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Oceanographic and acoustic data from a voyage near the ice edge in the Fram Strait summer 2016

by

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Innhold

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1 Introduction

The project "Iskantseilas - målinger i ishavet med to ubemannede farkoster" (Ice Edge Voyage - measurements in the Arctic Ocean with two unmanned vehicles) was granted funding from the Regional Research Fund for Western Norway in 2015. The partners in the project were Aanderaa Data Instruments AS (project leader), Nansen Environmental and Remote Sensing Center (NERSC), Offshore Sensing AS, and Christian Michelsen Research AS . The objective of the project was to develop new measurement technology for use in the ice edge zone. The unique marine ecosystem of the Arctic is sensitive to anthropogenic change, including acidification caused by CO_2 emissions. Better knowledge of how this natural system functions is needed, but it is a challenging area to observe. In this project, a new sensor package measuring parameters relevant to ocean acidification was integrated on an autonomous sailing platform, the SailBuoy.

The "Ocean Acidification Vehicle" was deployed in the Fram Strait, between Greenland and Svalbard, in the summer of 2016 during a research cruise on board the Norwegian Coast Guard vessel K.V. Svalbard. The research cruise was made as part of the NERSC-led project Arctic Ocean Under Melting Ice (UNDER-ICE). A second SailBuoy equipped with an echo sounder was also deployed. The two small autonomous "sailboats" collected data at high spatial and temporal resolution in the Fram Strait for two and a half weeks. The resulting data set has been analysed with regard to hydrography and acoustics.

