# Salinity and temperature structure of a freezing Arctic fjord—monitored by white whales elphinapterus leucas)

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[1] In this study we report results from satellite-linked conductivity-temperature-depth (CTD) loggers that were deployed on wild, free-ranging white whales to study the oceanographic structure of an Arctic fjord, Storfjorden, Svalbard. The whales dove to the bottom of the fjord routinely during the study and occupied areas with up to 90% ice-cover, where performance of conventional ship-based CTD-casts would have been difficult. During the initial period of freezing in the fjord, over a period of approximately 2 weeks, 540 CTD profiles were successfully transmitted. The data indicate that Storfjorden has a substantial inflow of warm North Atlantic Water; this is contrary to conventional wisdom that has suggested that it contains only cold Arctic water. This study confirms that marine-mammal-based CTDs have enormous potential for cost-effective, future oceanographic studies; many different marine mammal species target oceanographic discontinuities for foraging and thus may be good 'adaptive samplers' that naturally seek areas of high oceanographic interest. *INDEX TERMS:* 4294 Oceanography: General: Instruments and techniques; 4536 Oceanography: Physical: Hydrography; 4219 Oceanography: General: Continental shelf processes; 1635 Global Change: Oceans (4203); *KEYWORDS:* CTD-measurements, Arctic oceanography, marine mammals, satellite telemetry. **Citation:** Lydersen, C., O. A. Nøst, P. Lovell, B. J. McConnell, T. Gammelsrød, C. Hunter, M. A. Fedak, and K. M. Kovacs, Salinity and temperature structure of a freezing Arctic fjord—monitored by white whales *Delphinapterus leucas*), *Geophys. Res. Lett.*, *29*(23), 2119, doi:10.1029/2002GL015462, 2002.

## 1. Introduction

[2] Global oceanographic and climate models predict that the most extreme and acute effects of global warming will occur in the Arctic; and indeed oceanic environmental conditions in the Arctic have shown large changes during the last few decades. North Atlantic Water (NAW) making its way into the Arctic is warmer [*Grotefendt et al.*, 1998] and Arctic sea-ice is thinning [*Rothrock et al.*, 1999] and retreating northward [*Johannessen et al.*, 1999]. Model results suggest that the observed Arctic Ocean warming is caused by an increased transport of NAW through both the Barents Sea and Fram Strait [*Zhang et al.*, 1998]. However, it is not clear whether these changes are due to actual long-term climate change or natural decadal variability [*Grotefendt et al.*, 1998]. Tracking these changes and determining their source will require refinements to current models and their predictions, via improved water temperature and salinity databases from crucial areas where important hydrological phenomena occur, such as regions of deep-water formation or along ice edges. Storfjorden, Svalbard (Figure 1), is an excellent location for studying several of these processes. It is known to be a site of deep-water formation and it has extensive, seasonal ice cover [*Schauer*, 1995; *Haarpaintner et al.*, 2001a]. Deep and intermediate water is formed in the Arctic when dense shelf water sinks down continental slopes as cold plumes [*Jones et al.*, 1995]. Dense shelf waters are themselves formed when the process of ice formation, and concomitant brine release, occur in regions where offshore winds keep coastal polynyas open [*Martin and Cavalieri*, 1989]. The Storfjorden polynya is an example of such a coastal polynya [*Haarpaintner*, 1999; *Haarpaintner et al.*, 2001b]. CTD-measurements from areas such as Storfjorden are crucial for tracking and understanding ocean systems, but these measurements are expensive to obtain and depend on ships that operate primarily during summer and autumn in open water areas in Arctic regions or mooring which are also costly and difficult logistically in ice-covered areas. However, deployment of satellite-linked CTD-loggers on ice-adapted marine mammals may be an effective means to obtain large amounts of data from areas where oceanographic sampling is logistically difficult, in a cost-effective manner. Several marine mammal studies have collected temperature information concurrently with dive data [*McCafferty et al.*, 1999; *Campagna et al.*, 2000; *Boyd et al.*, 2001] and one study has collected temperature profiles in association with position information based on satellite tracking [*Boehlert et al.*, 2001]. Although these studies have provided valuable data they required recapture of the study animal to collect the temperature data and conductivity measurements were not attempted in these investigations.

