

ICEX-2011 XCTD Test

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SUMMARY:

This report describes results of a test deployment of under-ice submarine-launched eXpendable Conductivity Temperature Depth (U/ISSXCTD) probes conducted by the U.S. Navy Arctic Submarine Laboratory (ASL) during the 2011 U.S. Navy ICe EXercise (ICEX-11) in the Arctic Ocean. This test was conducted in order to evaluate the accuracy and reliability of XCTD probes when launched from submarines while operating under sea ice, and thus their suitability for further use in the SCICEX program of Science Accommodation Missions (SAMs) in the Arctic Ocean.

16 U/ISSXCTD probes were acquired for testing during 2010-11. Four of these were tested in open water in December 2010. The remaining 12 U/ISSXCTD probes were deployed under ice during ICEX-11. During the open water test of December 2010, 2 XCTDs failed pre-launch tests and were not launched; the remaining 2 probes were deployed and returned data: 1 of these exceeded the design depth and 1 returned data over a significantly shorter depth range. During the ICEX-11 tests, 4 failed pre-launch tests and were not launched, 1 was deployed but failed to return data, and the remaining 7 returned acceptable data: 5 of these returned data over the full design depth, and 2 returned data over significantly shorter depth ranges.

The conclusions from these tests are: (1) there is an unacceptably high rate of failure (37.5%) of pre-launch tests, (2) the overall rate of data return from launched probes (90%) is acceptable, and (3) the rate of achievement of design sample depth has improved (71%) but still falls short of acceptable levels. In short: if you prepare to launch an XCTD, you have a 62.5% chance of launching the probe, and if you do launch you have a 90% chance of getting data returned. Those data will be of acceptable quality, but only 71% of the probes returning data will return data to the full design depth.

Funding for the 2010-11 XCTD probes was provided by an Office of Naval Research grant to the Scottish Association for Marine Science (SAMS). Testing was accomplished by the Arctic Submarine Laboratory with the assistance of the officers and crew of the USS Connecticut (SSN 22) during ICEX-11.

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Note from the Office of Naval Research (ONR)

This report was prepared in February 2012 by Dr. Tim Boyd for ONR. Sadly, Tim died in February 2013. For more information about the submarine-launched XCTD measurement project, contact Dr. Scott Harper or Dr. Martin Jeffries, Arctic & Global Prediction Program, ONR Code 32/322.

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1. INTRODUCTION

Submarine-based observations of large-scale upper-ocean temperature and salinity variability during the SCICEX program of the late-1990's and early 2000's contributed significantly to early understanding of basin-wide changes that have continued throughout the first decade of the 21st century. With increased awareness and interest in sustained observations of the changing conditions that are likely leading towards a seasonally ice-free central Arctic Ocean, there has been a renewed appreciation of and interest in submarine-based sampling. Awareness of the high likelihood of a seasonally ice-free Arctic Ocean has led to development of an US Navy Arctic Road Map (Task Force Climate Change/Oceanographer of the Navy, 2009) which identifies understanding of the current and evolving Arctic physical environment as a key Navy objective, and calls for continuation of SCICEX Science Accommodation Missions (SAMs) as a specific action item. The renewed interest in submarine-based sampling has also resulted in the publication of a new science plan (SCICEX SAC, 2010), which was developed by the SCICEX Science Advisory Committee (SAC) with an eye towards becoming an integral part of the Arctic Observing Network (AON; IARPC, 2007) and to meeting the goals of US and international Arctic change programs (SEARCH, International Study of Arctic Change). Successful implementation of the new SCICEX science plan relies on the research community to obtain the resources necessary for the collection and processing of data, and relies on the US Navy Arctic Submarine Laboratory (ASL) to deploy instrumentation and collect water samples for later analysis.

Under-ice submarine-launched expendable Conductivity, Temperature and Depth (U/ISSXCTD) probes deployed on long, basin-spanning transects provided near-synoptic slices of temperature and salinity in the upper Arctic Ocean during the dedicated-science SCICEX cruises of the 1990's. Since then, the analog probes that were used with a high success rate during the dedicated-science SCICEX cruises have been replaced by digital probes, which have been used from submarines with only limited and intermittent success. The U/ISSXCTD system consists of a standard digital XCTD probe, developed and manufactured by Tsurumi Seiki (TSK) Company of Japan, configured and packaged for submarine deployment by Lockheed Martin Sippican, which also provides the submarine-based system for data acquisition and processing. Previous ONR-funded test deployments of the digital U/ISSXCTDs were conducted in the Beaufort Sea by ASL in conjunction with ICEX-09, as preparation for use during future SCICEX SAMs. While the ICEX-09 test revealed that the new, digital probes yielded higher quality salinity measurements than the earlier analog probes, the test also revealed that the probes uniformly failed to return data to their design depth of 1000 m (Boyd, 2010).

Following the mixed results of the ICEX-09 XCTD test deployments, the SCICEX SAC decided: (1) that further use of the U/ISSXCTDs in SCICEX could only be recommended after the probes could be shown to reliably achieve sample profiles to their designed maximum depth, and (2) that further testing would be considered only after Sippican had made new progress on resolving the maximum sample depth shortcoming. In summer 2010, Sippican informed the SAC that: (1) a specific cause of foreshortened profile data had been identified, and (2) a software solution had been identified and tested. At that time Sippican had identified the irretrievable loss of synchronization of the real-time digital data stream as the source of data acquisition failure, and their solution involved recording the full signal such that loss of synchronization in real time would be recoverable through later playback of the raw data. In response to an identified ASL test opportunity and the high probability of success, ONR funded the acquisition of 16 U/ISSXCTDs for testing in December 2010.

The remainder of this report consists of a brief description of the parameters surrounding the XCTD test, a description of the XCTD data in the context of major Arctic Ocean hydrographic features,

and evaluation of the accuracy of the XCTD data by means of comparison to contemporary CTD casts.

2. ICEX 2011 XCTD TEST

In fall 2010, ONR approved a request for funding to enable an open-water test of submarine-launched XCTDs using the new Sippican data acquisition software on Navy submarines in late 2010. The timing of this test was viewed as critical because:

1. a successful test of the depth capability of XCTDs was a pre-requisite to the conduct of future SCICEX SAM sampling;
2. a potential opportunity for SCICEX SAM sampling would occur during the planned ICEX of March-April 2011; and
3. the next opportunity for sampling by submarine along the ICEX ice camp approach tracks (as defined in the SCICEX Science Plan, 2010) was likely to be the subsequent ICEX, which is expected to be conducted in 2014.

The specific objectives of the project were to:

1. test the capability of U/ISSXCTD probes to achieve full design depth profiles;
2. demonstrate capability to launch U/ISSXCTD probes and recover data with high success rate; and
3. confirm the accuracy of the XCTDs through repeatability of measured temperature and salinity vertical profiles.

Under ONR funding, the Scottish Association for Marine Science (SAMS) contracted with Lockheed Martin Sippican to provide the Arctic Submarine Laboratory with the necessary U/ISSXCTD probes, test probes, data recording hardware, software, and instructions/guidance in order for ASL to conduct a test that would provide unambiguous results. For this test, Sippican provided 16 probes, as well as the loan of one USB Mk21 data acquisition (DAQ) board.

All of the necessary components were available for the open water test in December 2011; however, operational constraints restricted XCTD deployment to only 4 probes. These probes were launched with mixed results (Table 1). Subsequent enquiries revealed that the correct version of the Sippican data acquisition software had not been used during the test. The small number of probes launched severely limits the conclusions that can be drawn from the test, particularly with respect to the accuracy and repeatability of the returned data; however, the high failure rate of pre-launch probe tests is notable. Unfortunately, the probes that failed the pre-launch tests were not retained for return and subsequent analysis by Sippican.

1a. Overview of ICEX-11 XCTD Deployments

Because only 4 XCTDs were deployed during the open-water test of December 2010, 12 of the 16 probes procured by SAMS were available for future testing. At ONR's request, ASL agreed to launch the remaining probes during the ICEX-11 submarine exercise in the Arctic Ocean, splitting the probe deployments between the vicinity of the APLIS ice camp (where they could be deployed as a cluster and compared to ice camp-based CTD profiles) and along one of the defined SCICEX sampling corridors, if possible (SCICEX SAC, 2010). During ICEX-11, XCTDs were deployed under sea ice from the Seawolf-class USS Connecticut in four areas: near the APLIS ice camp in the Beaufort Sea (BS), over the Chukchi Plateau (CP), near the juncture of the Alpha Rise and Mendeleyev Ridge (AMR) in the northern Canadian Basin, and near the North Pole (NP, figure 1).