2 Data collection

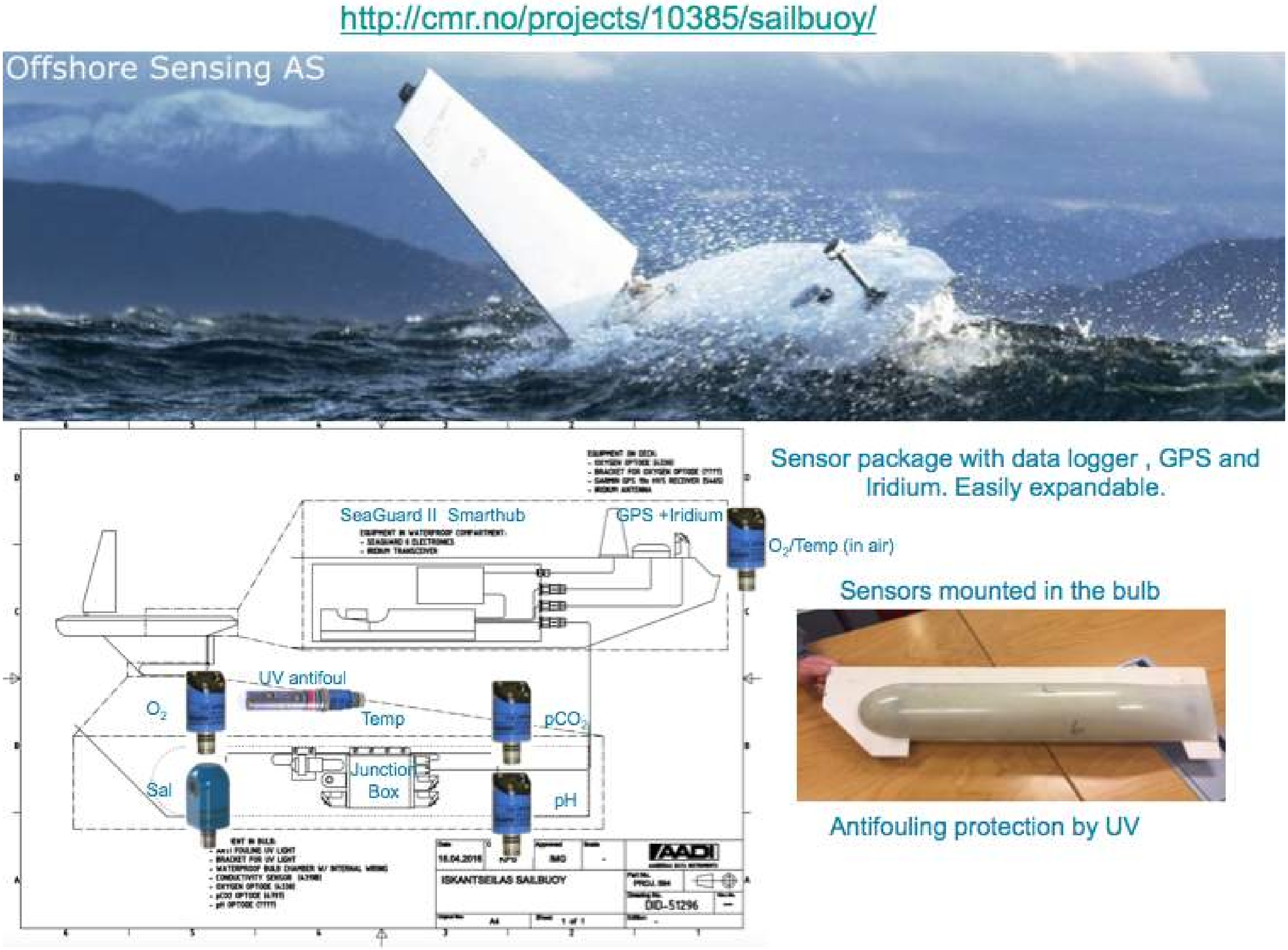
2.1 Fieldwork: Sailbuoy deployment

Objectives

The SailBuoy is a remotely controlled surface vehicle that uses wind power to sail towards pre-defined waypoints (Ghani et al., 2014). One of the SailBuoys deployed during the 2016 KV Svalbard cruise was equipped with a new sensor package for measuring parameters relevant to ocean acidification. The sensor package, developed by Aanderaa Data Instruments, integrates temperature, conductivity, pH, pCO_2, and dissolved oxygen (O_2) sensors housed in a bulb on the keel of the SailBuoy together with a UV-antifouling device. An O_2 and temperature sensor for measurements in air is placed on top of the ocean acidification SailBuoy. The other SailBuoy used during the cruise was equipped with a high-frequency echo sounder for detecting marine organisms and physical layering in the upper 100–200 m. The ocean acidification SailBuoy will hereafter be referred to as SB Iskant and the echo sounder SailBuoy as SB Nexos.

Work at sea

Deployment The two SailBuoys were deployed on Thursday 30 June. The SailBuoys were taken out of their boxes and assembled (sails put on) on the aft deck. SB Nexos was started up at 18:41 UTC and SB



Figur 1: Introducing the SailBuoy. Photo and drawing from CMR and Offshore Sensing.

Figur 2: The SailBuoy "Ocean Acidification Vehicle", SB Iskant, just after deployment in the Fram Strait. Photo by Espen Storheim.

Iskant at 18:43. We communicated by email and phone to David Peddie ashore, and received confirmation that the two buoys were transmitting their positions. Then we proceeded to take off the protective caps on the sensors of SB Iskant. The sensor coverings were removed at about 19:21, and the bulb closed up. The buoy was picked up by crane and placed in the water. SB Iskant was deployed at 19:33 UTC. We opened the release hook before removing the guiding rope, which meant that when the remaining rope was pulled out of the handle at the stern of the SailBuoy the very light buoy was pulled back somewhat towards the ship, but it went clear of the side of the ship and continued on its way without problems. The second SailBuoy, SB Nexos, was deployed at 19:47 UTC. The deployment position of the two buoys was approximately 77°59.37 N, 003°10.07 E. After deploying both buoys, a near-surface water sample for calibration was taken using a small hand-lowered Niskin bottle. Triplicate samples for analysis of alkalinity and DIC were taken in glass bottles and preserved with a drop of mercury chloride solution.

