Woods Hole Oceanographic Institution
Report to the
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Observing the Inflow of Pacific Water to the Arctic

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The principal activity during the project period was a summer field project conducted offshore of Barrow, Alaska. Results of this field work were reported in October 2005, and are repeated here for completeness. The project period was extended to allow further technical development towards the goal of obtaining observations beneath the ice in winter. These developments, completed in 2007, are described at the end of this report.

The summer field work was conducted in 2005. A three-person team was assembled to apply autonomous underwater vehicle (AUV) technology developed at WHOI to the problem of measuring the transport of Pacific Water past the "choke point" between Point Barrow and Barrow Canyon. Our goals were to obtain summer hydrographic transects from a location near the coast out to the eastern flank of Barrow Canyon using the REMUS AUV, and to demonstrate the capability of operating the AUV under the ice cover in winter.

We arrived in Barrow on 22 August 2005 and began assembling our field gear, which included the AUV, three moorings, and a variety of support gear. The next day we were in the Chukchi Sea on a 30-foot aluminum boat chartered from the Native Village of Barrow (Figure 1).

***Figure 1**: The 30-foot boat Nigiqpaq at the beach in Barrow.*

There are no harbors or docks in Barrow; all boat launches were from the beach. The "good" weather days were overcast, with near freezing temperatures, a combination of rain and snow, and 5-15 knot winds from the east or southeast. In contrast, winds of 15-20 knots with a northwest component generally meant that the boat would not go out. We were able to operate 7 days out of a possible 11. The moorings and AUV were deployed and recovered by hand over the side of the boat (Figure 2).

In addition to an externally mounted Seabird CTD (a conductivity-temperature-depth monitor), the AUV was outfitted with an inertial navigation system (INS) in place of a magnetic compass. We were the first scientific users of an INS-equipped vehicle, and we were expecting environmental conditions that would be challenging for vehicle navigation, namely water depths up to 100 meters, strong cross-track currents. We had partial success in meeting both the scientific and technical goals of the work and also encountered some unexpected problems, which ultimately changed our view of the best approach to under-ice operations.

Figure 2: *Deployment of the AUV.*

There were several technical areas of concern, including the acoustic environment, strong currents, and the suitability of the navigation algorithm. Indeed, we learned important lessons in all of these areas. Unlike the mid-latitude ocean, where the soundspeed profile typically causes acoustic rays to converge towards a "sound channel," the Chukchi Sea profile tended to cause rays to diverge and become "ducted" along the surface and bottom. This meant that, with tracking transponders near the surface, we could only contact the vehicle when it was also near the surface. This could have important implications for the winter work, where "homing" transponders deployed through ice-holes near the surface were envisioned, because they would likely have only intermittent contact with the vehicle.

Previous observations by other investigators indicated that strong currents toward the northeast would be found between the coast and Barrow Canyon. This was verified by visual observation of our offshore buoy (Figure 3) and by our measurements, which showed surface currents of up to 85 cm/s (1.6 knots) to the northeast. This is comparable to the coastal current inflow at Bering Strait and confirms the Barrow choke point as a critical site for monitoring inflow to the Arctic. Although flow to the northeast was the expected condition, the 8-day current-meter record from the offshore mooring showed that complete reversal could occur. The relationship of current variability to the wind field remains to be examined.

Figure 3: *The offshore buoy on a calm day. Note the wake due to strong currents.*

The strong currents influenced vehicle navigation in unexpected ways. The vehicle can attain 4 knots and, thus, could even make headway directly into the current. However, the power required to get underway from the surface could exceed the "failsafe" shutdown threshold in the navigation algorithm. This became an issue after GPS fixes. While on the surface for a fix (with propulsion off), the vehicle was carried downstream with the flow (perpendicular to the track line). In an effort to re-acquire the track line, the vehicle would attempt to dive while heading directly into the current, tripping the failsafe. This problem was addressed by modifying the failsafe threshold.

