Anonymous Referee #1

As a companion to the lead author's paper published (with some different co-authors) in Nature late last year (DOI:10.1038/s41598-017-15486-3) , Stranne and colleagues present what I would term a technical-demonstration paper showing how the depth of the ocean surface mixed layer may be sensed acoustically. The demonstration is set in the Arctic using data from two icebreaker cruises that sampled in both ice-covered and open-ocean regions at various vessel speeds. While the spin is largely positive, several limitations to the technique are discussed that will constrain where and when the approach will yield scientifically useful information.

Apologies for the cumbersome terminology, but I believe it is important to distinguish between the ocean surface "mixed layer" and the "mixing layer." I consider the latter to be the span that is actively being stirred vertically at the time of observation; it can be (and is frequently) thinner than the mixed layer whose base might mark the maximum depth of turbulent stirring in the past.

We agree with the reviewer on the terminology. Here we are following the definition of De Boyer, where the threshold value is chosen as to avoid the shallower mixing layer, caused by diurnal variability. This is now explicitly stated in the revised ms.

My sense is that the acoustic technique presented by Stranne and colleagues preferentially identifies the base of this deeper, possibly remnant surface mixing layer (in part due to the typically larger vertical gradient at the mixed layer base and its greater depth - at least in the data sets presented that were acquired from a large-draft vessel). Either way, I believe it is important to recognize this distinction and discuss if/how each class of "mixed" layer might be observed acoustically.

We agree with the reviewer. We have added a brief discussion on the mixed layer definition and how we seem to be imaging the "same" MLD with the acoustic method as we (and De Boyer) derive from CTD data using the threshold method.

One reason for worrying about (weak) stratification within the surface mixed layer is its possible manifestation of restratification processes including submesoscale instabilities (see Timmermans et al., 2011, doi: 10.1175/JPO-D-11-0125.1). Indeed, restratification processes are just as important as the surface stress and buoyancy forcing cited in the paper's introduction (page 1, line 41) in controlling mixed layer depth.

This is a good point. In the revised ms we mention "lateral advection" in relation to buoyancy fluxes, with reference to the Timmermans paper, as suggested by the reviewer.

The authors employ the de Boyer Montegut et al. (2004) protocol (at times modified to use a smaller temperature difference criterion) to estimate the depth of the mixed layer depth in CTD data used as ground truth for their acoustic scheme. Adoption of a technique based on temperature is a bit odd for Arctic data since at cold temperatures, density is so strongly controlled by salinity.

The density threshold approach presented in the De Boyer paper was tested with close to identical results. We opted to use and display the results from the temperature threshold method, as it is simpler plus there are more temperature data available (in e.g. WOD) than there are salinity data, thus rendering this method more useful in a general sense. Note that the same problems we had with the

temperature threshold (we had to adjust it for the central Arctic Ocean) also showed up for the density threshold. This is now stated in the manuscript.

While I doubt it would change the main conclusions of the paper, it might be worth trying the Holte and Talley (JAOTech, DOI: 10.1175/2009JTECHO543.1) algorithm, particularly for those cases where there was disagreement between the methods

As is pointed out by the reviewer, the focal point of this paper is on the fact that we can observe the MLD acoustically with a high success rate. As this is mainly a methods paper, the comparison with different protocols for deriving MLD from CTD data is, in our opinion, of secondary importance. We hope that a larger acoustic data set (or a compilation of several acoustic data sets) will be used in the future to study these differences more systematically. Currently, the number of groundtruth CTD stations are far too few for any conclusions to be drawn in this regard.

I would also quibble with the exclusion of very shallow mixed layers in the analysis, though I certainly understand the constraints deriving from vessel draft and acoustic blanking period.

We determine the presence of an MLD from CTD data by visually inspecting the profiles (as explicitly stated in the original ms). Note that the visually determined MLD can be shallower than 10 m and for all these, the acoustic method is interpreted as failing (this caused more than 50% of the failures during the SWERUS cruise). This is explained in the second comment to Table 1 (double asterisk). If we were to consider only the failures where the MLD is deeper than 10 m, our statistics would look much more convincing.

In the summer Arctic sea ice zone, the upper ocean can be stratified all the way up to the ice-ocean interface. (Drainage of melt ponds is an important summertime stratification mechanism.) The authors show one such example in figure S1 but I worry such stratification is common throughout much of the Arctic in summer, and that observations from a deep-draft vessel will give biased results. Speaking of vessel draft, there is of course the strong possibility that ships disturb the near-surface stratification, introducing yet another sourceof error.

In terms of the acoustic method, the placement of the echosounder transponder on the vessel's hull defines an absolute limit in terms of how close to the sea surface we can make observations. As discussed in the ms, the pulse length puts an additional constraint. This is inevitable.

Regarding CTD data – the method of making CTD casts from vessels have been around for many decades, and the accuracy and problems involved with such data acquisition can be found in the literature. In the high Arctic Ocean, with engines turned off, and the vessel drifting with the ice at a typical speed of less than 1 m/s, the risk of the vessel itself interfering with the shallow stratification is limited. CTD operations in high waves can be problematic due to the mixing induced by the CTD rosette (moving up and down through the water column with the waves). This is rarely a problem in the Arctic, however, and most of our CTD data seem to be reliable up to one meter or so from the surface.

My final general comment concerns the interpretation of the acoustic observations, exemplified by the sentence on page 2 line 20: "The increased SNR of wideband echosounders have made it possible to map density stratification in the ocean." The authors don't actually invert their acoustic data to estimate the ocean density profile. Rather, it is my understanding that they equate regions of enhanced acoustic backscatter with regions of enhanced vertical density gradients, the one discussed here being the mixed layer base.

This is really a question of subtle semantics. It is true that we are not mapping the actual properties of the stratification, but we are mapping density stratification in the sense that we are observing the location of more or less sharp transitions between water masses of different density, in time and space.

I continue with more specific comments/suggestions:

Page 1 line 32-34: I note that light is also a significant factor impacting phytoplankton growth, which can be impacted by MLD and residence time for phytoplankton near the air-sea interface.

Light, oxygen and nutrients place important constraints on the primary production, but these are often indirectly controlled by the MLD, as noted by the reviewer. Here we state that the MLD is one of the main factors controlling the primary production, and we hope that the interested reader will go on to read the two papers that we cite (where other aspects on primary production are discussed in detail).

Page 1 line 47: the term "temporal sampling frequency" could be confusing - I initially thought of the sampling rate of the CTD instruments, not the time between vertical profiles.

We agree with the reviewer and we have now deleted the words "temporal sampling".

Page 2 top: I note that the remote sensing observations from the GRACE satellite mission are indicative of more than surface ocean properties.

Agreed. We have changed the sentence to "..essentially restricted to near sea-surface properties".

Page 2 paragraph starting with line 3: I found it curious that this brief history doesn't begin with echosounding to determine water depth. See http://oceanexplorer.noaa.gov/history/electronic/electronic.html

Here we present a brief summary of acoustic water column mapping specifically.

Figure 1 (and others): I found the quality of the figures in this pdf to be not as crisp as I like. I'm hoping this is just a consequence of the review copy that was made available to me and that the published document will be better (i.e., quality more like the similar figures in the lead author's recent Nature paper).

Yes, this is a PDF issue. We guarantee that figure quality will be acceptable in the final version.

Page 3 line 21: The authors might wish to temper this phrase: "Together, the SWERUSC3 and AO2016 expeditions spanned the breadth and depth of the Arctic Ocean..." No observations were obtained in the Canada Basin for example.