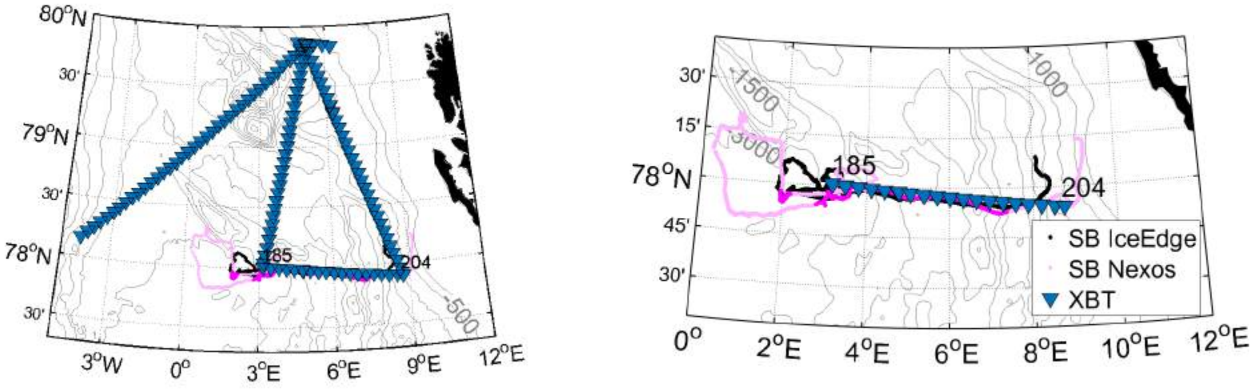
En route Piloting the SailBuoys was done from shore, by David Peddie at Offshore Sensing and Rune Hauge (now Øyerhamn) at CMR. For the first days after deployment, wind speeds were very low. It was decided that the SailBuoys should be kept as much as possible in position until we had an opportunity to test their manoeuvering in higher wind speeds, forecast for Sunday 3 July. Overall, the weather conditions during the SailBuoy mission were fair, with very little wind. This proved somewhat challenging to navigation, since the low wind speeds meant the SailBuoys had little force with which to counter currents. Especially SB Nexos was affected by this, and drifted further to the west than planned. A detailed account of the whole mission is given in table 1, which contains for every day of the mission: the position of each SailBuoy at noon UTC (if not otherwise noted), some notes on their activity such as the given waypoint, and the wind observation taken at KV Svalbard at 10:00.

Recovery The SailBuoys were recovered on Monday 18 July using a small boat (man overboard boat). SB Iskant was recovered first. It was taken out of the water into the small boat at about 10:05 UTC, and brought on board KV Svalbard where the whole buoy was rinsed with fresh water and the protective caps put back on the sensors and fastened with insulating tape to keep moisture inside. The small boat was deployed again to take a profile of the upper ca 200 m with a small, hand-held CTD. The CTD-profile was taken at ca 10:44 UTC, a short distance from KV Svalbard at about 78°10.5 N, 8 ° E. After the CTD profile was taken and the sensors on the SailBuoy were taped off, at 13:20 UTC, a water sample was taken with the hand-lowered Niskin bottle. Again, triplicate samples were taken and preserved with mercury chloride solution (note: sample NUM5 was given a larger amount of mercury chloride).

2.2 Complementary data

Some satellite remote sensing data products were used in the study.

- Chlorophyll data (chl) are provided as Level-2 product, generated from either a Level-1A or Level-1B product of MODIS Aqua or Terra, by OceanColor (https://oceancolor.gsfc.nasa.gov/). The spatial and temporal resolutions are 1 x 1 km and 10-12 times/day respectively.
- Copernicus Marine Environment Monitoring Service, CMEMS, (http://marine.copernicus.eu/), provides regular information on the physical state and variability of the ocean and marine ecosystems. We downloaded data from the Arctic Ocean Physics Analysis and Forecast `ARCTIC_ANALYSIS_FORECAST_PHYS_002_001_a`, produced by the NERSC-led Arctic Monitoring and Forecasting Centre (ARC-MFC) using the TOPAZ4 ocean data assimilation model system. The real-time data product contains three-dimensional daily mean fields at 12.5 km horizontal resolution for the area north of 65° N, based on the NERSC–HYCOM model fields. It includes temperature, salinity, sea surface height, zonal velocity, meridional velocity, sea ice concentration, sea ice thickness, sea ice velocity and sea ice type. In this study we used primarily the temperature from the uppermost level, 5 m, as an approximation of sea surface temperature.
- Wind speed data (ws) were also acquired from CMEMS. Level-4 products provided as 6 hourly mean data with 25 x 25 km spatial resolution were used in this study. The provided data are blended mean wind fields based on daily ASCAT (Metop-A and Metop-B) and QuikSCAT (OceanSat2) gridded wind fields with ECMWF analysis.
- Ice images from MODIS and Sentinel-1a were used. Mohamed Babiker at NERSC processed the images and produced up-to-date ice maps that were used for navigation and mission planning throughout the research cruise in 2016.



(a) XBTs 12–15 July

(b) XBTs along SailBuoy tracks

Figur 3: SailBuoy tracks and XBT profiles.