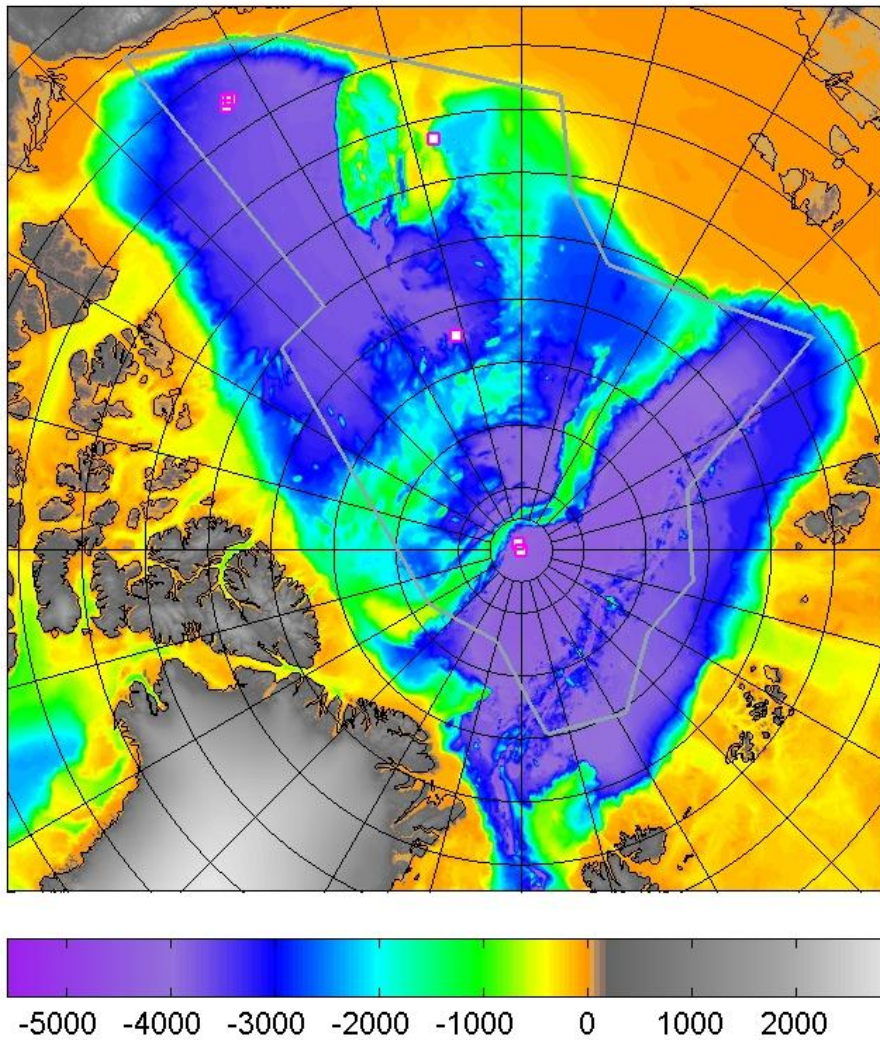


Figure 1. IBCAO bathymetric map of the Arctic Ocean showing location of the XCTDs deployed by the USS Connecticut (SSN 22) during ICEX 11 (Jakobsson et al., 2008).

Dates, locations, and results of each attempted probe deployment are shown in Table 1. XCTDs 6, 7, and 10 were deployed in the vicinity of the APLIS (APL Ice Station) ice camp, in the Beaufort Sea (APLIS is named after the University of Washington’s Applied Physics Laboratory, which has provided sea ice-based support for the Navy’s ICEX submarine program for many years). XCTD 5 was deployed in shallow water over the CP, and XCTD 12 was deployed in the deep water of the Mendeleev Plain of the northern Canada Basin, near the AMR. XCTDs 14 and 15 were deployed close to the North Pole in deep water in the northern Amundsen Basin.

Event No.	XCTD File Name	Time of Launch (Z)				Ship's Depth (ft)	Latitude	Longitude	Probe S/N	Probe Test OK	Post Launch Data Received	XCTD Termination Depth (m)	Closest APLIS/NPEO CTD cast name	CTD cast maximum depth (m)
		Date	Month	Year	Time									
1	CU_00005	04	Dec	2010	0511		West Coast		10058892	Y	Y	628.9		
2	CU_00006	05	Dec	2010	0106		West Coast		10058893	Y	Y	1087.9		
3		05	Dec	2010			West Coast		10058875	N				
4		05	Dec	2011			West Coast		10058874	N				
5	XCTD 05	14	Mar	2011	0640	410	76 - 38.6 N	168 - 00.6 W	10058869	Y	Y	1112.3		
6	XCTD 06	16	Mar	2011	0503	410	72 - 58.2 N	147 - 05.3 W	10058867	Y	Y	1112.3	03151130	36.5
7	XCTD 07	24	Mar	2011	2022	350	73 - 05.4 N	146 - 17.1 W	10058866	Y	Y	545.7	03241122	37.9
8		27	Mar	2011	0430	350			10058864	N				
9		27	Mar	2011	0519	350			10058868	Y	N			
10	XCTD 10	27	Mar	2011	0538	350	72 - 58.0 N	146 - 41.0 W	10058863	Y	Y	1112.3	03262015 03262100	544.2 542.2
11		31	Mar	2011	1618	305			10058872	N				
12	XCTD 12	31	Mar	2011	1645	305	82 - 49.9 N	163 - 00.5 W	10058862	Y	Y	1112.3		
13		01	Apr	2011	2240	350			10058873	N				
14	XCTD 14	01	Apr	2011	2312	350	89 - 59.2 N	024 - 30.1 W	10058865	Y	Y	1112.3		
15	XCTD 15	03	Apr	2011	0607	305	89 - 45.0 N	156 - 32.0 W	10058870	Y	Y	216.8		
16		06	Apr	2011	0445	305			10058871	N				

Table 1. Results of XCTD test deployments in open water off the US west coast in December 2010 (Events 1-4) and under sea ice in the Arctic Ocean in March-April 2011 (Events 5-16) from the USS Connecticut (SSN 22).

1b. XCTD data

ASL personnel have reported that the Sippican DAQ software provided to them prior to ICEX-11 did not include an option for the U/ISSXCTD probe type, as expected from their previous experience. The version of the software they were provided by Sippican in fact did not include that option. As a consequence of this, the resulting data files show vertical profiles beginning at the surface (0 m), as per SSXCTD probes, rather than 12.19 m (40 ft), as per U/ISSXCTD probes. This is illustrated by the example XCTD Export Data File (EDF) header and data excerpt shown in Appendix 1.

The XCTD profiler, containing the temperature and conductivity sensors and as widely used within the oceanographic research community, is obtained from TSK by Sippican and then repackaged for deployment from submarines in open water as the SSXCTD probe and under ice as the U/ISSXCTD probe. Packaged as the SSXCTD, the probe rises from the submerged vessel to the surface from which it profiles downward 1100m. Packaged as the U/ISSXCTD, the probe is designed to rise from the submerged vessel to the depth of 12.19 m (40 ft), and then profile downward 1100 m to a total depth of 1112.19 m. The probes are delivered to Sippican with probe-specific temperature and conductivity coefficients stored in memory, as they are individually calibrated, but with common fall-rate coefficients appropriate for surface-launching, the first of which is a depth offset, i.e., the depth of the first sample. Ordinarily, the Sippican DAQ software replaces the depth offset coefficient of 0 ft (0 m) with 40 ft (12.192 m) for U/I probes; however, this did not occur in the ICEX-11 case due to the absence of the U/I probe option. In this case, the DAQ software derived and recorded depth data appropriate for surface (SSXCTD) probes although U/I probes were actually launched (see Appendix 1). Except where explicitly described otherwise, the data shown in this report have been reprocessed using the depth coefficients appropriate for U/ISSXCTD probes – effectively all depths have been offset by 12.192 m relative to the depths recorded in the EDF files: with the first depth at 12.19 m and the nominal last depth of 1112.19 m

Complete profiles of potential temperature (relative to the surface) and salinity are shown in figures 2 and 3 for each of the successfully launched probes. The figure legends indicate the area of deployment for the probes which will be compared to lowered CTD data in section 2.