Actually, 3 of the total 21 CTD stations from the Arctic Ocean 2016 cruise were from within the Canada Basin (see Fig 1). We do agree with the reviewer, however, and have reformulated the sentence to "..spanned much of the breadth and depth…"

Page 4 line 38: "A CTD [profile] was collected..."

Fixed

Page 5 line 35: this sentence has no real content. Much better to make a technical statement and cite a figure in support.

We are not sure what the reviewer means by this comment. What kind of technical statement are we supposed to make? The figure represents our main result and different aspects of the figure are cited further down in the text.

Figure 2 and those similar: Please give the location and date that these data were collected. In this caption and those similar, panel B should, in my opinion, say CTD profile, not profiles, or CTD-derived temperature and salinity profiles.

Fixed

Page 6 line 11: "EK80 data [are] available "

Fixed

Page 8 line 3: might be good to note the different criteria for MLD used by these previous authors.

Fixed

In summary, I believe that after revision, this work will be suitable for publication in Ocean Science.

Anonymous Referee #2

This paper presents an interesting and concise account of an innovative acoustic method to detect with high spatial resolution the depth of the ocean mixed layer, or mixed layer depth (MLD), a quantity that is of interest for a number of practical applications in oceanography. It is shown, using acoustic mapping, in combination with CTD profiles, that reliable estimates of the MLD may be obtained using the former method. The main obstacles to reliable MLD estimates are very shallow MLDs (lower than 10 m), or the existence of excessive biological scatterers, which confuse the vertical distribution of the reflection coefficient, by introducing noise. The paper appears to be scientifically sound, and is clearly written, reporting novel results that are worthy of publication in Ocean Science. There are a few non-critical points (listed below) that I would like to see addressed before I can recommend acceptance. Therefore, at this point I recommend that the paper undergoes minor revisions.

Minor comments

1. Page 1, line 20: "These prerequisites [MLD well-defined and absence of biological scatterers] are often met in the open ocean". Given that the study focuses on the Arctic

Ocean, can the authors be sure that this remark is of general applicability, and not limited to that ocean? If not, then the necessary cautions should be noted.

We do not claim that these prerequisites are always met, but that they are often met. It is widely recognized that productivity is generally higher in coastal waters than in the open ocean, which is also consistent with what we see in our data (there are of course exceptions, for instance along the equator due to upwelling). This notion is supported by the difference between the estimated average primary productivity in the world oceans (~50 g C m^{-2} $year^{-1}$) and the estimated average primary productivity in estuarine waters (~250 g C m^{-2} $year^{-1}$), a factor of five.

From "Phytoplankton primary production in the world's estuarine-coastal ecosystems J. E. Cloern, S. Q. Foster and A. E. Kleckner".

2. Page 1, lines 27-28: "generated by wind stress and buoyancy fluxes at the air-sea interface", and lines 41-42: "The MLD is controlled primarily by surface stress (exerted by wind or sea-ice), buoyancy fluxes (heating/cooling, ice melt/formation, or precipitation/ evaporation), and dissipation". In this picture, the effect of waves is missing. It has been established that surface waves, through their interaction with the wind stress and generation of Langmuir circulations, exert a decisive control on MLD growth (e.g. Thorpe, 2004, Ann. Rev. Fluid Mech.). This should be recognized.

The primary cause for wave generation is wind stress, so waves and Langmuir circulation can be thought of as integral in the statement "surface stress (exerted by wind or sea-ice)".

3. Page 2, line 26: "ensonified". This word is probably unfamiliar to the readership of Ocean Science. Consider providing its significance on its first mention.

We agree with the reviewer and have now added a clarification.

4. Page 3, Figure 1: This figure looks somewhat fuzzy (I am not sure if this only occurs in the version available for review, as that happens in some journals). The green dots (particularly on the yellow track), and especially the blue dots, mentioned in the caption, have very limited visibility. Consider using different colours with a better contrast withthe blue background.

Yes, this is a PDF compression problem. We guarantee that the figures will look nicer in the final version. We have also improved the contrast between the different colors.

5. Page 4, line 13: "attitude", and line 23: "match-filtered": again, this terminology may not be familiar to the readers (it is perhaps over-technical), so provide a clarification of its meaning the first time it appears in the text.

These terms are only to be found in the methods section. While we agree with the reviewer that they are technical, it is likely that only readers that are specifically interested in these technical aspects of our method would go through these details.

6. Page 4, line 35: "Demer et al.", and page 5, line 2: "Lurton & Leviandier". These parts of the citations should not appear between brackets, as the corresponding references are incorporated in sentences. Please correct.

Fixed

7. Page 6, caption of figure 2: "Vertical magenta lines". These lines are rather difficult to discern in the blue background. Consider improving this aspect.

In the high resolution version of the figure, the magenta lines are easily discernable.

8. Page 6, paragraph between lines 20 and 27: The authors note that the criterion for detecting the MLD using CTD of using a temperature variation threshold of 0.2 degrees failed in the Central Arctic Ocean. Can they advance a physical interpretation for this behaviour, i.e., why in the Central Arctic Ocean and not elsewhere?

The simple explanation is that the temperature gradient between the mixed layer and the water mass beneath it is generally smaller. This is now stated in the text. However, the reason for this difference is a more complicated matter that is well beyond the scope of the present manuscript.

9. Page 7, figure 3: The horizontal scale of panel b in this figure appears no to be similar to that of panel a, but is not indicated. Please add that information.

The scale on the x-axis is "CTD observations" with equal distance between each observation. This has now been added.

10. Page 7, table 2: "rmsd". Not much is said in the text about how this quantity is defined and how it differs from the standard deviations in the two columns to the left. Please add that information.

The root-mean-square deviation is referring to the deviation between the two methods. The standard deviation represents the variability of the MLD observed within each method. We have now clarified this in the text.

11. Page 8, lines 19-20: "The acoustic method enables the study of internal waves propagating on the layer interface at the base of the mixed layer". What might generate these waves? Is there a possibility that the MLD measurements could be contaminated by waves generated by the remote interaction between the ship and the density interface at the bottom of the mixed layer (often called pycnocline)? It would be a good idea to discuss this aspect, as it might affect the proposed method in general (although not necessarily in the examples presented here).

We agree with the reviewer that it is possible that part of what we see, in terms of internal waves, might be generated by the vessel. We now discuss this possibility in the text. This would be a general problem for many ship-based observations, including observations made with CTD and free falling microstructure probes. In this study we settle with the fact that we can observe internal waves.

12. Page 9, line 11: "splitting/merging of layers". Can the authors be a bit more specific about what physical processes might cause this splitting/merging?

This is actually an open question, see Stranne et al. 2017.

13. Page 10, figure 6: This figure is presented as an example of measurements contaminanted by biological scatterers, which makes it difficult (or even impossible) to reliably determine the MLD using the proposed acoustic method. However, in the reflection coefficient graph shown in figure 6c it is still possible to distinguish the MLD as the depth below which the reflection coefficient starts to have a large variability. I wonder whether it would be still possible to usefully determine the MLD by appropriately exploiting that property?

This might indeed be a possibility. A similar approach has already been established: the gradient criterion method, see for example the De Boyer et al. 2004 paper where they review different methods.

14. Page 10, line 12: "rosette". This word is not used elsewhere in the manuscript, so consider replacing it by another, more standard word.

This is, as far as we know, the established term for the steel or aluminum structure on which CTD sensors and bottles are mounted.