During the 2016 research cruise, eXpendable Bathy-Thermographs (XBTs) were also deployed from the K.V. Svalbard. A total of 153 XBT profiles were done, 20 of which were along a 130 km transect from west to east parallel to the SailBuoys' track (see figure 3).

3 Data processing and quality

3.1 Physical and chemical data from SailBuoy (SB Iskant)

- **Initial data treatment**The original data from "SB Iskant" are found in the semicolon separated file $5650 - 1801 - 0 - 2016 - 06 - 30T19 - 42 - 04.599Z.csv$. The file contains a total of 2544 records at 10 minute intervals. Some basic editing was done to the file:

  1. The first column, Record Time, is in format [DD.MM.YYYY hh:mm] - this was split into separate columns [YYYY][MM][DD][hh][mm][ss]
  2. Many columns contain "status", these are all filled with OK. As there are no values flagged "not OK", all status columns were deleted.
  3. The header was edited: the description text (the first 14 lines above column labels) was shortened.
  4. Further header editing: the row of sensor numbers above column labels was edited.
  5. The header was then commented out (prefaced with %) to facilitate direct loading of txt file into Matlab.
  6. Data clearly before or after deployment (salinity = 0: the first 5 and last 4 records) were removed.
  7. Two versions were saved: $Iskant\_full\_edited.csv$ and $sb\_fs2016\_full.txt$ (tab delimited).

  The readings from most sensors seem reasonable, but the first few salinities after deployment were suspiciously low. These were not edited out from the file, but were excluded before the scientific analysis or plotting (see sections 4 and 5).

  The truncated data file `sb_fs2016_full.txt` contains all the original variables, except only the status columns (see above), and the time stamp split into six separate columns. In Matlab (REF), the time stamp was converted to Matlab date format, and some relevant variables were selected for further analysis (see 2) and saved as `sb_fs2016.mat`.

- **Ocean acidification sensors** Anders Tengberg at the University of Gothenburg made the following initial assessment of the data quality:

  > Data from all sensors seem to be of high quality. There is a clear expected anti-correlation between O_2 ($287 - 347\mu$ M, salinity compensated, decreasing) and pCO_2 ($365 - 560$ uatm, increasing) as well as between pCO_2 and pH ($7.7 - 7.8$, increasing). pH has a stabilisation time of about 1 day in the beginning. Reference data will be needed to adjust absolute values of pH and pCO_2 and to determine if there was drift.

> All 4 temperature sensors ($4.9 - 9.0$°C, increasing) in the water give the same readings within 0.01°C. The temp sensor (on 4330 O_2 optode) on top of the hull is in the atmosphere and exposed to the sun and shows higher average temperature and higher variations ($3.0 - 17.3$°C). Salinity varies between $34.5 - 35.1$. Oxygen optodes show no sign of drift (close to 100% in air at start and end). Oxygen is mostly over-saturated (primary production) in the surface water. Comparing with atmospheric readings and taking into account wind speed will give possibility to calculate export/import of O_2 to/from the water/atmosphere. The resolution of the pCO_2 optode is better than 2 μatm and of the pH optode better than 0.005 units.

3.2 Echo sounder data from SailBuoy (SB Nexos)

The SB Nexos SailBuoy was equipped with a Simrad EK15 echosounder, with a single beam 200 kHz transducer, Simrad 200-28CM (28°beam width). The SailBuoy was deployed in the Fram Strait from 30th June to 15th July 2016. During periods of the operation, echosounder data were recorded on the 5th and 12 15th of July 2016. The data with 15 minutes long were recorded every 30 minutes. A total of 79 such recordings (4.4 GB of data) were available and stored in `/acoustic/Data_Store/UNDERICE2016/SailBuoy/Fram Strait ek15 data/`. The position of the SailBuoy is recorded in `/acoustic/Data_Store/UNDERICE2016/SailBuoy/fram_pos.mat`. The mean speed of the SailBuoy in the echosounder measurements was 24.3 m/min. Source codes for reading the recordings are stored in `/acoustic/Data_Store/UNDERICE2016/SailBuoy/readEKRaw`.

4 Data analysis

The analysis focussed on the upper 100 m of the water column, as we considered this to be the most important from a biological point of view. We used XBT profiles from the cruise to get a view of the vertical dimension for comparison with echo sounder data.

