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A comparison of CTD satellite-linked tags for large cetaceans - Bowhead whales as real-time autonomous sampling platforms

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ABSTRACT

There is an increasing need for comprehensive oceanographic sampling, and taking advantage of marine mammal studies of movements and habitat use for augmenting spatial and temporal coverage, especially in remote and inaccessible areas, is an attractive approach. Oceanographic sampling instruments that transmit profiles of temperature and salinity (CTD) via satellite were deployed on bowhead whales *Balaena mysticetus*. A novel satellite-linked CTD tag (WC) was compared to an established design (SMRU). The two types of tags were deployed equally on nine bowhead whales in West Greenland. Both tag types used Argos for relaying data and locations, while the WC tag also provided Fastloc-GPS for more accurate locations. One whale carried both tag types. When comparing the two tag types deployed on the same whale, more complete data were obtained from the WC tag in terms of number of profiles, locations and transmissions received, although placement of the tag on the back of the whale and antenna position may have affected some of these parameters. Why transmissions terminated is difficult to determine, however, physical loss of the tag from the whale and mechanical damage to the antenna are the most likely; none of the tags failed because of battery exhaustion. Although, differences in performance of the two tag types were found, we conclude that both satellite-linked CTD tag types deployed on large cetaceans can provide high resolution oceanographic profiles at times and in areas where traditional methods for collecting oceanographic data are logistically difficult and prohibitively expensive.

1. Introduction

To understand global ocean conditions and circulation patterns, it is important to have ocean measurements from polar regions where climate changes are amplified (e.g. Screen et al., 2010; Thornalley et al., 2018). However, due to high costs and logistical difficulties associated with operating in ice-covered areas, there have been relatively few icebreaker expeditions sampling oceanographic data from inaccessible and remote areas in polar regions. Argo floats (http://www.argo.ucsd.edu/) have been deployed in almost all oceans. They collect data for the Global Ocean Observing System and are designed for broad-scale ocean sampling and collection of high-quality temperature and salinity profiles from the upper 2000 m of the ocean (Gould et al., 2004; Roemmich et al., 2004). However, these floats mostly sample waters between 60°N and 60°S (Gould et al., 2004; Treasure et al., 2017), and thus not the polar regions. Marine mammal studies have included satellite-linked transmitters with conductivity-temperature-depth (CTD) tags to understand the behavioural ecology of the mammals (Fedak, 2004; Hussey et al., 2015). Since 2002, more than 500,000 oceanographic casts have been generated by animals. The majority were from seals instrumented with CTD data loggers (Treasure et al., 2017), with a large contribution in polar regions. CTD data loggers have also been deployed on beluga whales (Lydersen et al., 2002) and on a bowhead whale (Citta et al., 2015). In addition to marine mammal ecological studies, major contributions have been made in oceanographic data collection in remote areas (e.g. Fedak, 2004, 2013; Nakanowatari et al., 2017; Roquet et al., 2014, 2017). Although, CTD tags have been widely used, measuring conductivity is not trivial due to interference from biofouling, electric fields, physical impacts and nearby objects like the animal itself. Temperature and pressure are easier to measure accurately as the sensors are less affected by the surroundings. As temperature, pressure and conductivity are used to calculate salinity, the problems and inaccuracy mainly stem from conductivity measurements (e.g. Boehme et al., 2009).

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There are challenges with satellite-linked telemetry and marine mammals, especially whales, due to the brief periods of time they spend at the surface during breathing events and placing the tag in a position on the whale where the tag comes out of the water during surfacing. The short surface periods decrease the probability of successful reception of data strings from satellite-linked tags deployed on whales. The tags need 0.5–1 s in the air to reliably transmit data and for acquisition of positions. Also, animal-borne tags have a limited number of transmissions available because of the restrictions on battery packages. Due to these limitations, CLS-Argos (http://www.argos-system.org/) is the only suitable satellite system for marine mammal data collection and tracking. The probability of receiving data increases with latitude and the performance of CLS-Argos is particularly good in polar regions where satellite coverage is the highest. The Argos system is limited to 32 bytes per transmission, however, and with cetaceans submerged up to 95% of the time (Teilmann et al., 2012; Schorr et al., 2014), only a few hundred transmissions per day are typically received from instrumented whales.

Accuracy, reliability and long-term performance of the data loggers are critical issues for collection of data on environmental parameters. Various issues, including the potential drift (temporal changes in offset) of CTD data loggers over time and whether or not the accuracy of measurements is adequate for monitoring long-term changes in dynamic oceans, are important to understand. Thus, deployment techniques and general performance should be assessed before the technique can be widely implemented on baleen whales. We instrumented nine bowhead whales in Disko Bay, West Greenland with two different CTD loggers in order to compare performance between the two instruments. The objective was to evaluate a new (not yet commercially available) CTD tag by comparing its overall performance with that of one commercially available.

Disko Bay, West Greenland (69°N 53°W) hosts about 1538 (CL 95%: 827–2249; Rekdal et al., 2014) bowhead whales (*Balaena mysticetus*) from winter to spring (Heide-Jørgensen et al., 2003). During late May, at a time when much of the area is ice covered, the bowhead whales leave Disko Bay and cross Baffin Bay *en route* to summering grounds in Canada, making tagging studies of bowhead movements and behavior especially useful for collecting oceanographic data in otherwise inaccessible, ice covered areas of Baffin Bay (Heide-Jørgensen et al., 2003; Laidre & Heide-Jørgensen, 2012).

2. Material and methods

2.1. Tag specifications

An electrode cell CTD Argos satellite-linked tag was developed for this study to resolve the issue with salinity measurements made by inductive conductivity technology being affected by mass of nearby objects, to use Fastloc GPS technology, and to build a smaller, lighter, more reliable tag for baleen whale studies by Wildlife Computers (hereafter called WC tags, Redmond, WA, USA). The WC tag was compared to an inductive cell CTD Argos satellite-linked tag manufactured by the Sea Mammal Research Unit (hereafter called SMRU tags, St. Andrews, UK, Boehme et al., 2009). WC tags (12x6x3.5 cm, 316 g) had a smaller footprint and were lighter than the SMRU tags (16x7x5.5 cm, 594 g). Both tags had an output of 0.5 Watt and the WC tags were powered by 4 AA lithium batteries, while the SMRU tags had 6 AA lithium batteries.