Another issue was related to the combination of strong currents and deep water. The navigation system estimates the cumulative position error and "requests" a GPS fix when the errors reach a predetermined threshold. When underway after a GPS fix, the vehicle would sometimes re-surface for another GPS fix before re-acquiring the track line. This was due to the relatively rapid accumulation of position errors in the absence of bottom tracking, combined with the relatively long time needed to re-acquire the track line while running against the current. Since the drift during each GPS fix took the vehicle farther from the track line, this sequence could repeat indefinitely. Modifications made to the navigation algorithm minimized this problem in future missions.

The rapid accumulation of position errors was exacerbated by "noisy" velocity data, obtained by an acoustic Doppler current profiler (ADCP). It was found that the power supplies of the INS injected noise into the ADCP, resulting in less accurate bottom-track velocities. In addition, the error tolerances are reduced when the INS is in place, due to its superior heading reference capability. Thus, replacing the compass with the INS had the unexpected result of position errors that exceeded the threshold more quickly, resulting in more GPS fixes. Each fix made in deep water had the potential to initiate the failure loop described above. Since returning from the trip, the source of the INS noise has been identified, and we believe that this problem has been resolved.

During navigation test runs, we were able to show that the INS-equipped vehicle with bottom tracking but without external navigation aids (GPS or transponders) has navigation errors of about 30 meters per kilometer (km) along track (3%). This error is about three times larger than our expectation (since the Barrow field work we have identified the major contributors to this error). The 3% navigation errors indicated that under-ice missions (requiring errors of < 1 km for a 20-30 km round trip) would be marginally feasible. However, we failed to achieve our objective of actually simulating such a mission by running a full round-trip transect without external navigation aids. We now recognize that maintaining bottom lock with the ADCP is critical to this objective.

When the proposal was written, we felt that adding the INS was the principal ingredient necessary for under-ice Arctic work. The INS clearly improves navigation accuracy; but, by itself, does not provide the capabilities necessary for under-ice missions. The most pressing navigation need, whether using a compass or the INS, is ADCP bottom tracking. We investigated the option of integrating a lower frequency (600 kHz), phased-array ADCP into the AUV, so that bottom tracking could be maintained to depths of ~80 meters. However, technical problems with the phased-array ADCP indicated that this would not be an option in the near term, and the standard 1200 kHz ADCP was retained.

Despite the unanticipated technical problems, we were able to obtain important scientific results. Five transects were completed between 1 and 10 km offshore (10 m to 90 m water depth), with the vehicle executing a series of "triangles" between the surface and bottom (Figure 4a). Sensors on the vehicle measured water properties along the track (e.g., temperature, Figure 4b), which can be smoothed and interpolated to produce a "map" of water property versus distance and depth (Figure 4c).