15. Page 10, line 28: "lower success rate in coastal areas". Could this also be related to the greater abundance of biological scatterers in those regions? If yes, please adda comment explaining this.

Fixed

16. There are a number of figures (S1-S5) referenced in the text (page 6, lines 24-25; page 7, lines 3 and 11-12; page 8, line 44; page 10, lines 20 and 34), but not included in the manuscript. Is this just a referencing problem, or are those figures really omitted, in which case allusions to them would need to be removed, with some detriment to a few justifications in the text?

These figures are included in the Supplementary Information (hence the S in front of the figure number).

Acoustic mapping of mixed layer depth

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Abstract. The ocean surface mixed layer is a nearly universal feature of the world oceans. The depth of the mixed layer (MLD) influences the exchange of heat and gases between the atmosphere and the ocean and constitutes one of the major factors controlling ocean primary production as it affects the vertical distribution of biological and chemical components in near-surface waters. Direct observations of the MLD are traditionally made by means of conductivity, temperature and depth (CTD) casts. However, CTD instrument deployment limits the observation of temporal and spatial variability of the MLD. Here, we present an alternative method where acoustic mapping of the MLD is done remotely by means of commercially available ship-mounted echosounders. The method is shown to be highly accurate when the MLD is well defined and biological scattering does not dominate the acoustic returns. These prerequisites are often met in the open ocean and it is shown that the method is successful in 95% of data collected in the central Arctic Ocean. The primary advantages of acoustically mapping the MLD over CTD measurements are: (1) considerably higher temporal and horizontal resolutions and (2) potentially larger spatial coverage.

1 Introduction

The surface mixed layer is an important and nearly universal feature of the world oceans. It is defined as a quasi-homogeneous layer that extends from the surface down to the penetration depth of turbulent mixing, generated by wind stress and buoyancy fluxes at the air-sea interface (Kraus & Turner, 1967; Price et al., 1986). The MLD is an important parameter within several atmospheric and oceanographic research disciplines as the transfer of mass, momentum, and heat across the mixed layer provides the source of almost all oceanic motions (de Boyer Montegut et al., 2004). Variations in MLD influence air-sea interactions through the storage of various gases, such as carbon dioxide and methane (Kraus & Businger, 1994). The MLD also affects the vertical distributions of dissolved and particulate biological and chemical components in surface waters (Gardner et al., 1995), and is thus one of the main factors controlling the primary production (Behrenfeld & Falkowski, 1997; Sverdrup, 1953). The surface mixed layer~~MLD~~ is also of importance since it represents a reservoir for pollutants that are deposited from the atmosphere and cycled between the atmosphere and the surface waters (Nerentorp Mastromonaco et al., 2017). Furthermore, temporal and spatial variability in the MLD is essential for validating and improving mixed layer parameterizations (Ling et al., 2015; Martin, 1985; Noh et al., 2002), and as diagnostics in mixed layer budgets (Hasson et al., 2013; Montégut et al., 2007). ~~Its depth~~The, properties, depth and behavior of the surface mixed layer also play an important role in understanding acoustic propagation in the ocean.

The MLD is controlled primarily by surface stress (exerted by wind or sea-ice), buoyancy fluxes (heating/cooling, ice melt/formation, lateral advection, or precipitation/evaporation), and dissipation (Large et al., 1994; Timmermans et al., 2012). Thus, any variation in the MLD can be linked to these processes. It is well established that the MLD varies on diurnal to inter-decadal timescales (Bissett et al., 1994; Kara et al., 2003; Li et al., 2005; Polovina et al., 1995), but higher frequency variability is poorly understood due to observational limitations. For direct measurements of the MLD, various forms of conductivity, temperature, depth (CTD) sensor data are collected from ships, moorings, or gliders. These collect discrete profiles through the water column with a ~~temporal sampling~~ frequency of typically less than one profile per 10 minutes. Broad global coverage of the distribution of the MLD is becoming increasingly available through salinity and temperature stratification data from the ARGO float program (Freeland et al., 2010), but the high spatial frequency of ocean thermohaline variability is still strongly undersampled (Guinehut et al., 2012). Satellite-derived products provide global synoptic coverage of, for example, sea level (MacIntosh et al., 2016), sea surface temperature (Donlon et al., 2009) and sea surface salinity (Font et al., 2013; Lagerloef et al., 2012), but are essentially restricted to near sea surface properties.

Since the early 20th century, active acoustic sensors have been used to track military targets in the water column (MacLennan & Simmonds, 2013). Not long after the first military applications, acoustic water column mapping with echosounders was applied to fisheries science, where detection and quantification of fish distributions were the primary focus (Kimura, 1929; MacLennan, 1990). The applications of acoustic water column mapping have broadened in recent years to include marine ecosystem acoustics (Benoit-Bird & Lawson, 2016; Godø et al., 2014), observations of gas bubbles and oil droplets associated with natural seeps (Jerram et al., 2015; Merewether et al., 1985), and fossil fuel production (Hickman et al., 2012; Weber et al., 2012). Acoustic imaging of the water column has also been used within the field of physical oceanography; single beam echosounders can capture fine-scale oceanographic structures, typically attributed to biological scatters or turbulent microstructures (Klymak & Moum, 2003; Pingree & Mardell, 1985; Trevorrow, 1998). Larger scale thermohaline structures have been observed with lower frequency seismic systems (e.g., Holbrook et al., 2003). Custom-built echosounders utilizing wideband frequency-modulated pulses have been deployed since the 1970s (e.g., Holliday, 1972), but have received renewed attention as they have become commercially available (Duda et al., 2016; Lavery et al., 2010; Stranne et al., 2017). Advantages of wideband echosounders, compared to conventional narrow-band systems, include increased signal-to-noise ratio (SNR) and increased range resolution through pulse-compression processing (Stanton & Chu, 2008; Turin, 1960), and the ability to study the frequency response of individual targets (Lavery et al., 2010; Stanton et al., 2010).

The increased SNR of wideband echosounders have made it possible to map density stratification in the ocean. Stranne et al. (2017) were able to acoustically image individual thermohaline steps resulting from the intrusion of warm and salty Atlantic waters into the colder and less saline Arctic waters. The range resolution provided by the wideband sonar enabled the detection of individual density layers separated by less than 0.5 m to depths of about 300 m. These thermohaline layers represent change in temperature of typically 0.05 °C and change in salinity of 0.015, with corresponding acoustic reflection coefficients at the layer interface as low as $2 \cdot 10^{-5}$. Although the ensonified area, (i.e., the region covered by the beam), is smaller at shallower depths for a downward-looking echosounder (leading to a weaker scatter strength) this is compensated by generally higher reflection coefficients at the base of the mixed layer, meaning that the MLD is more readilycan be detectable with wideband echosounders. Here we show that underway profiling using wideband echo sounding systems at up to several pings per second can map the behavior of the MLD at very high spatial resolution.