The WC and the SMRU tags both had a depth range of 0–2000 m and collected conductivity, temperature and depth data (CTD). To make the necessary limitations in satellite data transmissions, PSU was reported rather than conductivity. The WC tag had a temperature range of −3 to 40°C and a salinity range of 0–50 PSU. The temperature range for the SMRU tag was −2.5 to 31°C and the salinity range 20–36 PSU. The resolution for both tags was 0.001 for salinity and temperature, and 0.5 m for depth. Both CTD tags detected the deepest point of a dive and started sampling the various parameters once per second for its internal memory until reaching the end of the dive (WC, pers. comment; Boehme et al., 2009). Conductivity was measured using an electrode cell in the WC tags, whereas the SMRU tags used an inductive cell (as in Valeport CTDs, www.valeport.co.uk). The electrode cell measures the ability of a liquid to conduct an electric current between two electrodes. The more ions in the liquid the higher the current and thereby conductivity. The inductive cell consists of two coils that form a closed conductive current path. When current is applied to the primary coil, it induces an alternating voltage in the liquid loop, which causes a current flow captured by the second coil, which is again proportional to the conductivity of the sample solution. As conductivity increases with temperature, accurate temperature measurements are equally important to calculate salinity (Bennett, 1976). There are advantages and disadvantages with both sensor types. The main advantage of electrode cells is that there is no proximity effect, while the inductive cell may be affected by the mass of nearby objects (Boehme et al., 2009), e.g. by the large body of a whale and should therefore be calibrated when on the whale, which is practically impossible. The main disadvantage of the electrode cell is that any changes in the cell constant will be reflected in the conductivity. This could happen when the electrodes are subject to corrosion, biofouling or damage. The main advantage of the inductive cell is the robust construction and the absence of exposed electrodes (http://www.coastalwiki.org/wiki/Salinity_sensors). The SMRU inductive cell was encapsulated in titanium and ceramic construction that reduced shrinking under pressure and thereby offsetting the measurements, while the WC electrodes were placed inside a glass tube mounted between two epoxy “bumpers” to reduce the risk of physical damage. Another difference between the tags was that locations for the SMRU tags were estimated via the Argos location system alone, whereas the WC tag used Fastloc GPS in addition to Argos locations.

The WC tags were programmed to store the deepest profile for every 6-h period (for a total of 4 profiles per day) and were set to transmit each profile repeatedly. Every message was transmitted eight times to increase the chance that a given profile would be received by an Argos satellite. During each summary period, the WC tags stored the CTD profile of the deepest dive from the whale’s dive profiles. The first dive that crossed a preset depth threshold (10 m depth) set the baseline for that 6-h period and the Fastloc GPS location was stored. To overwrite the stored CTD data, a subsequent dive needed to be 10% deeper than the baseline dive. A new Fastloc snapshot of satellite positions (used to post process GPS locations) was also stored for each new profile collected. This continued until the end of the summary period, after which the CTD data and all Fastloc snapshots were formatted into Argos messages for transmission during subsequent surface events in the following 6-hr period. The depths transmitted for WC tags were based on the Levitus World Ocean Atlas (WOA94, 0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400, 500, down to 2000 m) standard depths. Argos transmissions formatted with CTD data contained 8 depth pairs of salinity and temperature. Consequently, if a dive was deeper than 125 m, the profile data were transmitted in two separate messages to the Argos satellites.

The SMRU tags were set to record the two deepest profiles every 2 h, resulting in 24 profiles per day, based on a previous transmission success rate of 35%, obtained by another project (pers. comm. Phil Lovell), and each Argos message contained up to eight temperature and salinity pairs. The SMRU tag also used the WOA standard depths, with 8 predefined depth levels (dependent on the depth of the dive) as well as 6 ‘broken stick’ depths. This method used the points of greatest change in the profile to determine each break point in the ‘stick’ and determined the 8 transmitted depth levels accordingly (Boehme et al., 2009; Fedak et al., 2002; Roquet et al., 2011). Each CTD profile for this tag were split into two Argos messages. Measurements for the eight predefined depths (e.g. 0–125 m) were sent in the first Argos message, whereas the 6 broken stick measurements plus the shallowest and deepest depth triplets were sent in the second (Boehme et al., 2009). Both WC and SMRU

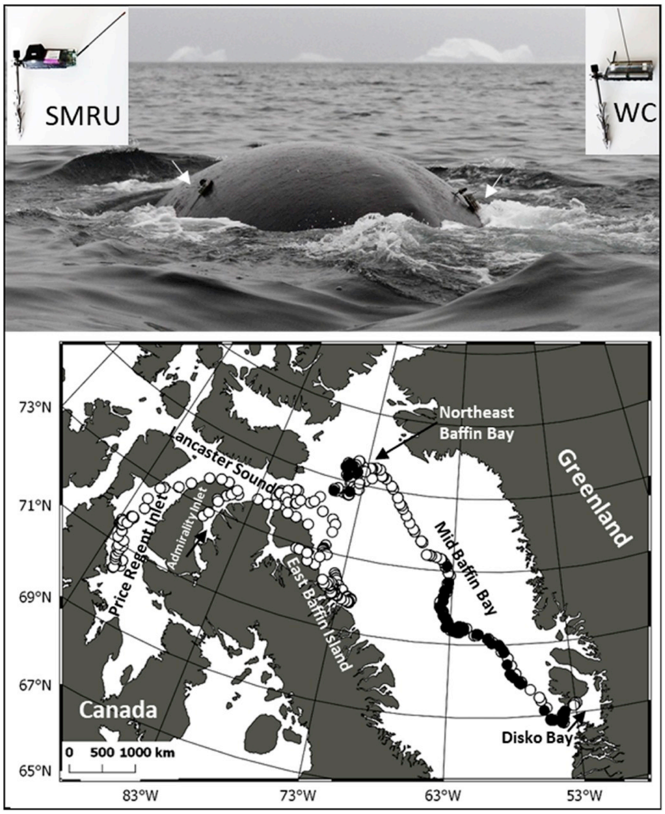

Fig. 1. A) Photo of the back of a bowhead whale just after deployment of two CTD satellite tags. The SMRU tag (16x7x5.5 cm, 594 g, left insert) and the WC tag (12x6x3.5 cm, 316 g, right insert). The white arrows are pointing at the Argos antennas of the two tags. Note that the two tags have similar height above the water level. B) Map of the positions received by the two tags on the same whale. The SMRU tag is shown with black dots (7 May to 29 June) and the WC tag with white dots (7 May to 23 August). Note the breaks in the track from the SMRU tag. Only positions with associated CTD profiles are shown.

tags were programmed to transmit at a standard rate of no more than one message every 45 s.

2.2. Comparison of CastAway CTD and WC/SMRU tags

The tags were initially calibrated weeks prior to the field work by the manufacturers; therefore, it was decided to perform on-site comparisons right before deployment of the instruments to a CastAway CTD (salinity range = 0–42 PSU, accuracy = 0.10 PSU, resolution = 0.01 PSU, temperature range = −5-45°C, accuracy = 0.05°C, resolution = 0.01°C, www.sontek.com). After equilibration at the surface for 10 s, the CastAway CTD and the satellite tags were lowered vertically through the water column at a speed of around ~0.5 m s^{-1} down to 100 m (the maximum depth range of the CastAway). For comparison, all CTD and WC tag values were rounded to the nearest meter (as they both sampled continuously and not at certain depths when data was manually offloaded from the tag) and compared to the transmitted SMRU depth intervals (that could not be offloaded). The salinity measurements from the CastAway CTD were calibrated against *in situ* water samples collected from various depths on 7 May (n = 6 depths) and 15 May (n = 7) and later analyzed at a certified laboratory at Aarhus University, Denmark using salinity standards for calibration.