## 2. Methods

[3] In this study we deployed a newly designed, version of the Sea Mammal Research Unit's (SMRU, University of St Andrews, Scotland), Argos-linked (System Argos, Toulouse France) satellite-relayed, data logger (SRDL). Normal SMRU SRDLs relay information on the movements (geographic position) and diving behaviour (depth) of marine mammals [*Fedak et al.*, 2001, 2002], but for the purposes of this study we integrated onboard oceanographic-quality conductivity-temperature (CT) sensors (Compact CT, Alec Electronics, Ltd; Kobe Japan) in addition to the basic package (Figure 2). The specified accuracies of the CT sensors were ±0.01mS/cm and ±0.01 C. These values were confirmed by a series of labo-

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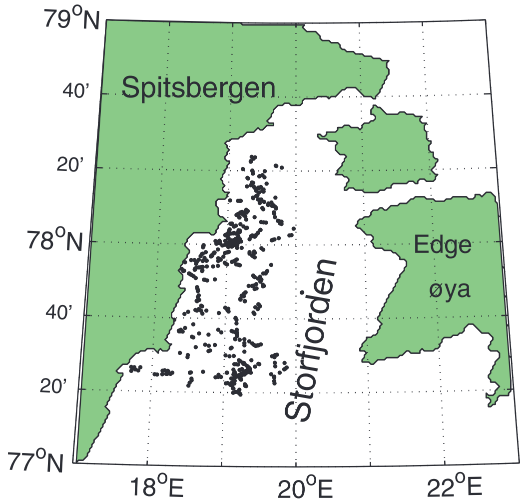


**Figure 1.** Distribution of CTD-casts performed by a white whale during the initial period of winter ice-formation in Storfjorden, Svalbard, 7–24 November 2001. Each dot (N = 540) represents the location of a CTD profile collected by a satellite relayed data logger.

ratory and field tests using water samples that were calibrated with a Guildline 8400B salinometer (Guildline Instruments Ltd., Ontario, Canada) and an unmodified Compact CT. Depth was measured by the pressure transducer and circuitry onboard the SRDL (KellerPA-7, Keller, Winterthur, Switzerland). The output from the depth transducer was sampled with 16bit A/D that, after calibration and offset correction provided 20 cm accuracy. Depth and CT sensors sampled data within approximately 10 ms of each other in each sampling interval (i.e. virtually simultaneously and at the same location given that the animals change depth at about 1.5 m/s).

[4] The SRDLs were programmed such that the depth and CT sensors sampled once every second during the ascent phase of dives (upcast) on a schedule that was designed to provide data coverage throughout the 24-hour cycle, from the deepest dives performed. The day was divided into four 6 h blocks, beginning at midnight, GMT. The SRDL sampled CT data, starting at the bottom of the first six dives of the period that were deeper than 45 m. It then performed additional CT data collection in any subsequent dives within the 6 h period that were deeper than these first records. Transmission bandwidth constraints, resulting from the interaction of Argos transmission requirements and the limited time spent at the surface by the animals, meant that data profiles had to be compressed [*Fedak et al.*, 2001, 2002]. Therefore, upon completion of each upcast, a "broken stick" compression algorithm (as used in XBT casts [*Rual*, 1996]) was applied to identify and retain the 12 most important inflection points in the temperature, conductivity and computed salinity profiles. This method first applies a median filter with a 5 m window, followed by a Hanning smoothing filter (11 m window) prior to the broken stick reduction method. At the end of the 6 h period, temperature, salinity and conductivity profiles from the 6 deepest dives were put into a buffer from which they were chosen at random for transmission. The SRDL was programmed to send data for up to 100 days (likely duration of attachment) during which time up to 500 transmissions per day could be sent. However, only a fraction of these were received each day because of satellite availability and transmission interruptions when the antenna is submerged.

[5] White whales were chosen as the deployment "platform", because previous satellite tracking of white whales in the Storfjorden area has shown that they stay in coastal waters during summer, but that they are forced offshore when areas become ice-covered during autumn and winter [*Lydersen et al.*, 2001]. White whales are known to utilize ice edges as well as areas with high ice cover [*Richard et al.*, 2001a]. This species is capable of maintaining sustained, benthic diving [*Suydam et al.*, 2001] and routinely dives to depths that are much deeper than the deepest areas of the Barents Sea in other parts of their circum-Arctic range [*Richard et al.*, 2001b; *Suydam et al.*, 2001]. Their resident status in the area of Storfjorden and their body size made them good candidates for carrying CTD loggers. They are small enough to capture and handle, while they are large enough to carry early-generation CTD tags without undue stress. Two white whales were captured in shore-set nets in the northern part of Storfjorden 17–18 October 2001, and a SRDL was attached to each animal's dorsal ridge using standard methods [*Martin and Smith*, 1992]. Only one SRDL was still sending data when ice began forming in Storfjorden in November. The results presented below originate from this tag, which collected data for 63 days.