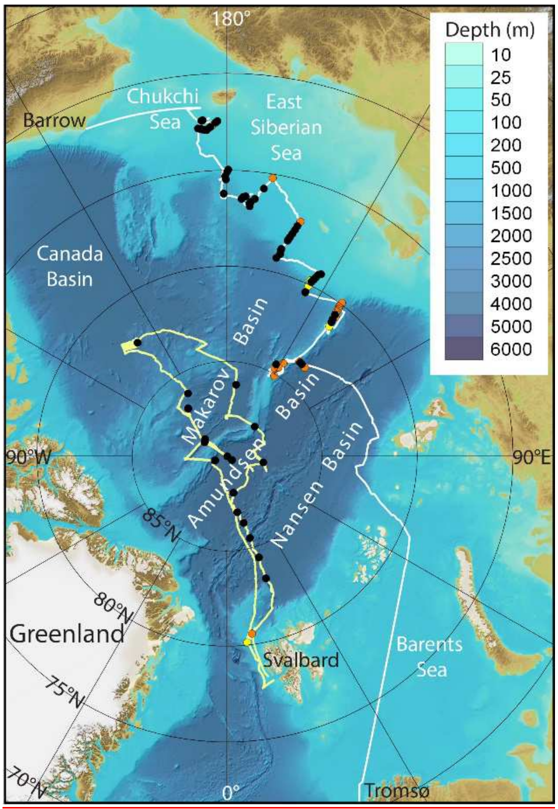

Figure 1. Map showing cruise tracks for the SWERUS-C3 cruise (white) and the Arctic Ocean 2016 cruise (yellow). CTD stations are shown as dots where ~~green~~ black indicates the MLD was successfully observed acoustically, red indicates the MLD was not successfully observed acoustically, and ~~blue~~ yellow indicates no mixed layer was present.

2 Methods

2.1 Data and the regional setting

Acoustic water column data were collected throughout the Arctic Ocean during two expeditions with Swedish icebreaker (IB) *Oden*:~~;~~ Leg 2 of the Swedish-Russian-US Arctic Ocean Investigation of Climate-Cryosphere-Carbon Interactions 2014 Expedition (SWERUS-C3) and the Arctic Ocean 2016 Expedition (AO2016).

Leg 2 of SWERUS-C3 departed 20 August 2014 from Barrow, Alaska, and ended 4 October in Tromsø, Norway. The expedition covered mainly the shallow areas of the East Siberian Sea continental shelf and shelf slope (Fig. 1). The median water depth of the 78 CTD stations investigated from SWERUS-C3 is 340 m. The hydrography of this area can be characterized as dynamic and seasonally variable as it is influenced by large river runoff, coastally trapped waves, ice formation and melting, and brine rejection in coastal polynyas.

The AO2016 expedition took place between 8 August and 19 September, 2016, departing from and returning to Svalbard (Fig. 1). One specific research goal during AO2016 was dedicated to investigating the possibility to detect and map thermohaline stratification using a midwater wideband echosounder. The cruise track covered mainly the central Arctic Ocean and the median water depth of 24 CTD stations investigated is 4000 m (Fig. 1). Together, the SWERUS-C3 and AO2016 expeditions spanned much of the breadth and depth of the Arctic Ocean and provided wideband acoustic data in a variety of oceanographic settings.

2.2 Wideband water column acoustic data collection

The wideband water column backscatter data presented here were collected with a Simrad EK80 split-beam scientific echosounder (SBES) installed in IB *Oden*. The system was operated continuously during both the SWERUS-C3 and AO2016 expeditions.

The SBES consisted of a Simrad EK80 wideband transceiver transmitting through a standard Simrad ES18-11 transducer installed in the ‘ice knife’ near the bow of the vessel and protected by an ice window. This transducer model is widely installed in fishery research vessels, typically operating at 18 kHz with a -3 dB beamwidth of 11°. In 2014, the transducer model was tested with a Simrad EK80 wideband transceiver and determined to have a useable two-way frequency response over 15-25 kHz. Thus, a frequency range of 15-25 kHz was used throughout the EK80 data collection period on IB *Oden*.

Transmit power was maintained at the maximum setting of 2000 W to compensate for losses through the ice protection window and improve signal-to-noise (SNR) characteristics, especially during noisy hull-ice interactions. Transmission pulse lengths were adjusted over a range of 1-8 ms, in an effort to minimize the extent of autocorrelation sidelobes (sidelobes are typically minimized with shorter pulses) while maximizing the SNR (better with longer pulses). All EK80 operation was controlled and monitored around-the-clock using the Simrad user interface to adjust pulse length and range recording duration. Data were logged in the Simrad .raw format.

Position and attitude information were provided to the echosounder as an integrated solution by a Seapath Seatex 330 GPS/GLONASS navigation and motion reference system. Vessel motion was minimal (typically less than 1° pitch and roll, in the data presented here) and thus does not appreciably affect the observations of horizontally-oriented backscattering layers occupying broad portions of the beam.

During the AO2016 expedition, a small delay was applied to the EK80 transmit-receive cycle trigger in order to avoid transmission interference from the two other echo sounding systems (Kongsberg EM122 12 kHz multibeam and SBP120 2-7 kHz sub-bottom profiler) in the earliest portion of the EK80 receive cycle, corresponding to the upper water column region of interest.

2.3 EK80 post processing methodology

The dataset collected with the EK80 was match-filtered with an ideal replica signal using a MATLAB software package provided by the system manufacturer, Kongsberg Maritime (Lars Anderson, personal communication). After match-filtering, ship-related noise was found within the signal band. A bandpass filter with 16 and 22 kHz cut-off frequencies was applied to the data to exclude the noise. Sound speed profiles were calculated from CTD-derived temperature, salinity and pressure data using the International Thermodynamic Equation of Seawater (Commission et al., 2010). Ranges from the transducer were then calculated using the cumulative travel times through sound speed profile layers based on the nearest (in time) CTD profile. These ranges were then converted to depths by compensating for the transducer location relative to the static waterline on IB *Oden* and the heave of the vessel.

2.4 EK80 extended target calibration procedure

The EK80 was calibrated onboard the *Oden* on 1 September 2015, following a standard method~~ology~~ described by ~~(~~Demer et al.~~,~~ (2015). A 64 mm copper sphere of known acoustic properties was suspended on a monofilament line and moved through the SBES field of view. The calibration data were collected in relatively calm seas and atmospheric conditions while the *Oden* drifted. All propulsion systems were secured during the calibration procedure in order to reduce noise in the water column. A CTD profile was collected immediately before calibration operations.

Utilizing a calibration sphere target strength model based on the work by Faran (1951) and MacLennan (1981) (MATLAB software package available at www.ices.dk), a calibration offset (C = 8.5 dB, averaged over the transducer beam width) was calculated using a temperature of 0 °C and a salinity of 34.5 at the sphere depth of approximately 80 m. This calibration offset represents the difference between the nominal target strength (*TS*) observed by the EK80, as predicted after match filtering, and the modeled *TS* of the calibration sphere. The offset is then applied to subsequent measurements of *TS*, yielding calibrated *TS* results for the EK80 datasets.

2.5 Estimates of the reflection coefficient from EK80 observations

The *TS* of an ideally smooth layer is a function of both the reflection coefficient (R), and the ensonified area (A). Here, we assume that A is limited by the width of the EK80 beam (rather than the length of the pulse), such that A can be estimated as

$$A(z) = \pi(\tan(\varphi)\, z)^2 \ ,$$

where φ is half the beam width and *z* is the depth in the sonar reference frame. Following (Lurton & Leviandier, (2010) the *TS* for a layer at depth *z*, with reflection coefficient *R*, can then be estimated as

$$TS(z) = 20log_{10}R + 10log_{10}(A(z)) \ .$$

For our estimates of observed *R*, we simply invert the above equation to solve for *R*:

$$R = \ 10^{(TS-10log_{10}A)/20} \ , R = A^{-1/2}10^{TS/20}$$

where *TS* is the calibrated acoustic backscatter observation from the EK80.