Collectively, these profiles embody many of the characteristics of the central Arctic Ocean hydrographic structure. In particular, the downstream cooling of the warm core of the Atlantic water (AW) is illustrated by the differences between the magnitudes of the subsurface temperature maxima from nearly 1.5°C at the NP (XCTDs 14 and 15), to about 0.8°C after flowing along the Mendeleev Ridge (XCTD 12), to about 0.7°C over the CP and in the BS (XCTDs 5, 6, 7, 10). In addition, the depths of the AW temperature maxima increase for that sequence from the NP to the BS/CP, due to the influx of fresher (less dense) and relatively warm (-0.5°C) water of Pacific origin above the Atlantic layer in the CP and BS profiles. Shimada et al. (2001) identify similar subsurface temperature maxima at 40-60 m depth (figure 2) and salinities (S) in the range of $31 < S < 32$ (figures 3, 4) with Eastern Chukchi Summer Water.

The water column in the BS is characterized by continuous salinity stratification to the surface or a shallow mixed layer, while the profiles from the CP, AMR and NP regions (XCTDs 5, 12, 14, and 15) are characterized by deeper surface mixed layers (to 50 m at the NP) across the base of which is a large salinity/density step above a generally less stratified halocline (smaller dS/dz , figure 3). Plots of potential temperature versus salinity (θ - S , figures 4, 7, 10) for the XCTD casts illustrate that despite differences in surface temperature and salinity, the near-surface water is at the freezing point at all locations. Divergence of the APLIS CTD cast from the freezing point is discussed while evaluating the accuracy of the BS XCTD deployments in section 2a (see figure 7).

Profiles from the AMR and NP regions (XCTDs 12, 14, and 16) include double-diffusive temperature-salinity (T - S) steps in the thermocline above the depth of the temperature maximum (figures 2 and 8). These steps are explored in greater detail while evaluating the accuracy of the NP XCTD deployments in section 2b (see figures 11-13). The subsurface maximum at 50-100 m depth in the AMR temperature profile (XCTD 12, figure 2) corresponds to summer Pacific halocline water with $32 < S < 33$ (figure 4 and Steele et al., 2004), whereas the subsurface maxima at 65 m depth in the NP temperature profiles (primarily XCTD 14, figures 2, 8) fall in a higher salinity range, $33 < S < 33.5$ (figure 10)

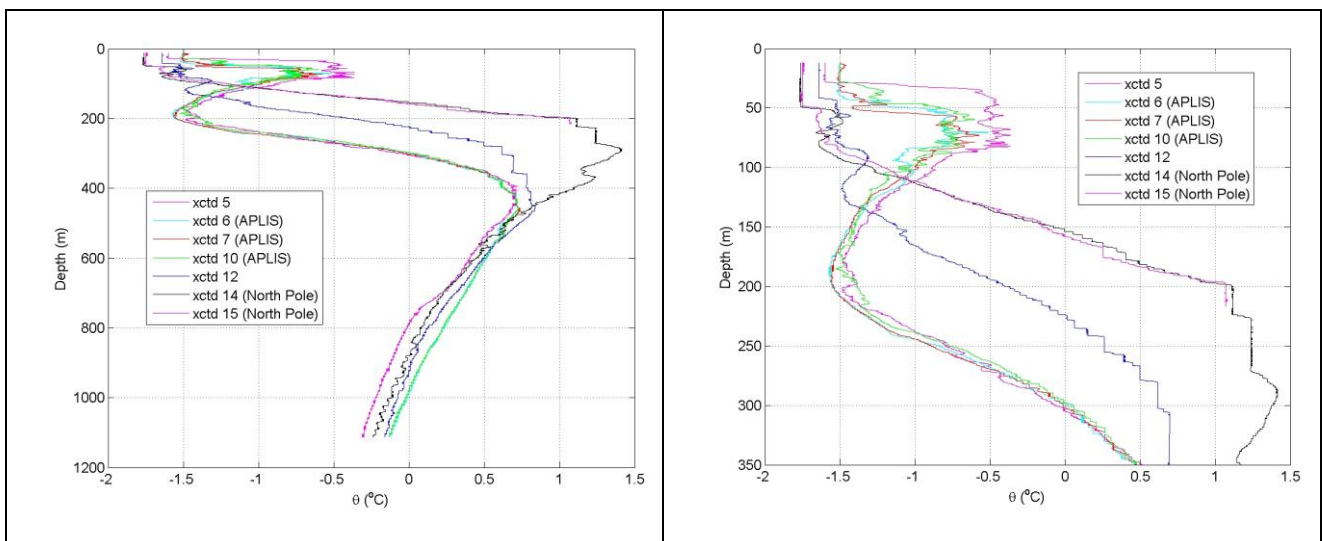


Figure 2. Complete (left) and upper water column (right) profiles of potential temperature (θ) in $^{\circ}\text{C}$ for the 7 XCTDs successfully deployed during ICEX-11.

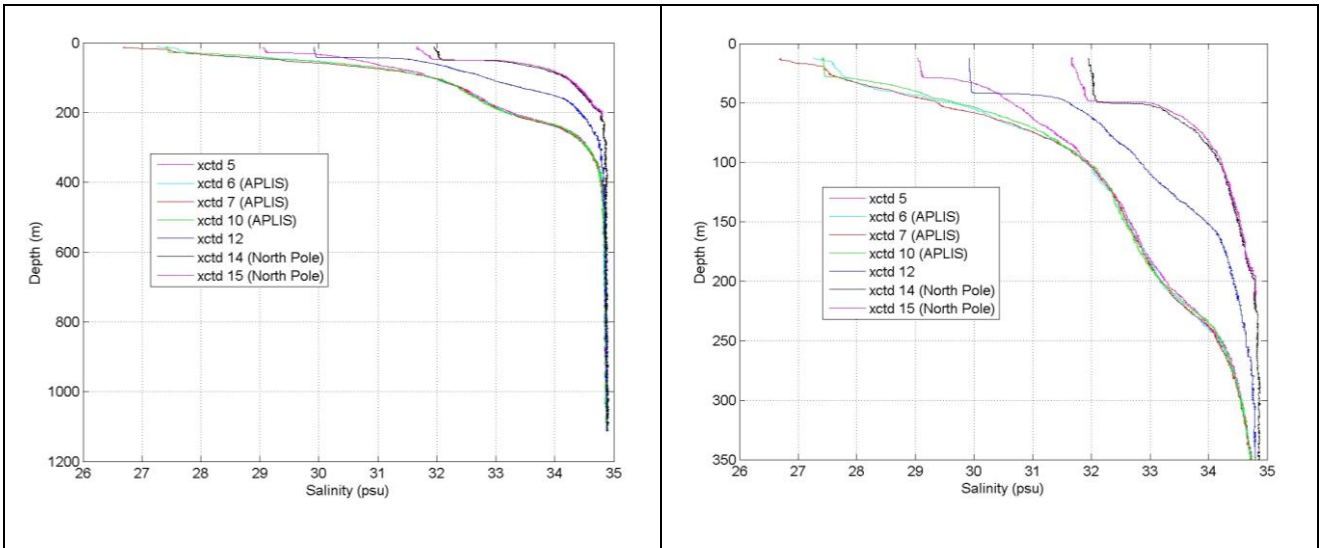


Figure 3. Complete (left) and upper water column (right) profiles of salinity in psu for the 7 XCTDs successfully deployed during ICEX-11.