## 3. Results and Discussion

[6] During the initial freezing period in the fjord from 7–24 November 2001, CTD-profiles were sent from 540 geographic positions (Figure 1), covering an area of ~8,000 km$^2$. During this period the whale occupied areas that had 4/10th to 9/10th ice-cover. The east-west transect shown in Figure 3 is from 18 November, while the north-south transect (Figure 3) is a composite picture of data collected during the period 10–20 November. A striking feature in both transects is the substantial heat in the water column (Figure 3). The warmest water is found in the deepest parts of the fjord, overlaying a layer of cold, more saline water, which was probably a remnant from dense water formed the previous winter. The most probable explanation for the warm tongue of water is that it is an intrusion of warm NAW from the south.

[7] *O Dwyer et al.* [2001] demonstrated that there is a topographically steered cyclonic circulation in Storfjor-

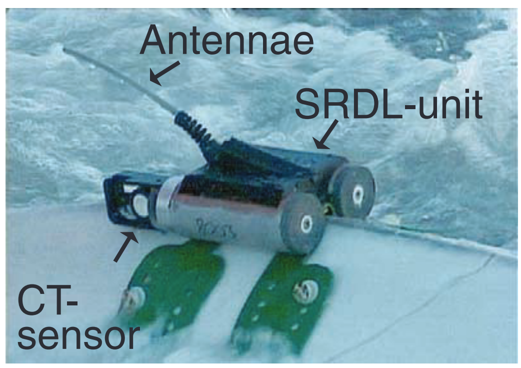


**Figure 2.** Satellite relayed data logger (SRDL) with integrated conductivity-temperature (CT) sensor that was deployed on a white whale. The unit is 15 cm long, 11 cm wide, weighs 650 g and displaces 490 g of water.