2.3. Instrument deployment

Both instruments were glued to a rectangular stainless-steel base plate (3 mm in thickness) (Devcon Flexane) and secured with screws.

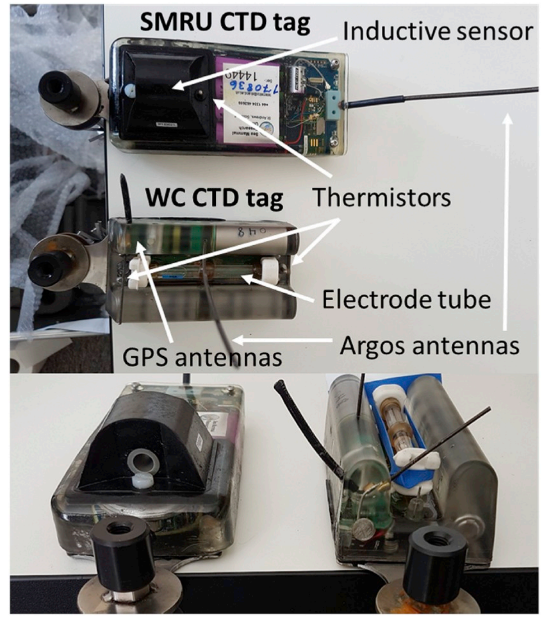

Fig. 2. Close-up of the SMRU and WC tags from the top (insert above) and from the front (insert below). The inductive conductivity sensor is a black box on top of the SMRU tag and on the WC tag the electrodes are placed inside the glass tube seen between the two epoxy "bumpers" reducing the risk of physical damage while still providing free flow through the tube. The white knobs and elastic band on the WC tag are protecting the electrodes and are removed prior to deployment.

The distal part of the plate had a rounded extension that included a hole for the attachment of a 0.8 × 27cm stainless-steel anchor with a cutting point to cleanly pierce the skin and three sets of 3 cm long retention petals to secure the anchor in the blubber under the skin. The single point attachment allowed the steel plate containing the tag to sit on the surface of the animal on a swivel. The plate itself could turn 360° with 30° lateral movement allowed via two steel washers welded on either side of the hole where the plate was attached to the anchor (Fig. 1 and 2).

Daily searches for whales were conducted from three small boats between 7 and 13 May 2017 in Disko Bay, West Greenland (69°N, 53°W). Tags were deployed only when the whale remained at the surface long enough to place the tag in a suitable position (procedure following Heide-Jørgensen et al., 2006). In one case it was possible to approach the whale twice and place one of each tag type on either side of the whale to facilitate a direct comparison. The tag was designed to be deployed by an 8 m carbon fibre pole. This involved placing the tag in a positively buoyant foam holder to ensure its protection and fixation prior to deployment. A plastic knob was screwed onto the threaded distal end of the anchora and a plastic pipe at the end of the deployment pole held on to the plastic knob. This attached the tag to the pole while the plastic pipe was weakened to allow the tag to detach from the pole when deployed on the whale. The same anchor and deployment system were used for both tag types.

The two tags are similar in size and mass and it was assumed that the relatively small size of the tags compared to that of a bowhead whale (<10-6% of the mass; Fig. 1), together with the anchor length being roughly half the thickness of the animal's blubber layer (Heide-Jørgensen et al., 2012), had limited impact on the behavior and health of the whales (Gales et al., 2009). Because successful transmissions require extended time at the surface to connect with satellites it was important that the tag was placed as high on the back of the whale as possible. This was not always the case and as individual behavior also affects transmission efficiency, the main comparison of the two tag types will be of those deployed on the same whale.

Table 1
List of the 10 CTD tags deployed on bowhead whales during 7–13 May 2017 in Disko Bay, West Greenland. The number of CTD profiles and positions received as well as comments on tag deployment are included. The average performance includes both the performance of the tags and the variability due to the deployment position of the tags.

Tag type	Argos PTT id	Deployment Date	Last CTD profile	Transmission days	All Argos positions (1,2,3,0,A,B)	High quality Argos positions 1,2,3 (% of total)	GPS positions	Received CTD profiles with associated positions	CTD profiles/ day	Comments
WC	170750	7-May-2017	23-Aug-2017	109	3120	2.6	633	306	2.8	High on the back of the whale, on right side.Double tagged on the same whale as SMRU tag 170835.
WC	170751	12-May-2017	18-Jul-2017	67	514	0.4	60	61	0.9	The tag was deployed low on the whale, which likely affected transmission quality.
WC	170752	13-May-2017	3-Jul-2017	52	41	0.0	10	13	0.3	The tag was deployed low on the whale, which likely affected transmission quality.
WC	170753	12-May-2017	18-May-2017	6	200	4.5	47	22	3.7	Placed high on the whale, tag not all the way in, lying on the back of the whale. Probably the reason for the short duration.
WC	170754	9-May-2017	11-Oct-2017	155	2984	2.2	479	393	2.5	High on the back of the whale. On 18 May the PSU shifted to constant low readings until tag stopped 11 October.
SMRU	170833	9-May-2017	17-May-2017	8	232	29.3	No GPS receiver	104	13.0	High on the back of the whale.
SMRU	170834	7-May-2017	25-May-2017	18	361	0.0	No GPS receiver	26	1.4	The tag was deployed low on the whale, which likely affected transmission quality.
SMRU	170835	7-May-2017	29-Jun-2017	53	481	0.4	No GPS receiver	80	1.5	High on the back of the whale, on left side. Double tagged on the same whale as WC tag 170750.
SMRU	170836	13-May-2017	16-Sep-2017	126	9	11.1	No GPS receiver	9	0.1	Uncertain how the tag was placed on the whale.
SMRU	170837	9-May-2017	Tag never transmitted	–	–	–	–	–	–	Tag never transmitted. Tag deployed too low on the whale to get the antenna clear of the water.
WC average performance				**78**	**1372**	**1.9**	**246**	**159(SD=178)**	**2.0 (SD=1.4)**	**WC tags have about 50% longer tag contact duration, > 5 times more Argos positions, but also 5 times fewer percentwise high quality Argos positions and only half the number of daily profiles compared to the SMRU tags.**
SMRU average performance				**51**	**271**	**10.2**	**No GPS receiver**	**55 (SD=45)**	**4.0 (SD=6.0)**	