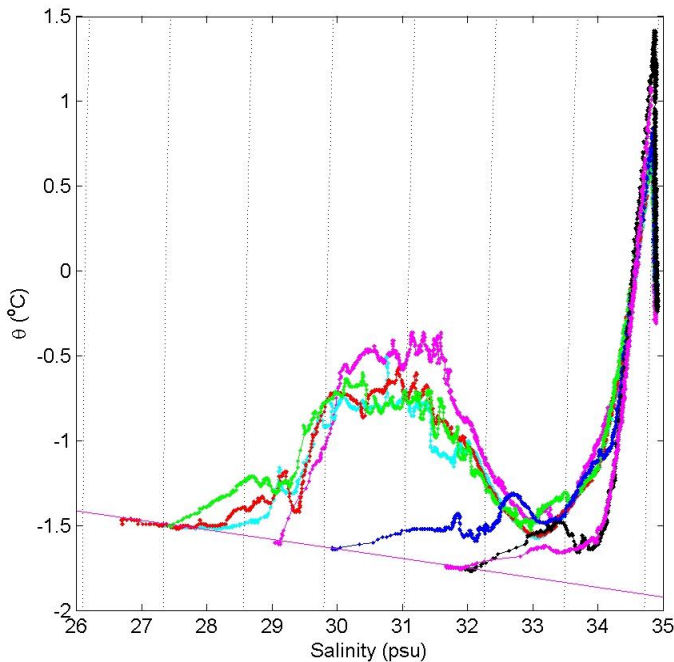


Figure 4. Potential temperature (θ , in $^{\circ}\text{C}$) versus salinity (in psu) for the 7 XCTDs deployed during ICEX-11. Lines of constant density are shown as nearly vertical dashed lines, and the freezing temperature is shown as a solid magenta line. For all casts, the surface water is at the freezing point.

2. ANALYSIS OF XCTD PERFORMANCE

XCTD performance is evaluated through comparison to CTD casts conducted by ASL at APLIS on 26 March, 2011, and by J. Morison, University of Washington, Applied Physics Laboratory, near the North Pole on 19 April, 2011. Table 2 shows the CTD casts conducted closest to each of the XCTDs considered for this comparison. Although the APLIS CTD casts on 15 and 24 March were

closer to XCTDs 6 and 7, these CTD casts were conducted through only the upper 40m; consequently, they have limited value for evaluating the XCTD casts.

CTD program name	CTD cast name	Time of Launch (Z)				Latitude	Longitude	deployed closest to XCTDs	CTD cast maximum depth (m)
		Date	Month	Year	Time				
APLIS	03151130	15	Mar	2011	1141	72 - 56.7 N	146 - 56.3 W	6	36.5
APLIS	03241122	24	Mar	2011	1022	73 - 02.0 N	146 - 33.9 W	7	37.9
APLIS	03262015	26	Mar	2011	2042	73 - 00.7 N	146 - 45.3 W	10	544.2
APLIS	03262100	26	Mar	2011	2128	73 - 00.7 N	146 - 04.3 W	10	542.2
NPEO	ctd 7	19	Apr	2011	1802	89 - 57.7 N	033 - 34.7 W	14, 15	515.8

Table 2. Arctic CTD casts which are closest in space and time to a subset of the XCTD deployments shown in Table 1. APLIS CTD data provided by ASL. NPEO data obtained from the University of Washington, Applied Physics Laboratory NPEO website (<http://psc.apl.washington.edu/northpole/>).

2a. Accuracy: ICEX XCTD/APLIS CTD comparison

Temperature

Both XCTD and CTD profiles from the APLIS region of the BS exhibit several extremes in the upper 600m. The differences between XCTD and CTD temperatures at these local minima and maxima provide a reasonable estimate of the accuracy of the XCTD probes (manufacturer's specifications for which are shown in Table 4), if we regard the SeaBird Electronics SBE-19 CTD used in both APLIS and NPEO sampling as the standard (specifications for which are shown in Table 5). The magnitudes of the CTD-XCTD temperature differences (ΔT) are: $\Delta T < 0.02^\circ\text{C}$ at the base of the surface mixed layer (25 m depth); $\Delta T < 0.04^\circ\text{C}$ at the 200 m local minimum; and $\Delta T < 0.03^\circ\text{C}$ at the depth of the AW temperature maximum (450 m depth). Taking into account natural variability associated with sampling at different locations and times, these values collectively are very close to the XCTD temperature accuracy of $\pm 0.02^\circ\text{C}$ shown in Table 4. Temperature variability is significantly larger in the region of the local maxima in the 50-100m depth range. The two APLIS CTD casts conducted 45 minutes apart exhibit well defined maxima at 75 m depth which differ in magnitude by 0.07°C . While the XCTD-CTD temperature differences in this depth region are often larger than 0.1°C , we disregard this region for comparison, appealing for justification to the larger range of natural variability indicated by the fast-repeat CTD casts. Significantly larger, very near surface APLIS CTD temperature values are almost certainly artefacts of lack of soaking of the CTD at the surface at the beginning of the cast. This is also results in divergence of the CTD surface values from the freezing line for salinities less than 28 psu (figure 7).

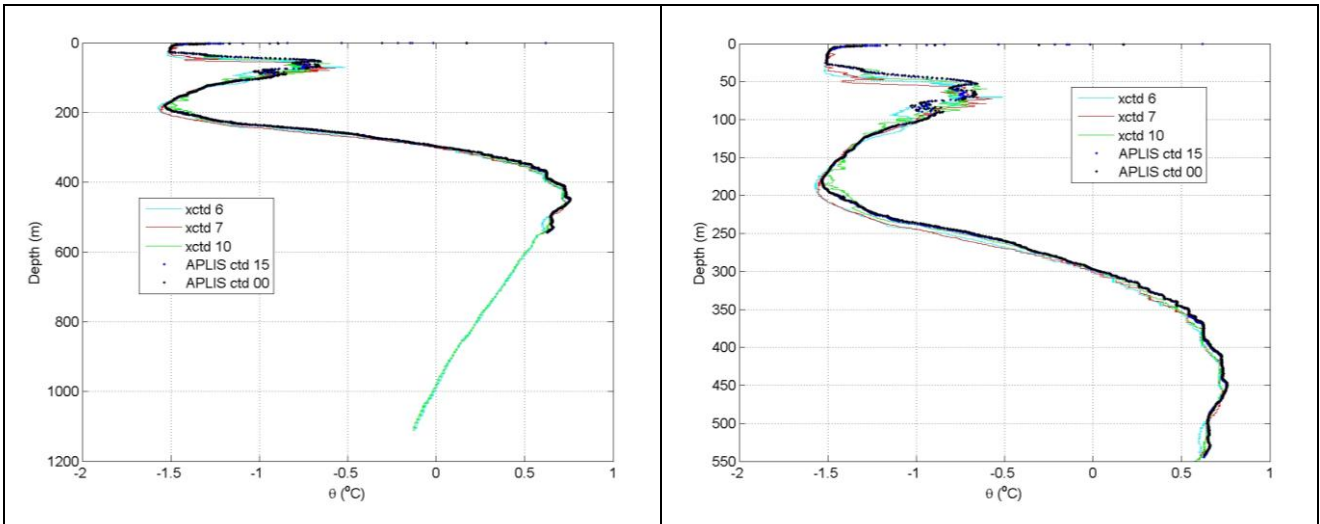


Figure 5. Complete (left) and upper water column (right) profiles of potential temperature (θ) in $^{\circ}\text{C}$ for the 3 XCTDs deployed close to the APLIS ice camp, together with two CTD casts from the ice camp. The CTD casts are identified by the last two digits in the CTD cast names shown in Table 2.

Salinity

Accuracy of XCTD-derived salinity is evaluated from the difference between APLIS CTDs and BS XCTDs over the deepest common region available, where the salinity profiles are stable and the fine scale (order 10s of meters) vertical gradients are all at a profile minimum. At depths between 400-550 m, salinity increases from about 34.82 to 34.85. Over this region, the XCTD salinities typically differ by less than 0.02 psu from the CTD salinities, which differ by less than 0.005 from each other. The observed salinity error of 0.02 psu is less than the salinity error (approximately 0.04 psu) derived from the stated XCTD conductivity accuracy of 0.003 S/m (= 0.03 mS/cm) for these ranges of pressure and temperature. Much of the observed salinity error in this low gradient region can be attributed to the relatively coarse resolution of the conductivity sensor (which is discussed in section 3c).