4.1 Analysis of physical oceanography data

For each XBT profile along the east–west section parallel to the SailBuoy track (cf. fig. 3) the Mixed Layer Depth (MLD) was computed. There are different ways to determine MLD, most commonly based on either on a density criterion $\Delta\sigma$ or temperature criterion ΔT, or based on a density or temperature gradient (see e.g. Kara et al., 2000 or Lavender et al., 2005). Here, the MLD definition was based on temperature. We tried both the temperature difference and the gradient method and plotted the resulting MLDs on top of a vertical temperature section. The gradient method was selected as giving the best result (figure 8). Using this method, MLD was defined as the depth in the upper 100 m where the vertical temperature gradient was the strongest.

4.2 Echo sounder data analysis

Figure2 (a) shows an example of the echograms. It is required for the analysis to remove various noise and quantify the information in the data. Procedures for post-processing of the echograms and categorization of objects in the echograms are as follows:

1. Read signal using `readEKRaw_Power2Sv()`. Size of the signalMatrix is (DEPTH x DISTANCE).
2. Normalize the signalMatrix from 0.0 to 1.0. (see: `tools_postProcessing.get_linearDepthFilter`)
    (a) Make a histogram with bin $= 5.0$ and range $= [-160, -25]$
    (b) Compute the cumulative relative frequency.
    (c) If the smallest cumulative relative frequency is larger than 0.1, set `minVal` $= -160$. If not, find a value with $max(cumulativerelativefrequency < 0.1)$ and use it as $minVal$.
    (d) Find $max(cumulativerelativefrequency < 0.99)$ and use it as the $maxVal$.
    (e) Using the $minVal$ and $maxVal$, normalize the $signalMatrix$.
3. Remove horizontal (depth) noise. (see Figure2 (b))

   (a) Compute a $mean\_signal\_vector(DEPTHx1)$ of the $signalMatrix$ along the second dimension.
   (b) Subtract $min(mean\_signal\_vector)$ from mean signal vector, and make a $subVector$ using the $80-100\%$ depths values of the subtracted vector. (i.e. $subVector = subtracted_vector(DEPTH * 0.8 : DEPTH)$)
   (c) Apply linear regression to the $subVector$ and get the slope.
   (d) Make a linear filter vector ($DEPTHx1$) with the slope
   (e) Make a filter matrix ($DEPTHxDISTANCE$) by repeat the filter vector $DISTANCE$ times.
   (f) Subtract filter matrix from the $signalMatrix$ and update the $signalMatrix$.

4. If strong mechanical noise is observed upper of the data, remove mechanical noise above 1000 pixel. (see Figure2 (c))
   (a) Check if mechanical noise is included: If $mean(mean(prctile(signalMatrix(1 : 50, :), 75 : 100))) > 0.8$, continue the following steps.
   (b) Smooth the $signalMatrix$ using $smooth()$.
   (c) Create the mean signal vector ($DEPTHx1$) of the smoothed $signalMatrix$ at the 2nd dimension.
   (d) Compute minimum and maximum values ($minPkVal$ and $maxPkVal$) in the smoothed mean signal vector using $findpeaks()$ with option "$MinPeakProminence, 1$".
   (e) $minMaxDiff = maxPkValminPkVal$
   (f) Iterate following procedures for each $iColVec$ ($\in DISTANCE$) in the smoothed $signalMatrix$:
      i. Find $iColMinVal$ which is a minimum value between $+-20\%$ of the row index of $minPkVal$ in $iColVec$, and its row index ($iColMinValIdx$) which has $iColMinVal$ in $iColVec$.
      ii. Append $iColMinValIdx$ in $noiseRowNum$ array.
      iii. Find $iColMaxVal$ which is a maximum value in i-th column vector of $signalMatrix$.
      iv. $iColMinMaxDiff = iColMaxValiColMinVal$
      v. Replace $iSignalMatrix(1 : iColMinValIdx, iCol)$ as $(iSignalMatrix(1 : iColMinValIdx, iCol) - iColMinVal) * (minMaxDiff/iColMinMaxDiff) + minPkVal$