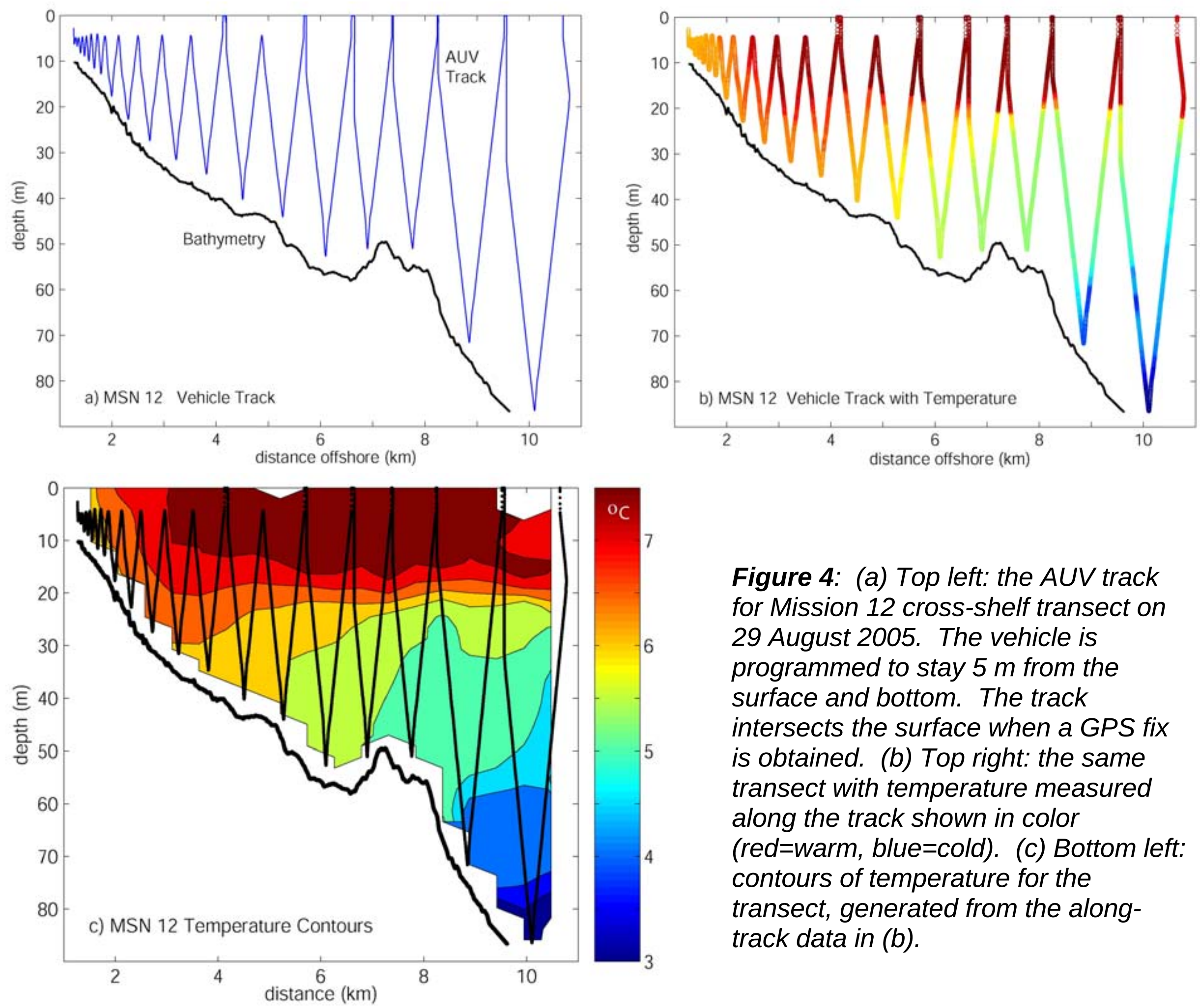

***Figure 4**: (a) Top left: the AUV track for Mission 12 cross-shelf transect on 29 August 2005. The vehicle is programmed to stay 5 m from the surface and bottom. The track intersects the surface when a GPS fix is obtained. (b) Top right: the same transect with temperature measured along the track shown in color (red=warm, blue=cold). (c) Bottom left: contours of temperature for the transect, generated from the along-track data in (b).*

The typical cross-shelf hydrography is best characterized by the transects from our last mission on 29 August (Figure 5). The warm, fresh surface water (above 20 m) is the Alaskan Coastal Current, which follows the coastal topography after passing through the Bering Strait, and in which the temperature and salinity properties below 20 meters are consistent with subsurface, summer-water inflow at Bering Strait. Four of the five transects were consistent with this relatively simple picture of coastal hydrography, but the first transect, obtained on 23 August (just prior to the observed flow reversal), shows a much more complex situation. The Alaskan Coastal Current and Bering summer water are still present, although they appear only inshore of 6 km. Further offshore, cold, fresh melt water is found overlying cold, salty winter water. It is possible that a reservoir of remnant winter water exists in central Barrow Canyon (~20 km offshore at this location) and is intermittently forced up the slope. Alternatively, the presence of winter water may be the result of different advective pathways (and thus different time lags) from the Bering Strait to the Barrow coast.