2.6 CTD

CTD data were collected with a SeaBird 911 equipped with dual SeaBird temperature (SBE 3) and conductivity (SBE 04C) sensors. The CTD data files were post processed with SBE Data Processing software, version 7.26.6 (available at www.seabird.com). The alignment parameter was tuned following the suggested method described in the SBE Data Processing manual (available at www.seabird.com). All CTD data presented are averaged in 10 cm vertical bins.

The reflection coefficient from CTD data (R_{CTD}) was calculated through

$$R_{CTD}(i) = \frac{\eta(i)-\eta(i-1)}{\eta(i)+\eta(i-1)} \ ,$$

where each element *i* has a corresponding depth *z*(*i*), the depth of $R_{CTD}(i)$ is the average of *z*(*i*-1) and *z*(*i*), and η is the acoustic impedance given by

$$\eta(z) = V(z)\rho(z) \ ,$$

where *V* is the sound speed and *ρ* the seawater density. The accuracies of the pressure, conductivity and temperature sensors are 0.0015%, 0.0003 S/m and 0.001 °C, respectively (www.seabird.com). All conversions (salinity, density and sound speed) were made according to the International Thermodynamic Equation of Seawater (Commission et al., 2010).

2.7 MLD derived from CTD

To determine the MLD, we apply the method presented in de Boyer Montégut et al. (2004), where successively deeper data points in each of the CTD potential temperature profiles are examined until one is found with a potential temperature value differing from the value at the 10 m reference depth by more than the threshold value (ΔT) of ±0.2 °C. Using this approach, the MLD is then assumed to be at least 10 m deep, and any shallower well-mixed sections in the water column are not taken into consideration (de Boyer Montegut et al., 2004). The reference depth applied by de Boyer Montegut et al. (2004) was chosen so as to avoid the diurnal variability of the mixing layer (typically found at depths < 10 m) while keeping the longer-term variability of the mixed layer.

3 Results

We investigated the shallow (<50 m depth) EK80 water column data from approximately one hour before to one hour after the time of each CTD cast, for a total of 102 CTD stations throughout both expeditions (Fig. 1). An example of acoustic mapping of the MLD over a 117 km long cruise track (about 12 hours) in the central Arctic Ocean is shown in Figure 2.

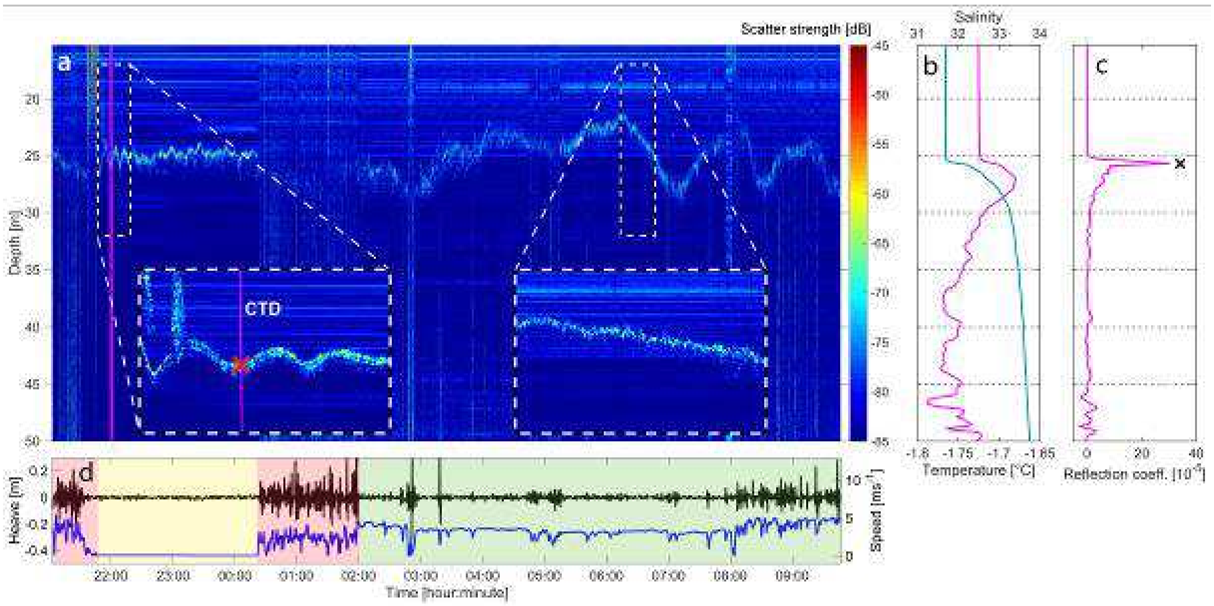

Figure 2. Continuous tracking of MLD in central Arctic Ocean over a 117 km cruise track. Data were acquired 12-13 September 2016 at 14.5 °E, 86.1 °N. (a) EK80 echogram (2 ms pulse length) with magnified insets (dashed boxes) showing the MLD while drifting (left) and while steaming (right). (b) CTD profiles showing temperature (magenta) and salinity (cyan). (c) Rreflection coefficients derived from CTD data (magenta) and from scatter strength (black cross represents the observed scatter strength of -65 dB at this depth extracted from the left inset in (a). (d) Hheave (black), speed over ground (blue), and time periods corresponding to ice breaking (red), steaming (green), and drifting (yellow). Vertical magenta lines in a show the position of the CTD. The red cross in (a) (left inset) marks the depth of the reflection coefficient spike in (c). Note that the ability to detect MLD acoustically is severely reduced while breaking ice.

We categorize CTD stations where EK80 data is are available into three classes (Fig. 1): green black indicates that a mixed layer is present in the CTD data and the MLD is visible in the EK80 data (success); red indicates that a mixed layer is present in the CTD data but the MLD is not visible in the EK80 data (failure); and blue yellow indicates that a mixed layer is not present in the CTD data. The classification is done subjectively by visual scrutiny of each echogram and subsequent comparison with CTD profiles; this process is meant to provide a general idea of how often a mixed layer is present in the *in situ* CTD data and the success rate of the remote EK80 MLD detection. In order to automate the EK80 MLD detection process, a stratification tracking tool needs to be produced. No such tool is available but methods used within the seismic processing or seismic oceanography fields can likely be applied also to sonar data.

Of the 102 CTD stations investigated, a mixed layer is present in 91 CTD profiles (90%); of these 91 confirmed MLD profiles, the MLD is simultaneously visible in the EK80 data in 69 instances (76%) (Table 1). The ΔT threshold estimate method yielded similar results to that of using acoustic data, with a root-mean-square deviation (rmsd) between the two methods of about 3 m (Table 2). The original ΔT threshold (0.2 °C) as presented in de Boyer Montégut et al. (2004) worked well for the SWERUS-C3 CTD stations but generally failed in the central Arctic Ocean due to the generally weaker density contrast at the base of the mixed layer (as shown in Fig. S3). Therefore, we used a modified ΔT threshold of 0.05 °C on CTD data from AO2016. Note that, even though instances where the ΔT threshold method clearly fails are excluded in these statistics, there are still instances where it provides less than ideal MLD estimates. The deviation therefore reflects inaccuracies in both methods. The CTD ΔT threshold method is constructed so as to avoid the *mixing layer* (i.e. shallower and generally weaker stratification that varies on a diurnal time scale, not to be confused with the *mixed layer* which is the focus of this study). We note that the nice agreement between the acoustic method and the CTD ΔT threshold method implies that we are generally catching the mixed layer also with the acoustic method. The density threshold approach presented de Boyer Montégut et al. (2004) was tested with close to identical results. We opted to use and display the results from the temperature threshold method, as it is simpler plus there are more temperature data available -than there are salinity data (in e.g. World Ocean Database), thus rendering this method more useful in a general sense. Note that the same problems we had with the temperature threshold (we had to adjust it for the central Arctic Ocean) also showed up for the density threshold method.