5. Remove vertical noise (see Figure2 (d))
   (a) Compute $vSum3000$ which is sum of $signalMatrix$ below 3000 pix along 1st dimension. $vSum3000 = sum(signalMatrix(3000 : DEPTH, :), 1);$
   (b) If $abs(skewness(vSum3000)) < 0.5$ (suppose there is no large object below 3000 pixel)
      i. Compute square each element of $signalMatrix$ and a mean vector of the squared matrix below 3000 pix along the 1st dim ($= vNoiseMean3000$).
      ii. If absolute value of standard deviation of $vNoiseMean3000$ is larger than 1.0 (suppose there are vertical noise):
         - Make a histogram of $vNoiseMean3000$ and find a threshold with an interval at 20%
         - Find indices which have $vNoiseMean3000 >$ the threshold.
         - $noiseCol =$ the indices and $objectCol = [\,]$
      iii. If not:
         - $noiseCol = [\,]$ and $objectCol = [\,]$
   (c) If not:
      i. Compute $meanVecL50$ which is a mean vector of $signalMatrix$ under 50% percentiles along 2nd dimension. $meanVecL50 = mean(prctile(signalMatrix, 0 : 50, 2), 2)$
      ii. Subtract $meanVecL50$ from $signalMatrix$ for each column
      iii. Make a histogram of $vNoiseMean3000$ and find a threshold which has the biggest difference between two frequencies with adjacent bins. Find indices ($= noiseCol$) which have a larger frequency than the threshold.
      iv. Make a submatrix of $signalMatrix$ as $signalMatrix(3000 : DEPTH, noiseCol)$
      v. Compute a sum of the submatrix along the 2nd dimension.

vi. If absolute value of skewness of the sum vector of the submatrix is less than 0.5 (suppose only vertical noise exists) :

- Classify the sum vector of the submatrix into 2 using K-means clustering and set the ID numbers of data (column numbers) which belong to the cluster with larger cluster center into $noiseCol$. $objectCol = [\,]$. vii. If not (suppose large objects exist below 3000 pix):
- Compute a standard deviation of the submatrix along the 2nd dimension.
- Make a histogram from the standard deviation vector. Find a threshold which has the biggest difference between two frequencies with adjacent bins and set the ID numbers of data (row numbers) which has higher frequency than the threshold into $objectRows$.
- Make $objectRows$ vector consist of continuous values with larger than 300 pix. (e.g. $[300, .760, 765, 1080] \rightarrow [228, ..1152]$). If the size of a group is more than 300 pix ($760 - 300 = 360$), the group is enlarged ±20% of the group size. i.e. from the $300 - 360x0.2$ to $760 + 360x0.2$. It shows row numbers of large objects.
- Make a submatrix excluded$1 : 3000$ rows and $objectRows$ form $signalMatrix$.
- Compute a $submatMean$ which is a mean vector of the submatrix at the 1st dimension.
- If absolute value of skewness of $submatMean$ is less than 0.5 (suppose existence only large object):
  - Make an $objectCol$ vector which consists of continuous values with longer than 10 in $noiseCol$.
  - Make a $standardCol$ vector which subtracted $objectCol$ form $1 : DISTANCE$.
  - $noiseCol = [\,]$
- if not (suppose existence of both objects and vertical noise)
  - Classify smoothed $submatMean$ into two classes using K-means clustering and set the ID numbers of data (column numbers) which belong to the cluster with larger cluster center into $noiseCol$.
  - Calculate $objRowSum$ which is a vector of sums of $signalMatrix(objectRows, :)$ along the 1st axis.
  - Classify smoothed $objRowSum$ into two classes using K-means clustering and set the ID numbers of data (column numbers) which belong to the cluster with smaller and larger cluster centers into $standardCol$ and $objectCol$ respectively.
  - Update $standardCol$ by subtracting $noiseCol$ from $standardCol$.

(d) Make a logical filter matrix with size $(DEPTHxDISTANCE)$. The matrix values in $noiseCol$ have NaN values. The matrix values in $(objectRows \& objectCol)$ have also NaN values. Otherwise, the matrix values are 1.