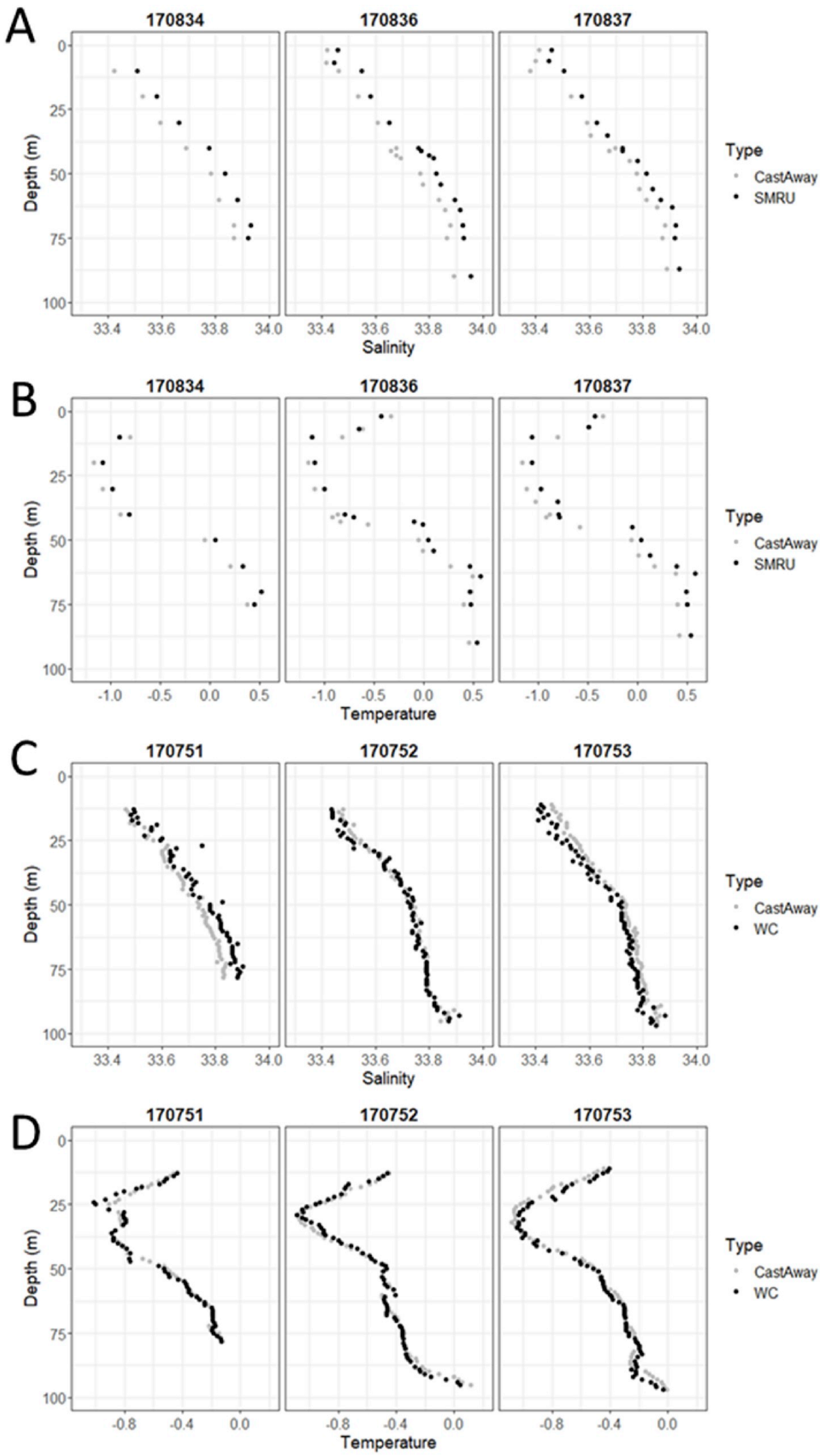

Fig. 3. Measurements of salinity and temperature from the SMRU (A, B) and WC tags (C, D) plotted against the Castaway CTD corrected for offset. Note the fewer samples from the SMRU tags as data was only available through satellite transmission, while data from the WC tags was downloaded from the tags. Data from CastAway and WC tags was binned to nearest meter and averaged for comparison. See also Table 2.

Table 2
Comparison between the CastAway CTD and SMRU and WC tags. Measured salinity values by the CastAway CTD was compared to measured salinity from *in situ* water samples analyzed in a certified laboratory. CastAway CTD measurements were then corrected for this offset when compared with the tag data (CastAway calibrated using average offset from water samples collected 7 and 15 May). Note that only data from tags that were lowered with the CastAway in the same cast is displayed. See also Fig. 3.

Comparison	Date	Offset salinity (PSU)	Offset temperature (°C)
CastAway CTD against water samples	7 and 15 May	Average offset from 7 and 15 May: 0.06 ± 0.03 (n = 13).	Not calibrated for temperature
SMRU tags against CastAway CTD	7 May	170834: -0.08 ± 0.01 (n = 8)	170834: -0.06 ± 0.07 (n = 8)
		170836: -0.08 ± 0.03 (n = 16)	170836: -0.1 ± 0.2 (n = 16)
		170837: -0.06 ± 0.02 (n = 16)	170837: -0.1 ± 0.2 (n = 16)
WC tags against CastAway CTD	10 May	170751: -0.04 ± 0.02 (n = 59)	170751: 0.01 ± 0.04 (n = 59)
		170752: 0.007 ± 0.02 (n = 74)	170752: 0.01 ± 0.05 (n = 74)
		170753: 0.03 ± 0.02 (n = 80)	170753: -0.004 ± 0.05 (n = 80)

2.4. Comparison of WC and SMRU tags

One bowhead whale was fitted with both tag types (WC 170750, SMRU 170835; Table 1). The two tags were positioned at approximately the same height over the water level on opposite sides of the whale, with equal opportunities to transmit data, although the SMRU Argos antenna may have been compromised due to the orientation (see Fig. 1). Two-tailed paired t-tests were used to compare salinity and temperature pairs from the same depth for time stamped profiles within the same hour. As both tags transmitted the deepest profile within a certain hour, we believe that the comparison should include measurements from the same dive. Only data sampled at the same depths (from 0-300 m) in the period (7 May to 29 June) were included in the analysis. Ocean Data View software (Schlitzer, 2018) was used to plot the CTD data.

3. Results

During 7–13 May 2017, nine bowhead whales were tagged with CTD tags in Disko Bay, West Greenland. Of the five SMRU tags one never transmitted and one whale was tagged with two transmitters, resulting in ten tags deployed (Table 1). Transmissions lasted between 6 and 155 days and the tags provided between 9 and 393 CTD profiles.