Table 1. Success and failure rates of acoustic detection of MLD when present in CTD data.

Category of detection	SWERUS-C3	AO2016	Total[*]
MLD present in CTD profile	69	22	91
MLD in CTD and in EK80 (success)	48 (70%)	21 (95%)	69 (76%)
MLD in CTD but not in EK80 (failure)	21[**] (30%)	1 (5%)	22 (24%)

[*]Of the total 102 CTD stations investigated, 11 stations (9 in SWERUS-C3 and 2 in AO2016) did not have a well-defined MLD (blue yellow category in Fig. 1) and are not included in these statistics. An example of this category is shown in Fig. S1.

[**]Of the 21 acoustic detection failures in the SWERUS-C3 data, Mmore than half of the 21 acoustic detection failures in the SWERUS-C3 data are related to the relatively deeplarge ship draft of IB *Oden* and f, and four of the failures are related to noise of unknown source that appeared in the EK80 data towards the end of the cruise. When not counting these particular modes of failure stations, which could possibly be addressed with different vessel parameters, the MLD acoustic detection success rate is close to 90% in the SWERUS-C3 data.

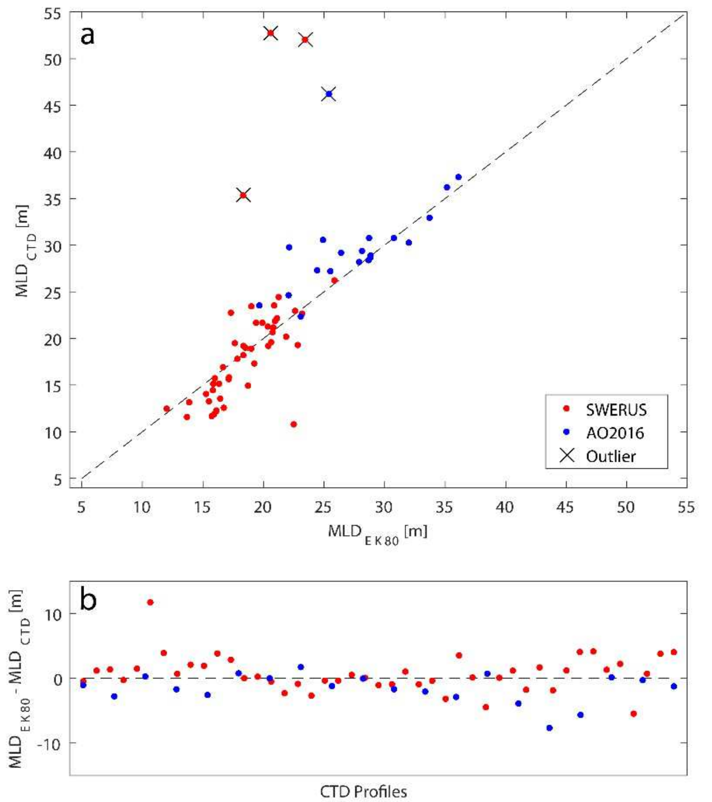

Figure 3. (a) MLD for the individual stations derived from CTD (MLD_{CTD}) versus MLD derived from EK80 data (MLD_{EK80}). (b) Difference between MLD_{EK80} and MLD_{CTD}. In total, four outliers (black crosses in (a)) where the ΔT threshold method fails (as exemplified in Figure S2) are excluded from the statistics. Note that the original ΔT threshold (0.2 °C) as presented in de Boyer Montégut et al. (2004) generally failed in the central Arctic Ocean (Figure S3) and that we instead used a modified ΔT threshold of 0.05 °C on CTD data from AO2016.

Table 2. Statistics for MLD_{EK80} and MLD_{CTD} with the four outliers (Figure 3) excluded; all units are meters.

MLD (m)	mean MLD_{CTD}	mean MLD_{EK80}	std MLD_{CTD}	std MLD_{EK80}	rmsd

SWERUS-C3	17.7	18.6	4.2	2.9	2.8
AO2016	29.2	27.5	3.6	4.3	2.7
ALL MLD DETECTIONS	21.3	21.3	6.7	5.3	2.8

4 Discussion

4.1 MLD observations

The typical summer MLD of the Arctic Ocean is ~20 m (Steele et al., 2008). By applying a density threshold method for determining the MLD, Toole et al. (2010) reported~~,~~ for the central Canada Basin~~,~~ an average summer MLD of 16 m and an average winter MLD of 24 m. The shallower mean MLD in the SWERUS-C3 data is consistent with the large river runoff into the Siberian shelf seas, which should lead to a generally shallower mixed layer compared to the AO2016 data from the central parts of the Arctic Ocean (Large et al., 1994). Given the dynamic nature of the more coastal Leg 2 SWERUS-C3 cruise track compared to the open ocean-dominated AO2016 cruise track, we were expecting larger MLD variability in the SWERUS-C3 data. We cannot see such tendency in our data (Table 2), but again the basis of the statistics is rather poor.

In general, MLD variations between the different regions of the Arctic Ocean covered in this study match well with mean Arctic Ocean MLD based on other field observations (Ilıcak et al., 2016; Peralta-Ferriz & Woodgate, 2015), with shallow MLDs along the East Siberian Sea, slightly deeper MLDs in the Canada Basin and deepest MLDs in the central Arctic Ocean. As the emphasis of this paper is mainly on the acoustic method rather than the actual MLD observations, we are hesitant to draw any conclusions based on the MLD statistics presented in Table 2, especially when considering the small number of observations on which the statistics are based on.

4.2 Sampling frequency

With the acoustic method we can observe the MLD at a horizontal resolution far exceeding alternative *in situ* methods, such as CTD profiles. The acoustic method enables the study of internal waves propagating on the layer interface at the base of the mixed layer (left inset, Fig. 2a). Internal waves are a ubiquitous phenomenon in the ocean and drive vertical mixing that is important for the global ocean circulation and primary production (Garret and Munk, 1979; Denman and Gargett, 1983; Munk and Wunsch, 1998). Stranne et al. (2017) observed internal waves that caused vertical undulations of the stratification down to depths of about 300 m. While these deeper internal waves were clearly not excited by the vessel, we cannot exclude the possibility that some of the vertical undulations of the MLD seen here are due to near-surface internal waves generated by the *Oden* (Nansen, 1905). The recording duration of the EK80 was set to observe the full water column~~,~~, resulting in a ping rate~~frequency~~ of around 0.1 ping s^{-1} ~~in deep water~~when synchronized with the multibeam echosounder in deep water (i.e., ping rate is ~~determined~~limited by~~ maximum~~ recording range on the ~~ multibeam ~~outer swath, which can be more than twice the water depth~~slant range~~). T~~, though t~~he ping rate can be set much higher (up to several pings per second) in shallow water or if only data from the shallow part of the water column are to be collected. In our data the MLD is clearly visible while drifting and steaming, but the quality of the data underway would benefit from a higher ping rate; specifically, the highest-frequency temporal and/or spatial variations in MLD are likely undersampled at this lower ping rate while the vessel is moving (right inset Fig. 2a).