(e) If $noiseCol$ is not empty, iterate following procedures for each $iNoiseCol (\in noiseCol)$:

i. Make a $weightVec$ as $[1 : 1 : iNoiseCol, (iNoiseCol - 1) : -1 : (DISTANCE - iNoiseCol)]$

ii. Make a $weightMat(size(DEPTHxDISTANCE))$ by repeating $weightVec$ $DEPTH$ times.

iii. Update $weightMat$ by multiplying the logical filter matrix for each element in the matrix and normalize $weightMat$ by dividing $weightMat$ by $nansum(weightMat, 2)$

iv. Normalize $weightMat$ by dividing $weightMat$ by $nansum(weightMat, 2)$

v. Compute $iColMean$ which is a mean vector of $signalMatrix.xweightMat$ at the 2nd dimension.

vi. Compute $iColVec$ by subtracting $iColMean$ from $iNoiseCol - thcolumn$ of $signalMatrix$.

vii. Compute a $iColWeight$ as $sum(iNoiseCol - thcolumnofsignalMatrix)sum(iColMean)$.

viii. Compute $iColMean$ which is a matrix and each column vector is $mean(iColVec(i : i+250))$ for $i = 1, 251, 501,$ and $i < DISTANCE$

ix. Make a polygon function from $iColMean$. Compute values of the polygon function for $1 : DEPTH$ and put the values into $iColVec$.

x. Normalize $iColVec$ so as to be $sum(iColVec) = 1$.

xi. Update $signalMatrix(:, iNoiseCol)$ as $signalMatrix(:, iNoiseCol)iColWeightx1.15xiColVec$

xii. Update $weightVec$ by multiplying a row of the logical filter matrix, and normalize $weightVec$ to be $\|weightVec\| = 1.0$.

   xiii. Compute $iColStd$ which is a standard deviation vector of $signalMatrix.*$ logical filter matrix at the 1st dimension.
   xiv. Update $iColStd$ as $sum(iColStd.xweightVec)$.
   xv. Compute $iColStdRatio = suqrt(standarddeviationofiNoiseCol{-}thcolumnofsignalMatrix/iColSt$
   xvi. Update $signalMatrix(:,iNoiseCol)$ as $iColMean+(iNoiseCol{-}thcolumnofsignalMatrix-iColMean)/iColStdRatio$.

6. Remove mechanical noise above 1000 pixel, if $mean(mean(prctile(normalizedsignalMatrix(1:50,:),75:100))) > 0.5$

   (a) Iterate Step4.b- 4.f

7. Remove salt and pepper noise of $signalMatrix$ using MATLAB $wiener2()$ function with neighbourhoods option [55].

8. Convert signalMatrix to an image using sigmoid function as colour bar. (see Figure2 (d))

9. Binarize the colour image. (see Figure2 (e)) item If more than 2 objects overlap in the binary image, manually edit. (see arrows in Figure2 (d) and (e))

10. Compute shape scripters for each object, e.g. $Centroid$, $Area$, $MajorAxisLength$, $MinorAxisLength$, $Perimeter$, $Extrema$, $ConvexArea$ and $Orientation$, using MATLB $regionprops$ function. (see Figure2 (f))

11. Select objects which have area > 200 pixel and width > 20 pixel.

12. Compute depth, longitude, latitude, width for the selected objects.

13. The objects are categorized into 7 types, by the depth (shallow, middle and deep) and area (small and large) / width. The criteria are shown in Table1. For instance, data type “ds” represents deep-small object. “# of objects” is total number of objects in the 79 echograms.