3.1. Comparison to CastAway CTD

The CastAway CTD gave significantly lower values than the true salinity measured from *in situ* water samples. Therefore, a mean offset value of 0.06 (SD = 0.03) PSU was used to correct the CastAway CTD values in the comparison of the measurements from the tags (Table 2, Fig. 3). After the tags were deployed, three CTD casts to 100 m were made with a recently calibrated SeaBird 25 (www.seabird.com) and the Castaway tied together. The mean difference in salinity was 0.03 (SD = 0.02) and the mean difference in temperature was 0.02°C (SD = 0.05), which is better than the accuracy of 0.1 PSU and 0.05°C specified by CastAway specifications.

In general, there was a smaller offset between salinity values measured by CastAway CTD (after correction for salinity offset) and WC tags (not significant; two-tailed paired t-test; $p = 0.52$, $df = 212$), compared to the SMRU tags (significant; two-tailed paired t-test; $p<0.001$, $df = 39$). The WC tags measured an average difference of −0.04, 0.007 and 0.03 PSU compared to the CastAway CTD (Table 2, Fig. 3). SMRU tags all measured slightly higher salinity offset than the corrected salinity values measured by the CastAway, with average offsets of 0.06–0.08 PSU (Table 2, Fig. 3). No corrections were applied to the measurements reported by the tags.

Temperature measurements by the WC tags measured offsets of 0.004–0.01°C compared to the calibrated CastAway CTD, and were not significantly different (two-tailed paired t-test; $p = 0.14$, $df = 212$) (Table 2, Fig. 3). The temperature from the SMRU tags compared to the CastAway CTD measured offsets of 0.1-0.06°C and was significantly different (two-tailed paired t-test; $p = 0.001$, $df = 39$) (Table 2, Fig. 3).

3.2. Accuracy in measurements

When comparing each pair of salinity and temperature measurements taken by the SMRU and WC tags at the same position and depth, the SMRU tags measured increasingly higher salinity compared to the WC tag over the range from 32.3 to 34.1 PSU (Fig. 4A). An example of a measured salinity depth profile is shown in Fig. 4C, where there is an offset at 34 PSU of ~0.05 PSU between the two tags. For the temperature, the SMRU and the WC tag provided similar readings for temperatures colder than 0°C and depths <120 m, while the difference increased for unknown reasons at deeper depths (Fig. 4B and D).

Conductivity measurements were calibrated for WC and SMRU tags in the laboratory before deployment, where the average error in conductivity measurements was 0.019 (SD = 0.007) mS/cm (SD) for the WC tags and 0.005 (SD = 0.003) mS/cm for the SMRU tags, indicating higher accuracy and better repeatability for SMRU tags. If conductivity has an error of 0.01 mS/cm, the salinity will change with ~0.01 PSU (when measured at 0 atm); therefore, the mean deviation values detected for WC and SMRU tags will have a small effect on the calculated salinity. Additionally, an increase in temperature of 0.01°C will result in a decrease in the calculated salinity of ~0.01 PSU, and vice versa. The SMRU tag had an average temperature offset of 0.1 ± 0.2°C (SD) and WC of 0.004 ± 0.0004°C (SD) compared to the CastAway CTD. Thus, the temperature deviations in the SMRU tags would have an impact on the calculated salinity, whereas the small temperature deviation in WC tags would not impact the calculated salinity.

3.3. Performance of the two tag types

The eight whales (5 WC and 4 SMRU tags, incl. one whale with two tags) that provided position data moved extensively throughout the Baffin Bay region over a stretch of approximately 3000 km during a period when ice conditions were changing from dense pack ice to open water (Fig. 5). During May, the whales either stayed around the restricted coastal open water areas in West Greenland or moved to the northern part of Baffin Bay passing through what appeared in satellite imagery to be almost complete ice cover. In June the whales chose different migration routes by either crossing west to Canada in heavy ice, moving north in coastal water along West Greenland or staying within open water in northern Baffin Bay. In July, the ice was mostly gone, and one whale stayed in Northwest Greenland, while others moved south along Baffin Island in Canada. In August, the whales were spread along the east coast of Baffin Island and one whale went into Prince Regent Inlet (Fig. 5).

The WC and SMRU tags deployed on bowhead whales relied on reception of tag transmissions during surfacing events when one or more Argos satellite receivers passed overhead. The position of the tag on the whale was therefore critical. It was expected that the WC tags would collect and transmit 4 profiles per day while the SMRU tags collected 24 profiles per day. In reality, on average two of the potentially four profiles were received from the WC tags (51% ± 35% SD), while four of the potentially 24 profiles were received from the SMRU tags (17% ± 25% SD).

Two of the five WC tags (tags 170751 and 170752) were deployed low on the whales, which likely reduced the chance of successful transmissions to Argos. This resulted in the average number of daily