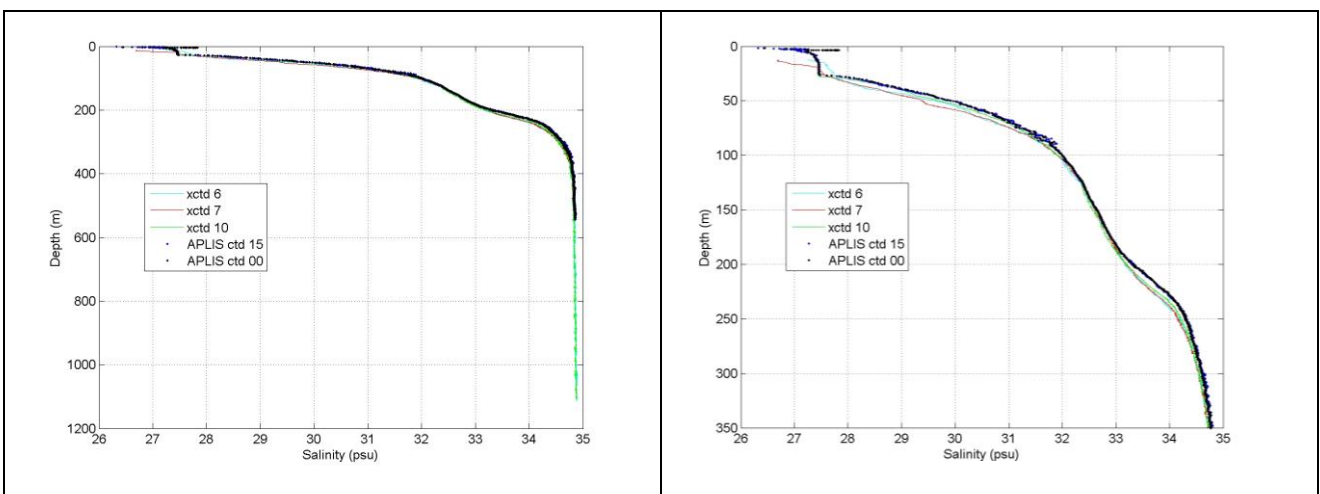


Figure 6. Complete (left) and upper water column (right) profiles of salinity in psu for the 3 XCTDs deployed close to the APLIS ice camp, together with two CTD casts from the ice camp. The CTD casts are identified by the last two digits in the CTD cast names shown in Table 2.

Depth

Because the XCTD and CTD temperature profiles shown in figure 5 display very similar behaviour with depth, the locations of the local minima and maxima can be considered as potential points for evaluation of XCTD depth accuracy. CTD depth is derived from a pressure measurement, which is accurate to 0.1% of the pressure sensor full range, or 1-6 m for sensor full ranges of 1000-6000 m (Table 5). In contrast, XCTD depth is determined from elapsed time of descent and a prescribed probe descent rate, the accuracy for which is stated as 2% (Table 4).

The high variance in XCTD and CTD records at the depth of the subsurface temperature maximum near 60 m is suggestive of interleaving activity associated with the intrusion of Pacific origin water (figure 7), which makes this an unsatisfactory point for comparison. In contrast, all BS XCTD and CTD profiles are stable around the depths of the AW temperature maximum (T_{max}) and the Pacific Winter Water (PWW) temperature minimum (Itoh et al., 2007). Some variability in the observed feature depths should be expected due to local variations in surface mixing and temporal variations in vertical displacement of isopycnals by internal tides and waves; however, the depth comparisons shown in Table 3 indicate that collectively the XCTD depths are biased deep relative to the CTD casts.

Comparison of XCTD and CTD salinity profiles in the upper ocean (figure 6) reveals greater detail about the XCTD depth error. Only one of the three XCTD profiles shown in figure 6 (XCTD 10) exhibits a classic, homogeneous salinity surface mixed layer (SML), the base of which is deeper by 1 m than in the CTD profile. The other two XCTD profiles have shallow fresh water layers (as does the CTD profile) above a weakly stratified layer ending with a sharp transition to higher stratification below, which is identified here as the base of the SML. Within the upper halocline (just below the SML), all three of the BS XCTD salinity profiles are offset deeper/fresher than the APLIS CTD profiles. Within the steep salinity gradient of the halocline, the observed offset corresponds to a depth error of 3-8 m equivalent to a salinity error of 0.2-0.4 psu. As this observed bias is more than 10 times the XCTD salinity ‘sensor’ error, it suggests that the XCTD-CTD biases in the halocline are due to errors in derived XCTD depth.

Feature for Comparison	Beaufort Sea		North Pole	
	APLIS CTD depth (m)	XCTD depths (m)	NPEO CTD depth (m)	XCTD depths (m)
Base of surface mixed layer	26	30 26 27	42	48 49
Pacific Winter Water (S=33) temperature minimum	180	187 190 179		
Atlantic water temperature maximum	449	458 461 458	275	290

Table 3. Comparison of depths of well-defined hydrographic features in XCTD and CTD potential temperature and salinity profiles

The XCTD probe samples the temperature (T) and conductivity (C) sensors at 25Hz, and attributes a depth to each of these T/C pairs through application of a depth equation incorporating a starting depth and a descent rate that decreases slightly with increasing time (and therefore depth). The depth coefficients recorded in the headers of each of the ICEX-11 data files are identical, and reflect the surface-launched and open-water submarine-launched values for the TSK XCTD probes: $z = a + bt + ct^2$, where a = starting depth = 0.0 m; b = velocity term = 3.425432 ms⁻¹; and c = acceleration term = -0.00047 ms⁻² (see Appendix 1). As noted earlier, the value of a was replaced by 12.192 m to compute the U/ISSXCTD depths. For the profiles shown in figures 5 and 6, the

probe velocity decreases slightly from $v = 3.43 \text{ ms}^{-1}$ at 12 m to $v = 3.30 \text{ ms}^{-1}$ at 460 m, the depth of the warm core of the AW. The results here, showing increasing depth error with increasing depth, suggest that the acceleration term may require adjustment. More detailed analysis of the XCTD depth errors reflected in figures 5 and 6 is possible, but is beyond the scope of the present report.

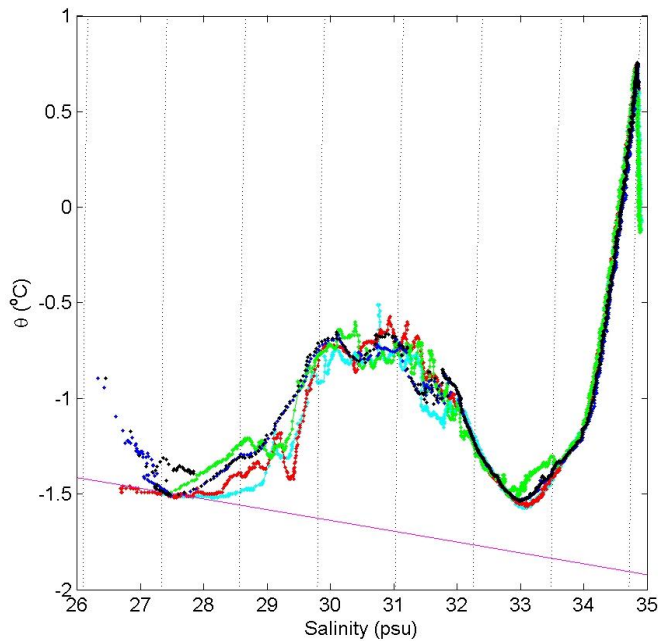


Figure 7. Potential temperature (θ , in $^{\circ}\text{C}$) versus salinity (in psu) for the 3 XCTDs deployed close to the APLIS ice camp, together with two CTD casts from the ice camp. Lines of constant density are shown as nearly vertical dashed lines; the freezing temperature is shown as a solid magenta line. For all XCTD casts, the surface water is at the freezing point.