4.3 Vertical detection limits

The cruise track of the SWERUS-C3 expedition during Leg 2 covers mainly the shallow areas of the East Siberian Sea shelf and shelf slope, an area that is heavily influenced by river runoff (e.g., from the Lena River). The freshwater input (or negative buoyancy flux) to the coastal waters leads to generally shallower MLD (Large et al., 1994). This is clearly manifested in our data where the average MLD from the shelf-dominated SWERUS-C3 cruise is more than 60~~ ~~% shallower than that of the sea ice-covered, deep basin-dominated AO2016 cruise (Table 2).

The deep depth limit for detecting ocean stratification with this particular EK80 setup appears to be around 300 m (Stranne et al., 2017) while the shallow depth limit depends on the draft of the hull-mounted transducer and the pulse length. On the *Oden*, the EK80 transducer is mounted at a draft of 7 m and, depending on pulse length, we generally observe useful data starting at 7.5-12 m depth from the surface (0.5-5 m from the transducer, Fig. 4d). The amount of data lost at the upper boundary is reduced with shorter pulse length (Fig. 4d); these data also show the better range resolution obtained with shorter pulse length (Fig. 5), but there is a serious tradeoff in terms of reduced SNR (Fig. 4a). More data are needed in order to determine the optimal pulse length for EK80 MLD detection as it also depends on region and platform.

Due to ship draft and the data loss at very close range from the transducer, the shallow MLDs seen in some of the SWERUS-C3 CTD profiles are sometimes difficult to detect acoustically with the EK80 (Figure S4). This is the most common factor explaining more than 50% of the failures to acoustically detect the MLD during SWERUS-C3.

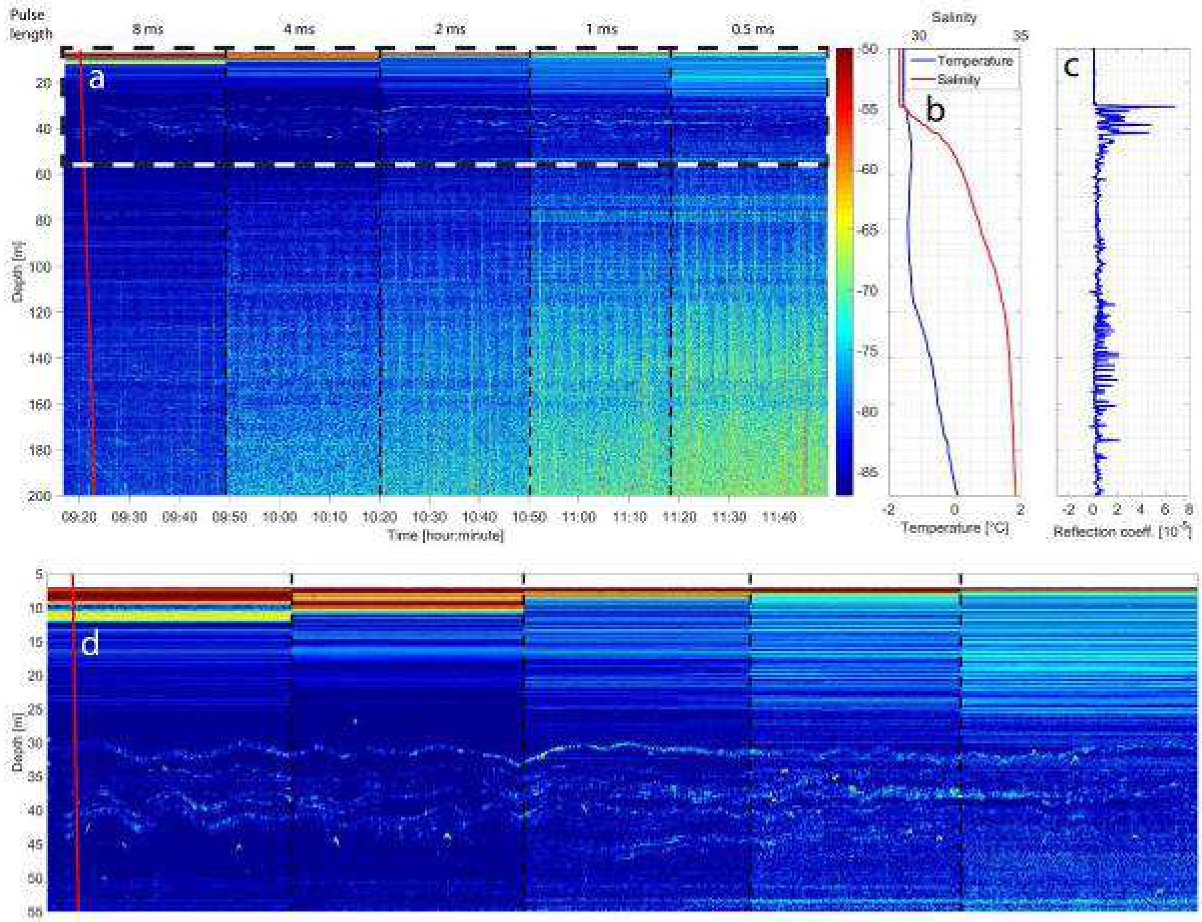

Figure 4. Comparison of EK80 data with different pulse lengths. Data were acquired 26 August 2016 at 140.6 °W, 86.8 °N. (a) EK80 echogram. (b) CTD profiles showing temperature (blue) and salinity (red). (c) Reflection coefficients derived from CTD data. (d) Enlargement of dashed box in (a). In (a) and (d), the vertical red line is the CTD position and the vertical dashed black lines indicate changes in pulse length (decreasing from 8 ms to 0.5 ms).

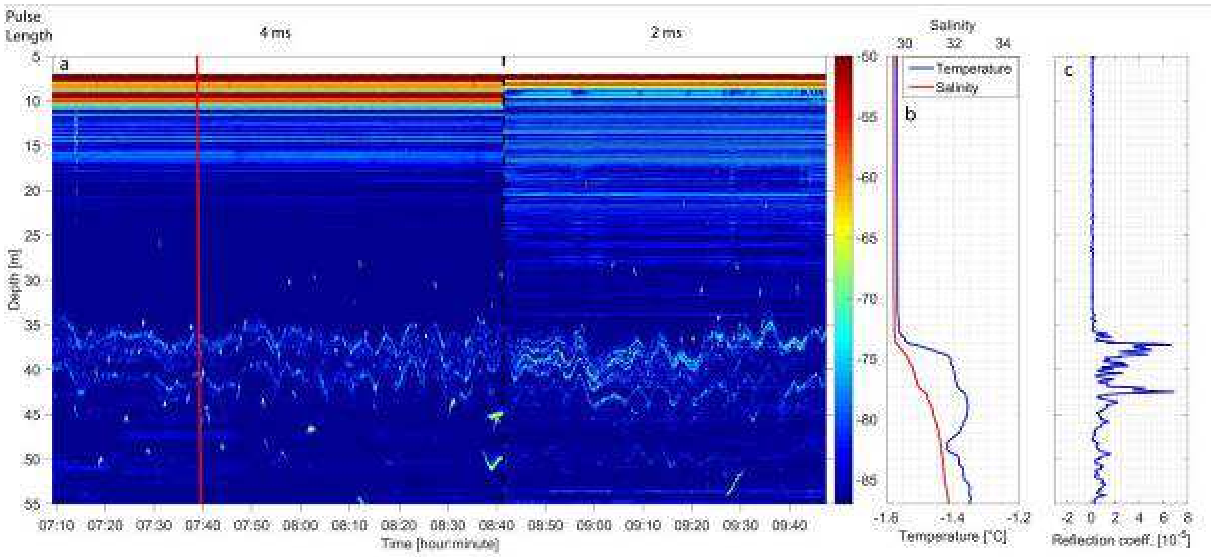

Figure 5. Tendency of increased range resolution in EK80 data with smaller pulse length. Data were acquired 29 August 2016 at 148.1 °W, 86.1 °N. (a) EK80 echogram with backscatter strength in dB on the color bar. (b) CTD profiles showing temperature (blue) and salinity (red). (c) Reflection coefficients derived from CTD data. Note that, as there is no ground truth CTD cast within the later section of the echogram, there might be splitting/merging of layers (as shown in Stranne et al., 2017) and other changes in the stratification behavior occurring near the change in pulse length.