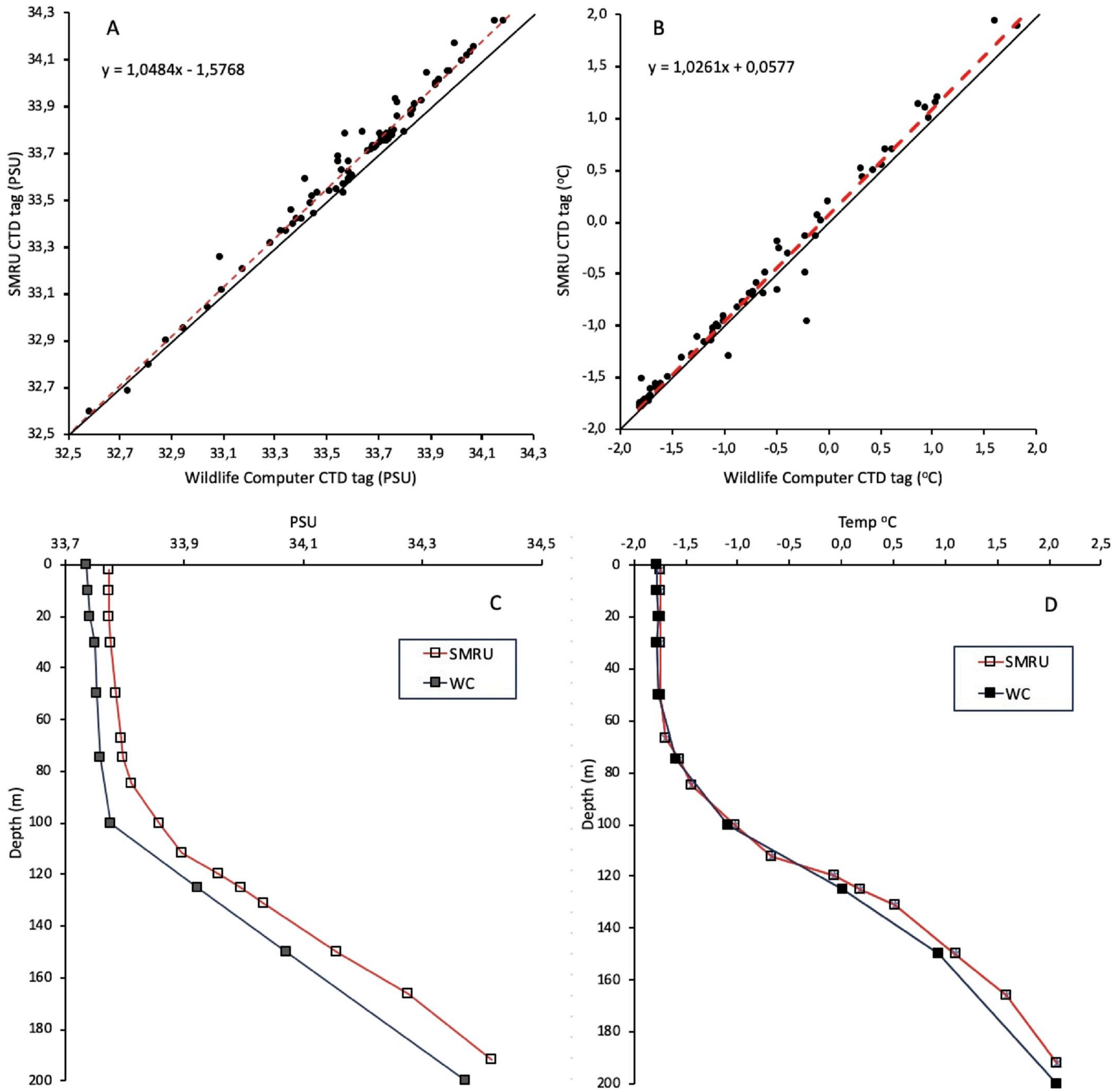

Fig. 4. Salinity (A) and temperature (B) comparisons between the WC 170750 and SMRU 170835 tags for all paired data collected during the same dive and depth. Black line is the orthogonal and the red stippled line is the linear regression. C) Example of a salinity profile from the two tags. D) Temperature measured by the two tags for the same dive as in C. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

received transmissions for the same profile to be <2 (1.7 ± 1.0 SD and 1.1 ± 0.3 SD for 170751 and 170752, respectively, data not shown) per profile. For the three other tags, the number of successful transmissions per profile was on average >2. On average, 0.9 and 0.3 profiles were received by Argos satellites per day for tags 170751 and 170752, respectively, while the other three WC tags transmitted 2.5–3.7 profiles per day. For WC tag 170754, something detrimental happened to the salinity measurements on 18 May 2017 when the received values turned unrealistically low (~10 PSU). This may have been caused by the electrode cell being damaged by ice, although that would more likely result in higher salinity values according to the manufacturer. Alternatively, something got stuck in the glass tube containing the electrodes, corrosion or biofouling of the electrodes, or loosening of the metal coating of the electrodes could have caused erroneous readings. All other functions of the tag were operating until the tag stopped transmitting on 11 October 2017.

At least one of the SMRU tags was also placed low on the whale, which likely prevented or reduced the transmission of data. SMRU tag 170837 was placed too low on the whale and never transmitted, while 170836 was deployed when the whale turned, and we were unsure where the tag was placed. Tag 170836 had the longest transmission period of all the SMRU tags and lasted for 126 days, but only 16 profiles were received with only 9 including corresponding Argos positions. Poor performance was also seen for SMRU tags 170834 and 170835, placed low and high on the whale, respectively. SMRU tag 170833 provided on average 13.0 CTD profiles per day and had a higher percentage of better

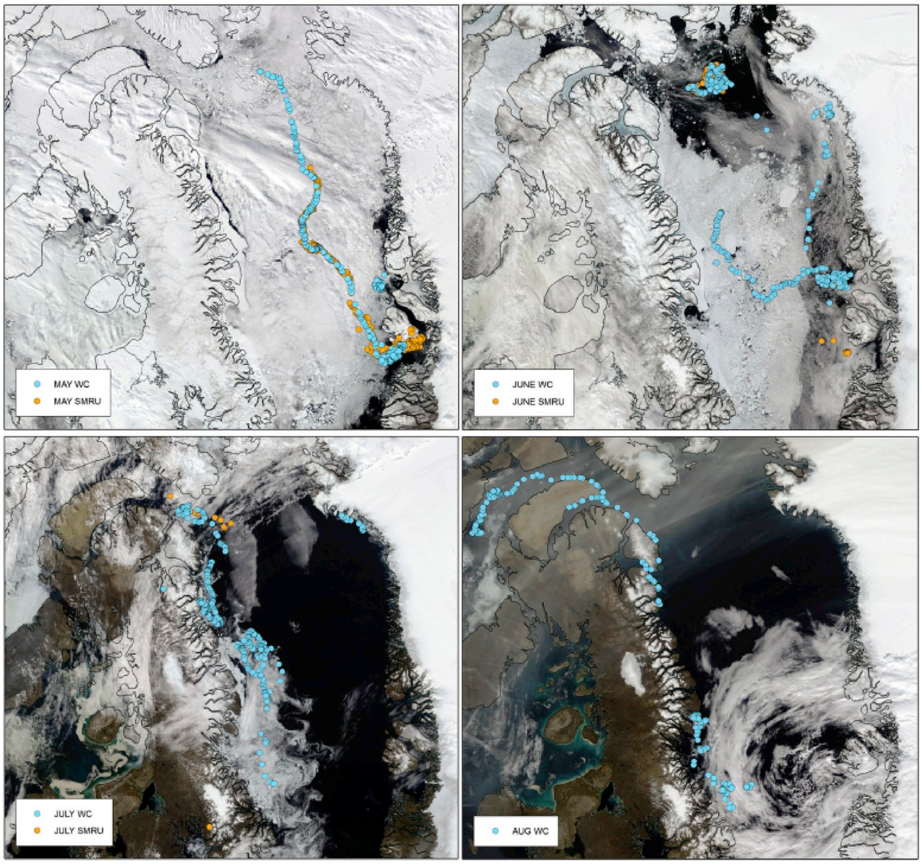

Fig. 5. Satellite images showing changes in sea ice cover in the study area. The day closest to the middle of the month and with the least cloud cover was selected from May to August (https://worldview.earthdata.nasa.gov/). GPS positions from the bowhead whales tagged with WC (blue dots) and Argos positions provided by the SMRU (orange dots) tags are super imposed on the satellite images. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Argos location classes than the other tags. Unfortunately, this tag stopped transmitting after 8 days.

Because each Argos message can only contain up to eight salinity and temperature pairs, 10% of the total profiles from the five WC tags were incomplete as only temperature and salinity measurements from depths of ≥150 m were received. It was only possible to detect incomplete profiles by studying profiles that only contained data from dives ≥150 m. Therefore, we may expect that a similar number of what appears to be shallow profiles (i.e. lack of data >150 m) are also incomplete, i.e. about 20% of the profiles in total. The profiles from the SMRU tags were generally shallower when comparing data from the two tags deployed on the same whale (WC 170750 and SMRU 170835), which indicates that the deeper parts of the SMRU tag profiles were more often missing.

