickly repaired and tested, and was then dispatched twice more beneath the ice shelf.

The main outcome of the campaign was the discovery of a 300 m high submarine ridge lying transverse to the flow of the ice shelf and effectively bisecting the sub-ice cavity (Jenkins et al., 2010). CDW in Pine Island Bay has free access to the outer cavity, but must clear the ridge to enter the inner cavity where the glacier goes afloat (Figure 3). The gap above the ridge is everywhere fewer than 300 m, and it has grown significantly over recent years as the ice shelf has thinned by nearly 100 m. Positive feedback between the expanding gap over the ridge, easier access of warm water to the inner cavity, and consequent thinning of the ice may account for much of the observed increase in melting (Jenkins et al., 2010; Jacobs et al., 2011). The glacier was fully grounded on the ridge sometime prior to the earliest observations; its downslope retreat into deeper water has possibly been a self-sustaining process that drove the inland acceleration and thinning (Schoof, 2007). By shining a light into the black box beneath its ice shelf, the *Palmer* and *Autosub3* have transformed our understanding of the processes that are changing PIG.

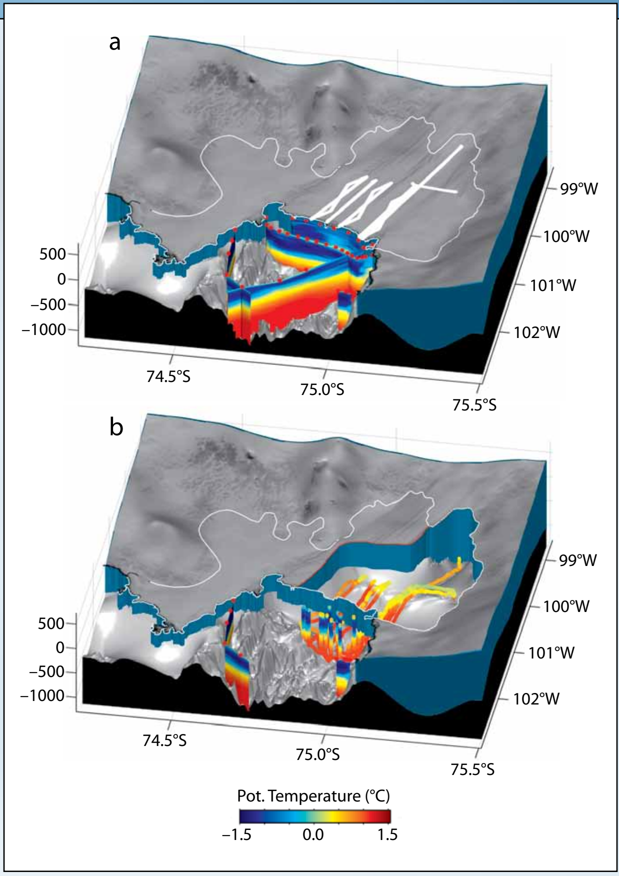

Figure 3. (a) Perspective view of Pine Island Bay showing surface and seabed topography along with potential temperature sections measured from the *Palmer* in January 2009. Bold white lines on the surface of Pine Island Glacier indicate the geographic location of *Autosub3* tracks beneath the floating ice shelf, whose boundaries are indicated by the faint white line. The fast-flowing central part of the ice shelf is apparent from the dark, linear, surface features apparent in the Moderate Resolution Imaging Spectroradiometer (MODIS) imagery that is draped over the surface topography. (b) As in (a), but with most of the ice shelf cut away to reveal potential temperature measured along *Autosub3* tracks.

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