These observations provide the first detailed look at the coastal hydrography offshore of Barrow in summer and indicate that multiple sources may be important for forming the relatively fresh, cold, winter water that is transported to the Arctic basin and maintains the halocline. Obtaining similar observations in winter conditions will be essential to the long-term goals of this work – understanding how these water masses are mixed and transformed by air-sea-ice interaction in the Chukchi Sea and transported to the Arctic basin.

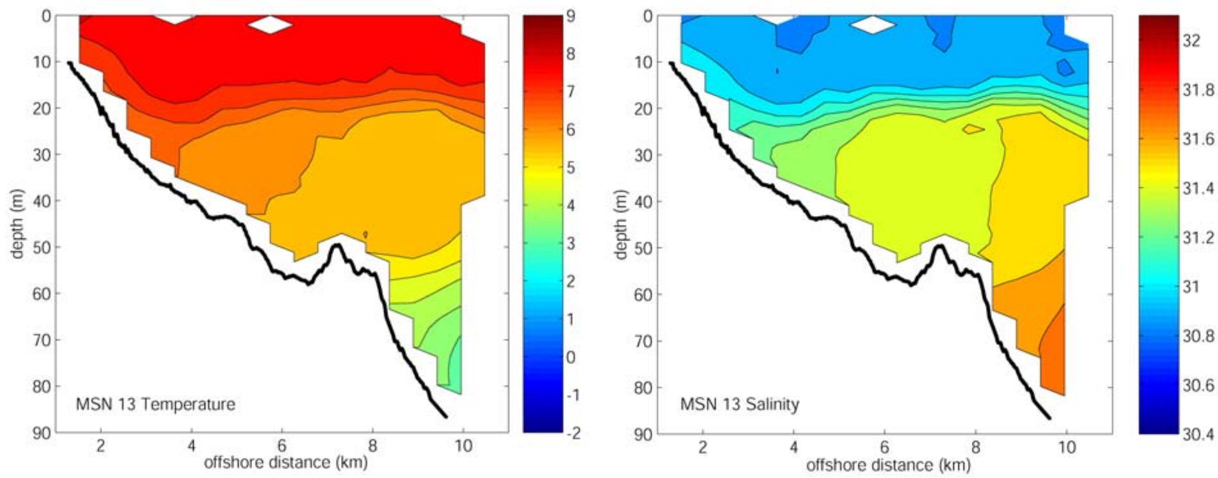

***Figure 5**: Cross-shelf transects of temperature (left) and salinity (right) obtained on 29 August 2005.*

Accurate vehicle navigation and deployment/recovery through the ice are the principal challenges to obtaining transects like those in Fig. 5 in winter. With $34K in matching funds from the Ocean and Climate Change Institute, it was possible to continue technical developments to meet these challenges. The project duration was extended by from its original completion date of 12/31/2005 to 1/31/2008 to accommodate this work.

In open water, REMUS determines its position by navigating within an array of subsurface acoustic beacons at known, fixed locations along the track, or by coming to the surface and obtaining a GPS fix. Neither approach is feasible when operating under ice. The burden of successful operation is then placed on accurate dead-reckoning by the vehicle. Navigation tests conducted in Buzzards Bay in 2006 and 2007 using the inertial navigation system showed that along track errors are as low as 0.2% (e.g. 60 m error for a 30 km round-trip) when ADCP bottom track is available continuously. This suggests that a single ice-camp beacon with an expected range of 1 km could be reliably re-acquired by the vehicle's long base line (LBL) navigation system after returning from a 15 km transect. However, recovery operations from an ice hole also require fine-scale navigation to a recovery point that is not possible with the LBL system. In order to provide this capability, our vehicle was outfitted with an ultra-short base line (USBL) homing system (previously developed by the WHOI REMUS team). This system was installed and tested in 2007.

Based on the field experience and technical advancements of this project, the goal of under-ice AUV transects to measure the Pacific Water inflow to the Arctic in winter is being pursued in a follow-on project supported by the WHOI Arctic Research Initiative http://www.whoi.edu/page.do?pid=16900 .