3.4. Performance of the two tag types deployed on the same whale

When comparing the longevity of the two tags deployed on the same whale, the WC tag transmitted data for 109 days until 23 August with only three days of no transmissions towards the end of the period, while the SMRU tag transmitted for 53 days until 29 June, during which there were transmission gaps of 9 and 15 days for unknown reasons (Table 1 and Fig. 1). Within the period when both tags were functioning, the WC tag had a better performance than the SMRU tag with regard to number of CTD profiles received (135 vs. 80), equalling 2.8 and 1.5 CTD profiles received per day, respectively. Because of the antenna angle on the SMRU tag and the tag orientation on the swivel plate the antenna points slightly downward at the surface. Because of this configuration, the SMRU tag transmissions may have been compromised. In future tag design, we would recommend the antenna be placed closer to the anchor shaft, coming straight up from the tag, to keep the antenna away from the water when the tag swivels down at the surface (Fig. 1 and 2). Both tag types were expected to have a battery life of approximately 150 days but the longest deployments of all tags were 155 (WC) and 126 (SMRU) days and none of the tags were low on battery during the last transmissions.

A cross section of the salinity and temperature regime in Baffin Bay and adjacent waters collected from the WC tag between 7 May and 23 August 2017, demonstrated the contrast between the warm saline water at depths >100 m in eastern Baffin Bay in relation to the colder less saline water in western Baffin Bay and the Canadian High Arctic (Fig. 6A and B). Furthermore, the profiles show that surface waters (<50 m) were warmer in the western region from solar heating during summer. From both salinity and temperature profiles, it is evident that data from the WC tag provided better coverage, both in time and depth, than the SMRU tag (Fig. 6C and D).

The Argos location class data for the two tags on the same whale showed that the SMRU tag transmitted approximately 9 positions per day with a slightly higher percentage of the least accurate Argos location class B, whereas the WC tag transmitted approximately 28 positions per day and had a correspondingly higher percentage of location class A (data not shown). All tags that transmitted for more than two weeks and provided at least one position per day had a very low frequency of high accuracy positions (0–2.6% location class 1–3 positions, i.e. <1/day, Table 1).

For the shallower profiles, the SMRU tag had a higher vertical resolution, with more data from the depths in the upper part of the water column (10 and 20 m). However, no data were available from the SMRU tag for depths >200 m even when the WC tag provided data for 200 to 300 m in the same region (Fig. 6).

4. Discussion

This study demonstrates the feasibility of deploying CTD tags on large cetaceans, the limitations of tag transmission longevity, and the

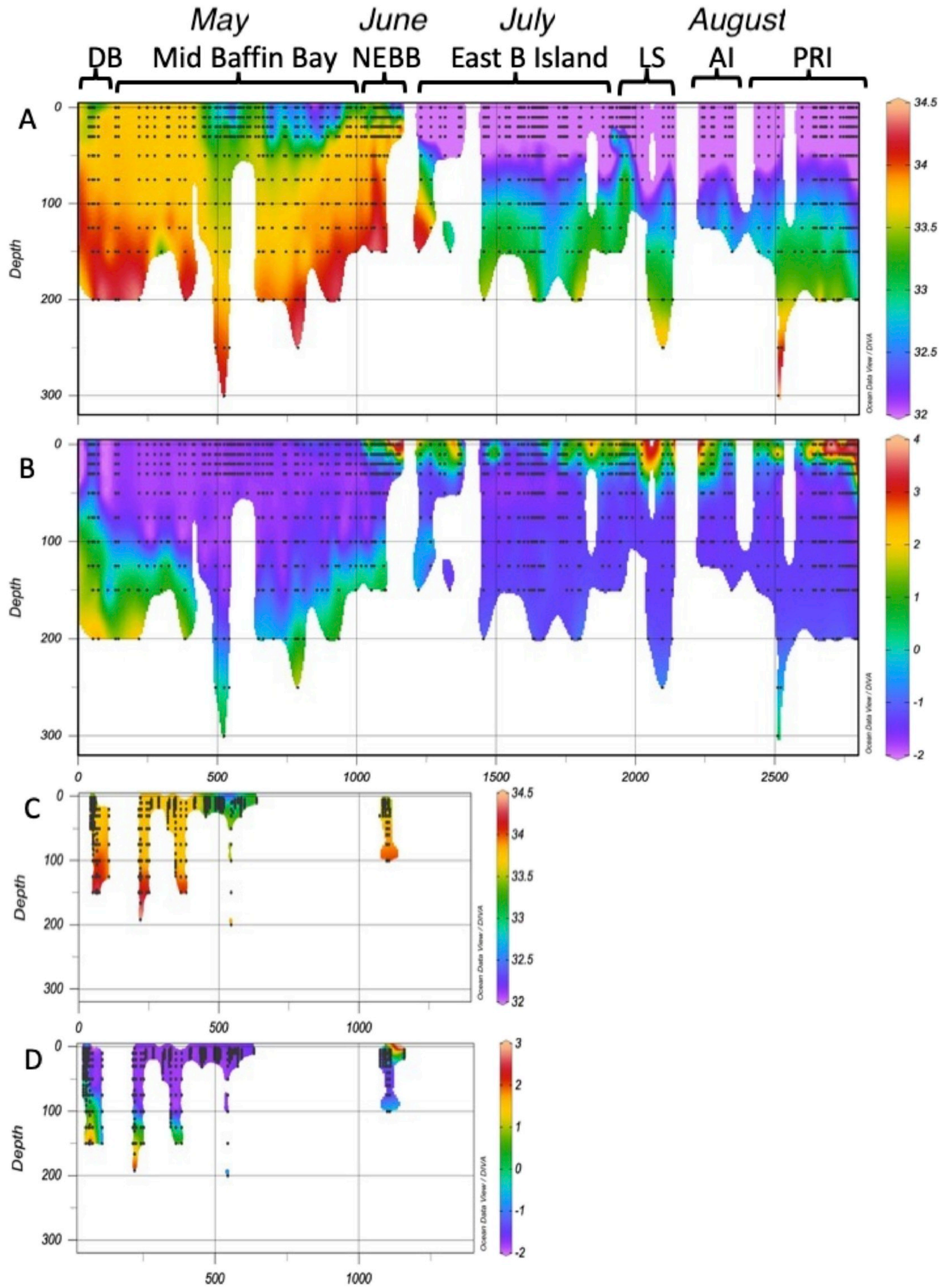

Fig. 6. Salinity and temperature profiles from the bowhead whale tagged with WC 170750 (7 May to 23 August 2017; A, B) and SMRU 170835 (7 May to 29 June 2017; C, D) tags. The upper x-axis shows month and region and the lower x-axis the distance in km since departure from Disko Bay. A) Gridded contour plots of salinity for the entire track from Disko Bay (DB), through Mid Baffin Bay, to Northeast Baffin Bay (NEBB), along Northeast Baffin Island (East B Island), into Lancaster Sound (LS), into Admiralty Inlet (AI) and west into Prince Regent Inlet (PRI) where the tag (WC 170750) stopped transmitting profiles on 23 August 2017. See also track in Fig. 1. B) Temperature plot of the same profiles as in Fig. 6A. C) Gridded contour plots of salinity for the entire track of SMRU 170835. D) Temperature plot of the same profiles as in Fig. 6C.

sensitivity of the tag placement on the whales. Both tag types provided useful oceanographic data from a remote Arctic region during a period in which sea ice conditions prevented standard ship-based oceanographic sampling. The new electrode-cell CTD tag developed by Wildlife Computers and the existing inductive-cell SMRU tag were compared. However, since this comparison is only based on five WC tags and five SMRU tags, one of which never transmitted and at least one with low placement on the whales, the results should be interpreted with caution.