2b. Accuracy: ICEX XCTD/NPEO CTD comparison

Temperature

The XCTD and CTD profiles from the North Pole region also exhibit features which allow for an evaluation of the accuracy of the XCTD probes using the NPEO SBE-19 CTD as the standard (with specifications shown in Table 5); however, these observations are from within the AW boundary flow and thus some caution is required. The AW flows circumferentially around the Eurasian Basin in a cyclonic (counter clockwise) boundary current keeping the sloping bathymetry to its right, while cooling downstream through vertical and lateral heat fluxes (e.g., Polyakov et al., 2010). The magnitude of the observed AW temperature is thus strongly dependent on the both the downstream and cross-stream locations of the observations relative to the boundary flow, and thus the distance between XCTD and CTD observations is an important factor: these distances are 2.8 and 41.7 km for XCTDs 14 and 15, respectively. Of these, only XCTD 14, closest to the NPEO CTD, extends to the depth of the AW Tmax. The magnitudes of the CTD-XCTD temperature differences (ΔT) are: $\Delta T < 0.01^{\circ}\text{C}$ through both of the 10 – 30 m thick constant temperature layers above the AW core and $\Delta T < 0.02^{\circ}\text{C}$ at the depth of the AW Tmax (figure 8).

Near the base of the surface mixed layer (35 m depth); the XCTD temperature profiles differ from each other by 0.01°C , and each of these differ from the CTD value by 0.005°C . The CTD sampling lagged the XCTD samples by 16-19 days. While this time lag is not so crucial for comparison between the deeper, more stable temperature structures, we expect larger temporal variability in the

SML and thus the near surface comparisons do not strongly constrain our conclusions regarding the XCTD sensor error. Overall, the differences between the XCTD and CTD values are all within the stated accuracy of the XCTD temperature sensors (Table 4).

Salinity

Accuracy of XCTD-derived salinity for the North Pole deployments is evaluated from the salinity differences (ΔS) between NPEO CTD 7 and XCTDs 14 and 15 over the 10-30 m thick, nearly constant T/S steps above the AW core. For the 10 m thick layer centered at 203 m, the magnitudes of the layer average salinity differences for XCTD 14 and 15 are $\Delta S = 0.0125$ and $\Delta S = 0.0014$ psu, respectively. For the 30 m thick layer centered at 239 m the layer average salinity difference between XCTD 14 and CTD 7 is $\Delta S = 0.003$ psu (figure 9). No comparison exists for XCTD 15, as the profile maximum depth (as corrected for an approximate XCTD depth error of 10 m) is 215 m. Overall, the differences between the XCTD and CTD values are all within the stated accuracy of the XCTD salinity sensors (Table 4).

Depth

As noted above for the BS, the few comparators using North Pole XCTD and NPEO CTD profile features do not provide an adequate description of the XCTD depth errors. Both XCTD and CTD profiles from the North Pole exhibit well defined mixed layers with clearly identifiable bases, though only one of the XCTD profiles extends to the depth of the AW Tmax. The XCTDs both show the base of the SML as 6-7 m deeper than the CTD, and the difference between the depths of the XCTD and CTD profiles increases with depth to about 15 m by the depth of the AW Tmax (figure 8).

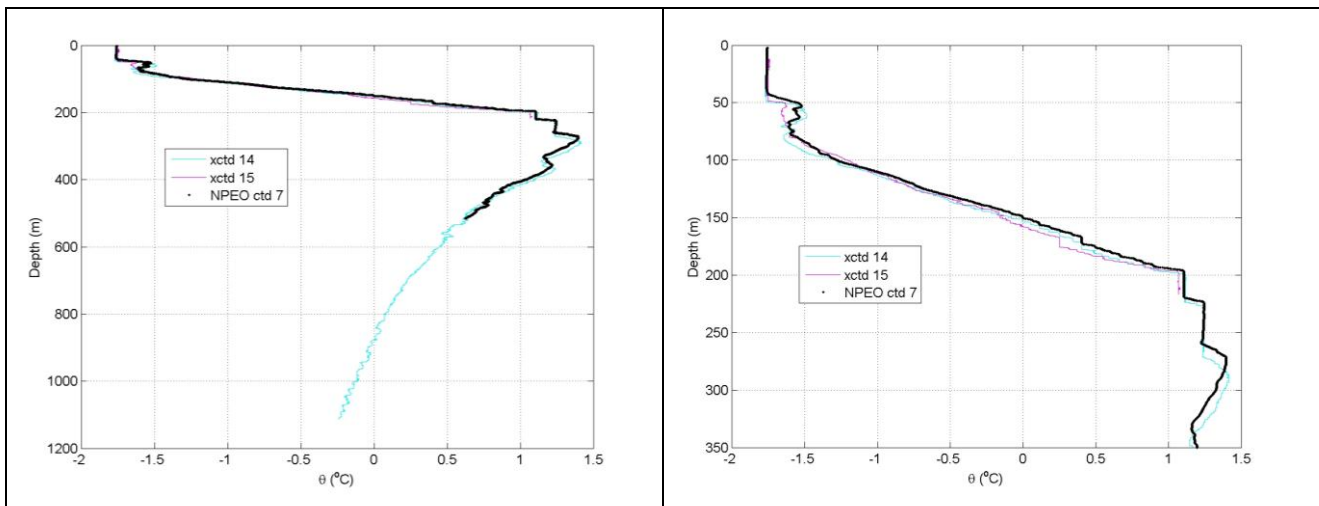


Figure 8. Complete (left) and upper water column (right) profiles of potential temperature (θ) in $^{\circ}\text{C}$ for the 2 XCTDs deployed close to the North Pole, together with NPEO 2011 aerial survey CTD cast that was closest to the pole. The date and location of the NPEO CTD cast are shown in Table 2.

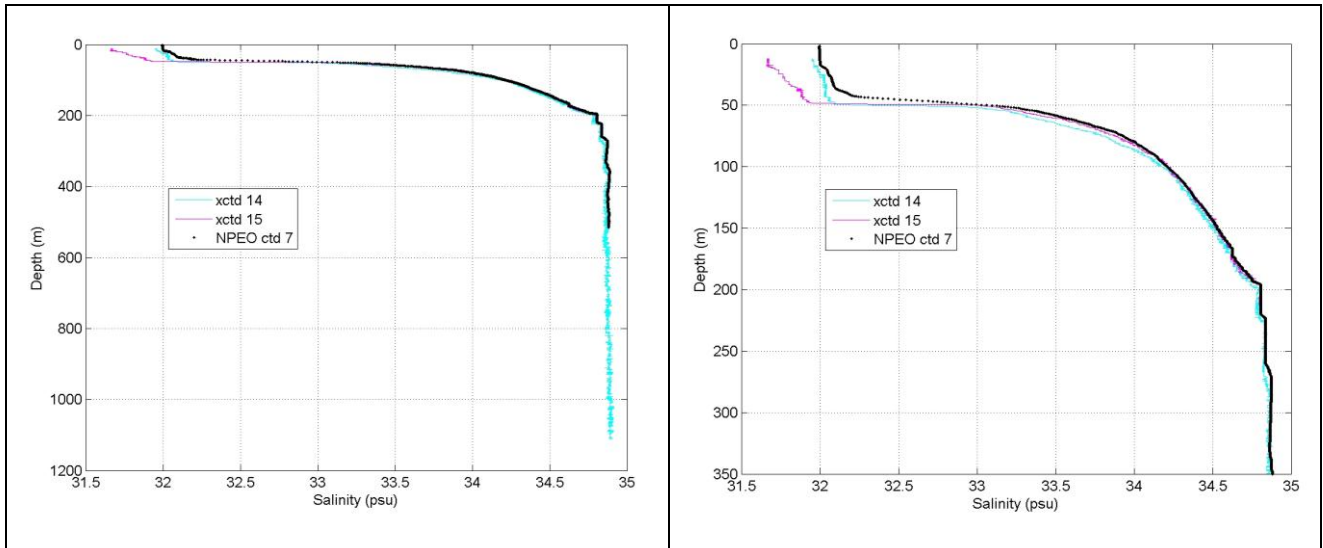


Figure 9. Complete (left) and upper water column (right) profiles of salinity in psu for the 2 XCTDs deployed close to the North Pole, together with the NPEO 2011 aerial survey CTD cast that was closest to the pole. The date and location of the NPEO CTD cast are shown in Table 2.