4.4 Biological scatter

In the example shown in Figure 2, the reflections are likely stemming from the impedance contrast from the ocean stratification alone; this is supported by the close match between the theoretical reflection coefficient calculated from the CTD data and the reflection coefficient derived from the calibrated acoustic backscatter data. This agreement among reflection coefficients is consistent with observations of deeper thermohaline staircase stratification from the central Arctic Ocean presented in Stranne et al. (2017). In the SWERUS-C3 data, biological scatterers are generally identified at CTD stations closer to the coast. Biological scattering can potentially obscure the reflections from MLD boundary (Fig. 6); at other times, the distribution of biological scatterers may coincide with the ocean stratification and enhance the layer reflections.

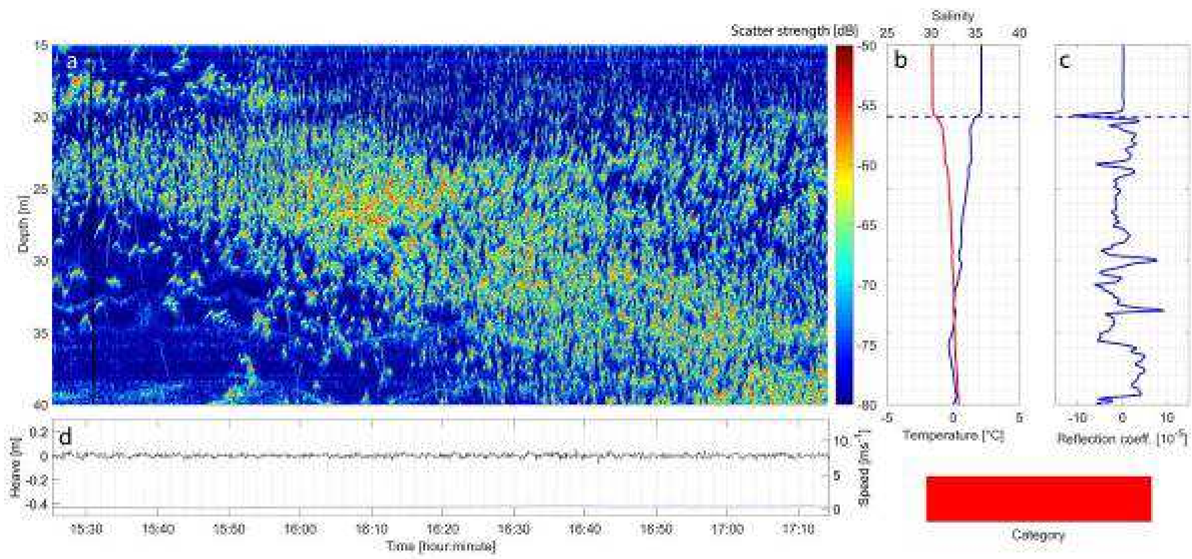

Figure 6. MLD obscured by biological scatter. Data were acquired 15 September 2014 at 143.2 °E, 79.9 °N. (a) EK80 echogram with black vertical line indicating the position of the CTD rosette. (b) CTD profiles showing temperature (blue) and salinity (red). (c) Reflection coefficients derived from CTD data. The horizontal dashed line in b and c show the MLD as defined by the ΔT threshold method. Also shown at the lower right is the category (red) of this particular

CTD station, indicating failure of the acoustic method to detect the MLD amidst strong biological scattering that spans across the MLD.

4.5 Further aspects

At the time of the SWERUS-C3 expedition, we did not yet realize that the EK80 was capable of MLD detection and, accordingly, nothing was done to optimize the performance of the EK80 to detect ocean stratification in 2014. At four of the SWERUS-C3 CTD stations, the MLD is obscured by noise from an unknown source (Fig. S5) but the source was not identified and no actions were taken to reduce it. This type of noise did not occur in the acoustic data from the later AO2016 cruise.

5 Conclusion

In this study we show that the MLD can be tracked acoustically, with high horizontal and vertical resolutions, over large distances (Fig. 2). The method is better suited for MLD tracking in the open ocean where it was successfully detected at 95% of the ground truth CTD stations, compared to coastal areas where the success rate was 70%. The lower success rate in coastal areas is partly related to greater abundance of biological scatterers, but in this case more importantly to the generally shallower MLDs which were sometimes impossible to detect acoustically due to IB *Oden's* vessel draft of 7 m and data loss close to the transducer. Smaller coastal vessels with shallower draft may be better suited to acoustically track the MLD in these regions.

The acoustic method of determining MLD yields results similar to the established ΔT threshold method with a root-mean-square deviation of about 3 m. There are large uncertainties associated with the ΔT threshold method and the MLD_{EK80} estimates should likely provide better precision, at least under some circumstances, as exemplified in Figure S2.

While the MLD is a crucial component within the Arctic Ocean in terms of physical, chemical and biological processes (Peralta-Ferriz & Woodgate, 2015), the discrepancy between observed and modeled MLDs in the Arctic can be quite significant (Ilıcak et al., 2016). The method of observing the MLD remotely, by means of ship-mounted echosounders, allows for larger and more efficient observational coverage. It should be noted, however, that the acoustic method cannot completely replace *in-situ* measurements (partly because of the need for ground-truthing the acoustic data), but rather it presents a ~~very~~ powerful complementary method to 'connect the dots' at high resolution between CTD stations.

Methods of utilizing ocean reflectivity from multi-channel seismic systems to reconstruct temperature and salinity stratification in between CTD casts have been investigated (Biescas et al., 2014; Papenberg et al., 2010; Wood et al., 2008). The increased vertical resolution (from ~10 m with multi-channel seismic data to <0.5 m with wideband acoustics (Stranne et al., 2017)) facilitates the detection of much finer thermohaline structures in the water column, including the MLD, and can potentially vastly improve these methods.

Many vessels are equipped with underway sonar systems and, thus, the method presented here is a step toward collecting large amounts of ocean stratification data globally. Such large scale acoustically obtained stratification data can become a fundamental link tying discrete ARGO float profiles (Freeland et al., 2010) with large scale synoptic coverage of sea surface temperature and salinity data derived from satellites (Font et al., 2013; Lagerloef et al., 2012). Furthermore, modeling approaches for estimating MLD are often based on remote sensing data, including LIDAR data for scattering layers and satellite data for sea surface salinity, sea surface temperature, surface wind speed and sea level (Ali & Sharma, 1994; Durand et al., 2003; Hoge et al., 1988; Yan et al., 1990). High-resolution acoustic mapping of the MLD will add important inputs to these models.

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