Boehme et al. (2009) reported an accuracy of salinity and temperature measurements of ±0.02 PSU and better than ±0.005°C, respectively, for the SMRU tag. Boehme et al. (2009) conducted experiments to investigate the effect of interference of the external field of the inductive cell sensor to the external environment and found that if the SMRU tag was in direct contact with an object (in this case a calibration tank wall), the resulting salinity values were up to 0.5 PSU lower than the actual values. It is unknown if the deployment anchor and plate or the mass of the bowhead whale affected the field of the inductive cell sensor and caused the slight offset detected in the salinity measurements. However, it has been proven that both the temperature sensor and conductivity cells on similar CTD tags (SMRU) are affected by a thermal mass-induced error when deployed on elephant seals (Siegelman et al., 2019) and when tested *in situ* at high temperature gradients (Mensah et al., 2018). These studies therefore suggest post-processing data to correct for such thermal mass-induced errors. Another potential error for both tag types is the thermistor response time that for fast moving animals require fast thermistor readings when passing through different water masses.

Only eight temperature and salinity pairs were transmitted to Argos in any given transmission. The choice of sampling depths will therefore be a compromise between high vertical resolution, target depth of sampling and the desire to receive complete profiles. It is therefore uncertain if allowing the tag to transmit more profiles during a day will result in more CTD data being received. For example, the SMRU tags were programmed to collect and send 24 profiles every day, but only a fraction of the profiles was received, though still resulted in more profiles received compared to the WC tags. The WC tags only collected 4 profiles per day and two profiles were received on average. The two tag types may therefore be reprogrammed in the future to optimize the number of representative profiles.

None of the tags ran out of battery power according to the voltage readings in the data received during the deployments that lasted from 0-155 days. It is not possible to determine why deployment lengths varied but possible explanations include tag loss, tag failure, and poor placement preventing transmissions. To take full advantage of the battery, WC tags could be programmed to collect and transmit more profiles per day, use a higher Argos transmission rate than the 45 s used in this study, increase the number of times a profile is transmitted, and provide more accurate time stamps. The SMRU tags could probably also benefit from using a higher Argos transmission rate (i.e. <45 s) and increasing the number of times each profile is transmitted. This should ensure a higher number of received CTD profiles with higher spatial and temporal resolution and precision of the data. However, as bowhead whales can be submerged below 2 m for about 73% of the day (Rekdal et al., 2014), there is a limit to how many transmissions can be sent to the satellites. Increasing the transmission rate, which is possible upon receiving special permission from Argos, may increase the number of received messages and number of profiles, provided that the tag comes out of the water, but it will also shorten the battery life of the tags.

The WC tag provided Fastloc GPS positions, which can increase the accuracy of the location of profiles, and is especially important when correlating profiles to real-time prey patch identification or specific submesoscale oceanographic features. However, the greater accuracy of GPS over Argos is only advantageous if the GPS location is acquired soon after a qualifying CTD profile has been obtained. With current time coding in the WC tags ($\pm$30 min), it may be just as accurate to locate a profile using Argos locations (0.5–10 km depending on location class; Costa et al., 2010), as the whale may move up to 3.6 km in 30 min.

Comparing the performance of two tag types deployed on large cetaceans in polar regions is difficult due to variability in the placement of the transmitter and antenna, the behavior of the whale, and sea ice conditions. In this study the tags were deployed with an 8 m long pole from a small dinghy with somewhat uncertain precision in placement on the back of the whale. Subsequent photographic documentation showed the ideal placement high on the back of the whales for two WC tags and two SMRU tags, but how exposed the transmitters were during normal surfacing is unknown. Adding to the difficulty, the antenna orientation and stiffness and material of the antenna varied between the two tag types. The soft whip antenna of the WC tag points straight up, while the stiff thicker SMRU tag antenna points backwards at a 45° angle. The tag can swing 360° around the axis of the anchor to point in the same direction as the whale in the water or downwards when at the surface out of the water due to the weight of the tag in air. The antenna on the WC tag had a more vertical position than the SMRU tag and therefore may have been dry sooner and longer resulting in better transmission conditions. However, the WC antenna was more flexible than the SMRU antenna, so the actual influence of antennas on the transmission performance is unknown. Experimentation with antenna design may be a productive avenue toward improving tag performance.

Salinity varied between 32 and 35 PSU within the study area at depths down to 300 m. Within this depth interval and salinity variation the observed accuracy in temperature and salinity readings are sufficient to identify water mass properties and stratification relevant to biology. In addition to the accuracy of the sensors, the water flow through the sensor as a result of how the tag is attached to the whale and how this might change over several months of deployment all together makes it challenging to know the exact accuracy of the measurements, why the tags performed differently on the same whale and whether there was drift in the measurements over time. However, using these tags in oceanography when monitoring the deep ocean general circulation (depths deeper than 1800 m), may not be appropriate, as accuracy of $\pm$0.002 PSU is needed, since these water masses change very little, and even small changes can have significant implications on the world's climate (Pawlowicz, 2013). This emphasizes the importance of choosing the right instruments with required resolution and accuracy depending on the study area and the target species, the questions asked, size of the instruments and cost of instruments.

Despite variations in tag performance, the data provided by these tags as whales crossed Baffin Bay in spring 2017 demonstrates that bowhead whales equipped with CTD satellite transmitters can provide data on the water column properties in ice covered areas that would otherwise require ice-breaking oceanographic vessels or moorings. Because of logistical difficulties, only 54 CTD casts are listed for the month of May over the past hundred years in the oceanographic database for Baffin Bay (Bedford Institute of Oceanography, http://www.bio.gc.ca/science/data-donnees/base/run-courir-en.php). Deployment of CTD tags on whales, regardless of the manufacturer, offers a promising opportunity for understanding whale ecology and oceanography from regions and seasons where traditional oceanographic measurements would otherwise be difficult.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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