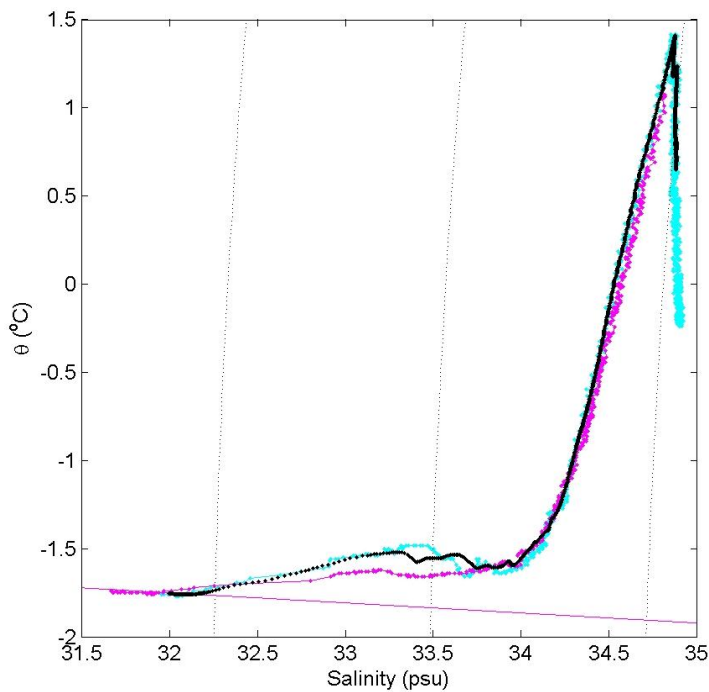


Figure 10. Potential temperature (θ , in $^{\circ}\text{C}$) versus salinity (in psu) for the 2 XCTDs deployed close to the North Pole, together with the NPEO 2011 aerial survey CTD cast that was closest to the pole. The date and location of the NPEO CTD cast are shown in Table 2. Lines of constant density are shown as nearly vertical dashed lines; the freezing temperature is shown as a solid magenta line. For all casts, the surface water is at the freezing point. NPEO CTD 7 is shown in black.

3c. Sensor Resolution

Below the depth of the AW temperature maximum, salinity is nearly constant with increasing depth in the upper 1000 m of the Arctic Ocean. In this regime, much of the salinity variability is expected to be below the resolution and accuracy of the XCTD sensors. However, within the constant T/S steps found widely across the Arctic Ocean in the thermocline above the core of the AW, the relatively coarse resolution of the XCTD sensors is a limiting factor in the accuracy of the derived properties, salinity and density (table 4). In the T/S steps observed in the North Pole profiles (figures 8-10, and close ups in figures 11-13), the resolution of the XCTD temperature and conductivity sensors is apparent as the ‘least count noise’ in the constant T-S layer. Note that constant temperature and conductivity result in a lower salinity at 220 m than at 200 m depth, and thus an apparent inversion in density. This is a result of the equation of state: specifically the pressure dependence of conductivity causes the conductivity to increase by a small amount with depth (pressure) within such a layer of constant temperature and salinity. In the case of the XCTD data from within constant T/S layers, the small increase in conductivity with depth is below the resolution of the conductivity sensor (i.e., the threshold for a change in conductivity value), and thus the derived salinity and density are inverted (decrease with increasing depth) within this layer (figures 11 and 12). This resolution-dependent salinity inversion is also manifest as a horizontal distribution of points in the T/S profile for the depth region of the T/S layers (figure 13)

Sensors	Temperature	Conductivity	Depth
Range	-2 to 35 C	0 to 7 S/m	1000 m
Resolution	0.01 C	0.0017 S/m	17 cm
Accuracy	+/- 0.02 C	0.003 S/m	2%
Response Time	100 mSec	40 mSec	

Table 4. XCTD specifications.

Sensors	Temperature	Conductivity	Pressure
Range	-5 to 35 C	0 to 9 S/m	0-1000 (typical)
Resolution	0.0001 C	0.00005 S/m	0.002% full range
Initial Accuracy	+/- 0.005 C	0.0005	0.1% full range
Stability	0.0002 C/month	0.0003 S/m/month	0.1 % full range/year

Table 5. Specifications for CTD sensors used at NPEO station 7, shown in figures 12-18.

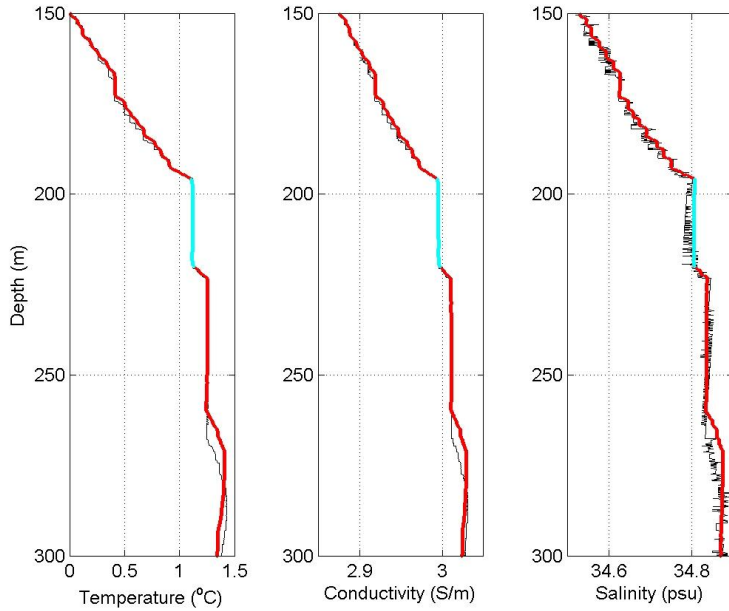


Figure 11. Short section of the vertical profiles of in-situ (measured) temperature (left), conductivity (center) and salinity (right) for XCTD 14 (black line) and NPEO CTD7 from close to the North Pole. Most of the NPEO CTD 7 data are shown as red dots, with cyan dots for the segment of data between 196 m and 220 m depth. XCTD depths have been reduced by 12 m to align the profiles in the T/S step. The close correspondence of the temperature and conductivity profiles over the T-S steps allows evaluation of the XCTD temperature and conductivity sensors.

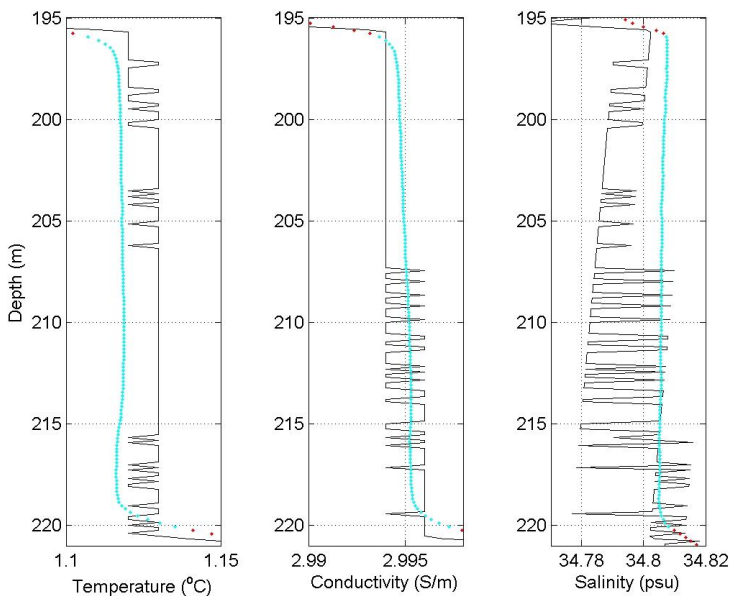


Figure 12. Vertical profiles of in-situ (measured) temperature (left), conductivity (center) and salinity (right) for XCTD 14 (black line) and NPEO CTD7 over a single T-S step. NPEO CTD 7 data are shown as cyan dots for the segment of data between 196 and 220 m depth. XCTD depths have been reduced by 12 m to align the profiles in the T/S step.