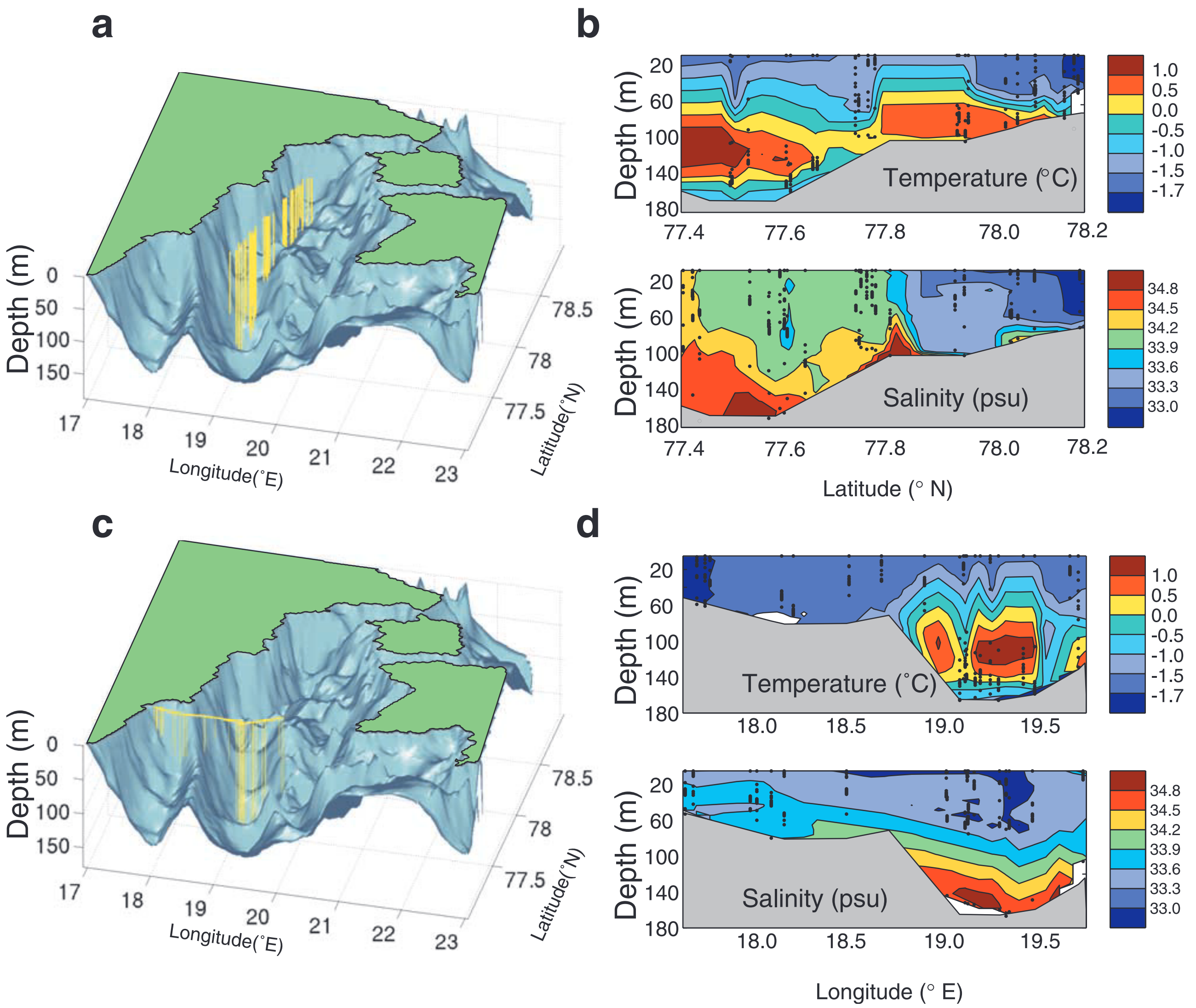


**Figure 3.** CTD transects in Storfjorden, Svalbard. The maps show the locations of selected dives performed by a white whale (each yellow spike represents a dive; the length of the spikes represents dive depth) carrying a CTD tag, along a north-south transect (a) and an east-west (c) transect superimposed on a three-dimensional bathymetric map of Storfjorden, Svalbard. CTD-casts produced during these dives are the basis for the temperature and salinity profiles shown in b and d respectively. Each dot in b and d represents a location where a CTD-measurement was taken.

drenna, just south of Storfjorden (Figure 4), and suggested, based on temperature and salinity data, that the water masses in this trough were a mixture of NAW and Arctic water (AW). Water masses situated above bottom depths of 100–150 m in Storfjordrenna appear to flow unhindered, and results from the current study strongly suggest that warm, southern water could also be topographically steered northward into Storfjorden (Figure 4), as well as being directed back through the trough. Although authors of previous work did not specifically mention this possibility, warm temperatures have been recorded previously from Storfjorden; from CTD casts taken in the summer [e.g. *Midttun*, 1985], but the origin of the responsible warm water mass received no speculation. The actual heat content of the water that makes its way northward will depend on how much of it is NAW, which will probably vary seasonally and inter-annually. Our oceanographic data, from the white whale's CTD-tag, show that this northward flow has the potential to have a large influence on the heat content of the water column and therefore also impact ice formation in the Storfjorden polynya area. Previous estimates of brine formation in Storfjorden have assumed the entire water column is near the freezing point in the fall and early winter [*Haarpaintner et al.*, 2001a], and that the water masses in inner Storfjorden consist mainly of AW [*Haarpaintner et al.*, 2001c]. This is clearly not the case and future oceanographic models of Storfjorden need to take into account the intrusion of NAW from the south.

[8] In this study we have demonstrated that marine mammals can be used to collect high quality CTD data from areas where oceanographic sampling is logistically difficult. The information from this first deployment has lead to new insights into oceanographic processes. Depending on the desire for specific sorts of oceanographic data and water-column profiles, observation programs can utilize suitable "support staff" to carry satellite-linked CTD equipment (e.g. ringed seals, bearded seals, hooded seals, white whales etc. could sample different Arctic environments). Many different species of marine mammal have been shown to target oceano-

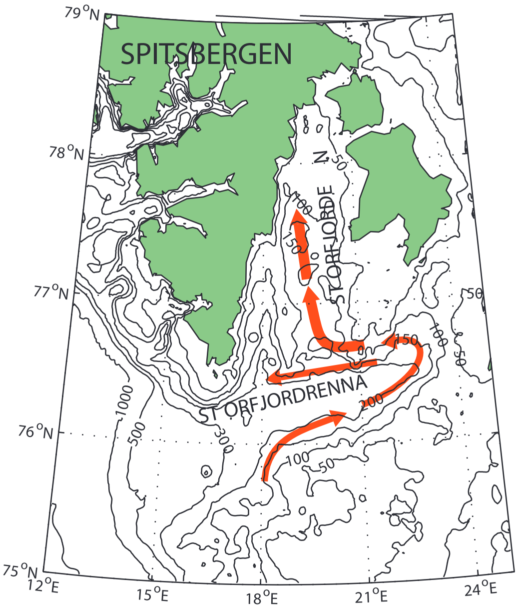


**Figure 4.** Circulation pattern for Storfjordrenna and Storfjorden. There is an anticyclonic circulation in Storfjordrenna [*O Dwyer et al.*, 2001] that results in the water between 100 and 150 m being topographically steered northward into Storfjorden (this study). This water is a mix of warm North Atlantic Water and cold Arctic water.

graphic discontinuities for foraging and thus may be good 'adaptive samplers' that naturally seek areas of high oceanographic interest [*Croll et al.*, 1998]. In addition to providing data suitable for oceanographic studies, the information gleaned from CTDs based on marine mammals will also provide very direct habitat information that is hitherto largely unknown for these animals. Improved technology, including marine applications of GPS and use of Iridium transmission are likely to be available in the not-to-distant future, which will increase position accuracy and the volume of potential data transmissions from marine mammal CTD deployments.

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