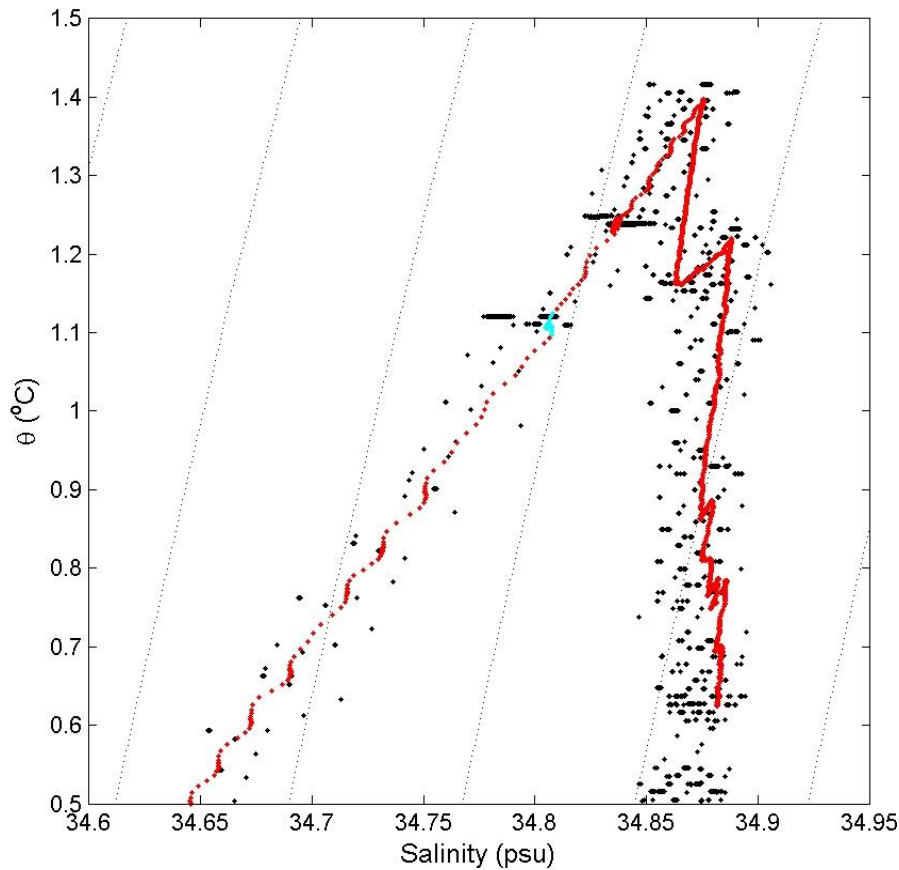


Figure 13. Potential temperature (θ , in $^{\circ}\text{C}$) versus salinity (in psu) for XCTD 14 and NPEO CTD7. Lines of constant density are shown as dashed lines. XCTD 14 data are shown as black dots. Most NPEO CTD 7 data are shown as red dots, with cyan dots for the segment of data between 196 m and 220 m depth.

3d. Reliability: Depth Range Profiled

At the time of XCTD procurement, the test specification was for an open-water test of the sensors and data acquisition (DAQ) software. During the open-water test cruise in December 2010, ASL had the opportunity to launch only 4 of 16 XCTD probes procured for this purpose. Two of these probes failed the pre-launch tests, and the remaining 2 returned data (see Table 1). Failure to provide the correct software version may have contributed to the failure of the DAQ software to record data to the full design depth of 1000m for one of the probes used the in December 2010 open water test. Twelve of the initial 16 probes were reserved for future use in ICEX-11 in the Arctic Ocean.

During the ICEX-11 testing in the Arctic Ocean, 4 of 12 probes failed pre-launch tests and consequently were not launched, 7 of 8 probes launched returned data, and 5 of those 7 returned data to the full design depth (1100 m).

4. CONCLUSIONS AND RECOMMENDATIONS

For the XCTDs considered in this test, the sensor resolution has been found to be as specified by the manufacturer. Within the limits of our ability to determine XCTD sensor accuracy with the ICEX-

11 XCTD data in conjunction with APLIS and NPEO CTD cast data, XCTD sensor accuracy was found to be within the bounds specified by the manufacturer. Within the Arctic Ocean, the relatively coarse resolutions of the XCTD temperature and conductivity sensors limit the ability of XCTDs to resolve: (1) small scale variations associated with T/S steps in the upper ocean, and (2) salinity variability beneath the depth of the AW temperature maximum. Nevertheless, these probes have sufficient resolution to resolve shifts in character and distribution of large scale water masses responsible for the major heat and freshwater features in the upper ocean. Errors in derived depth remain an issue to be resolved for these XCTD probes. Although detailed treatment of depth errors was beyond the scope of this report, feature comparison (Table 3) suggests that XCTD depths are biased by up to +10 m relative to CTD pressure sensor results for much of the depth range sampled. Reliability of probes remains an open issue: the high rate of failure of probes (out-of-the-box) to pass pre-launch tests is unacceptable. In contrast, the vast improvement in the rate of success for probes to achieve the designed maximum depth leads to the conclusion that this no longer a systematic problem

Three recommendations follow from the results of the ICEX-11 testing:

1. The significant increase from 2009 in the fraction of probes which failed the pre-launch test is a problem that must be resolved prior to significant additional investment in submarine-based XCTD sampling. At this point it is not known whether the ‘failed’ probes were really bad, or whether this was a case of misidentification of flawed probes during the pre-launch process. Further testing of the ICEX-11 failed probes is not possible as these were not retained for analysis by the manufacturer, Sippican. In the future, all U/ISSXCTD probes that fail pre-launch testing should be retained for future analysis.
2. The significant increase in the fraction of probes to achieve the designed maximum depth since the implementation of the data acquisition software revision indicates that this should no longer be considered a systematic problem and should no longer represent an impediment to increased submarine-based XCTD sampling.
3. The consistently deep bias (+10 m) of XCTD-derived feature depths relative to CTD measured depths suggests that the XCTD fall rate equation routinely underestimates the deceleration of the probe falling through the water column. The XCTD fall rate coefficients require further attention to reduce or eliminate this bias.

5. REFERENCES

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APPENDIX 1: Header from Sippican Export Data File (EDF)

```
// MK21 EXPORT DATA FILE (EDF)
// File Information
Raw Data Filename: D:\Documents and Settings\jeffrey.GOSSETT\Desktop\Mod XCTDs\XCTD
06.RDF
// System Information
Units      : Metric
// Probe Information
Probe Type   : SSXCTD-1
Terminal Depth : 1100 m
Depth Equation : Standard
Depth Coeff. 1 : 0.0
Depth Coeff. 2 : 3.425432
Depth Coeff. 3 : -0.00047
Depth Coeff. 4 : 0.0
// Launch Information
Num Info Fields : 6
Date of Launch  : 03/15/2011
Time of Launch  : 22:07:33
Sequence Number : 6
Latitude       :
Longitude      :
Serial Number   : 10058867
// Memo
// Hardware
MK21 Device    : Default
// Information - XCTD
// Calibration Coefficients - XCTD
Cal Coeff State : Original
Temperature1    : -5.866000E-02
Temperature2    : 9.945160E-01
Temperature3    : 0.000000E+00
Temperature4    : 0.000000E+00
Conductivity1   : -8.574220E-02
Conductivity2   : 1.040820E+00
Conductivity3   : 0.000000E+00
Conductivity4   : 0.000000E+00
// Post-Processing
Operations      : None
// Data Fields
Num Data Fields : 9
Field1         : Time (sec)
Field2         : Frame
Field3         : Depth (m)
Field4         : Temperature (°C)
Field5         : Conductivity (mS/cm)
Field6         : Salinity (ppt)
Field7         : Sound Velocity (m/s)
Field8         : Density (kg/m³)
```

Field9 : Status

// Data

0.000	96C05E67	0.0000	-1.50	22.11	27.28	1438.82	1021.87	8000	
0.040	96C05EAD	0.1370	-1.49	22.11	27.27	1438.81	1021.87	8000	
0.080	96C45E59	0.2740	-1.50	22.13	27.30	1438.85	1021.89	8000	
.									
336.640	9E387FF1	1099.8400		-0.07	29.40	34.89	1466.73	1033.24	8000
336.680	9E387FF1	1099.9644		-0.07	29.40	34.89	1466.73	1033.24	8000
336.720	9E347FD6	1100.0887		-0.07	29.39	34.89	1466.73	1033.24	8000