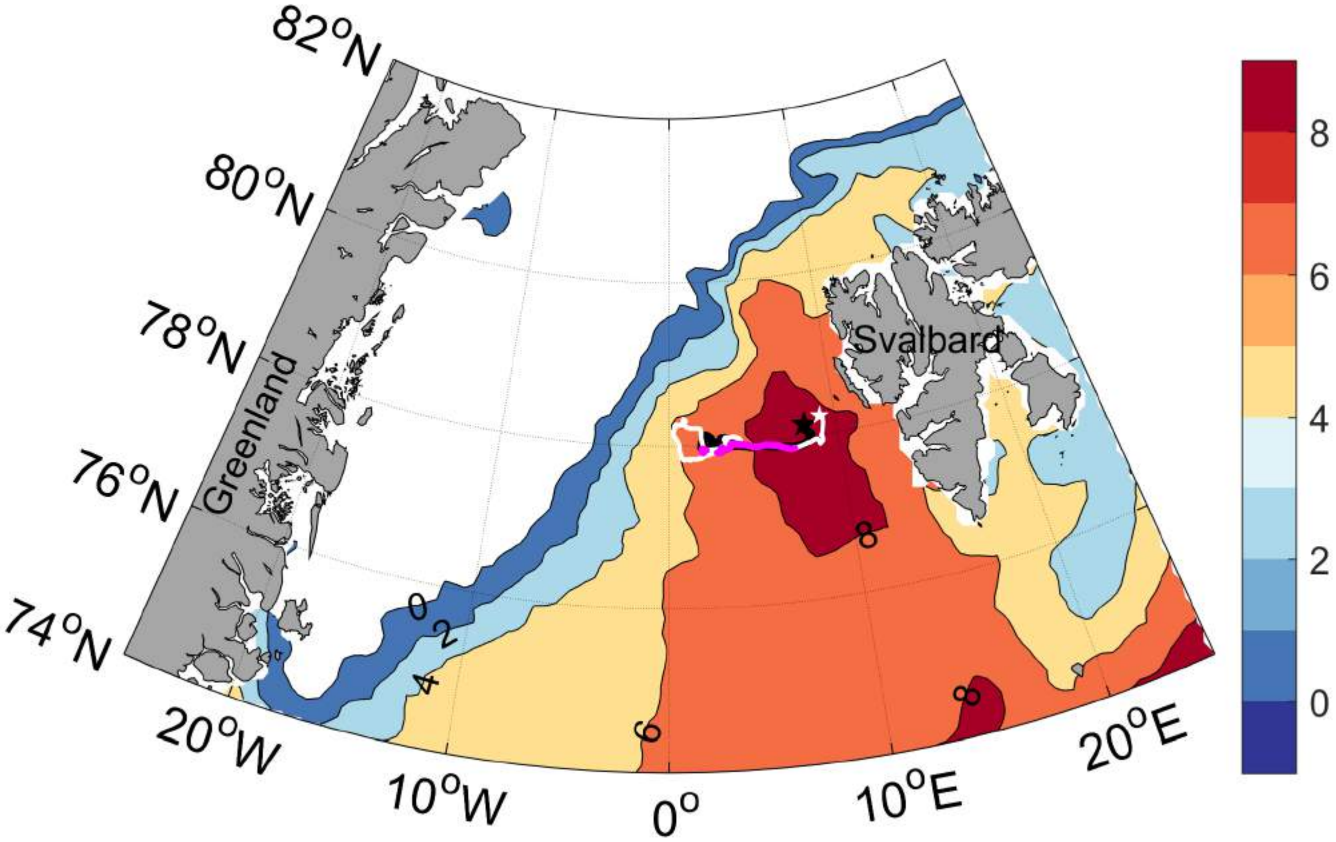
5 Results

Figure 4 shows the distribution of temperature at the 5 m depth level from TOPAZ on 18 July 2016. The 0°C contour roughly outlines the area covered by sea ice, which formed a wide tongue from the north along the western side of the Fram Strait. Along the Greenland coast and shelf, the sea ice extended almost as far south as 74°N, while the warmer eastern side of the Strait was ice-free beyond 81°N (north of Svalbard). The SailBuoy tracks were made in the latitude band where the east–west surface temperature gradient was the strongest, with the highest (> 8°C) and lowest (< 0°C) temperatures found only a few km apart. For comparison, south of Svalbard a much wider zone was occupied by water with “intermediate” surface temperatures, between about 4 and 8°C.

The time series of the various parameters measured by the “ocean acidification vehicle”, SB Iskant, are shown in Figure 5. Air temperatures reached as high as 17.75°C. Measurements from Longyearbyen airport (yr.no) around the same time showed lower temperatures, but summer air temperatures of 17–18°C do occur on these latitudes.

The SailBuoys spent the first days after deployment close to the deployment site (see section 2.1) before being given waypoints further away. The movement of the sea ice – which we wanted to avoid the SailBuoys getting into – meant that sailing plans had to be revised continually, and as mentioned in section 2.1, the sailing was sometimes made difficult by the combination of currents and low wind speeds. As a result, the SailBuoy tracks can be complicated to follow. In figure 6 the track of SB Iskant is shown with different colours for each calendar day, to make it easier to disentangle its route, especially where it covered the same ground more than once.

The variation of some of the measured parameters along the track of SB Iskant are shown in figure 7. Overall, the surface water temperature was lower on the western part of the track than in the east, in agreement with the satellite-measured temperature field (cf. figure 4). However, the along-track temperature plot shows that some of the lowest temperatures were measured in a location where, some days earlier, warmer water had been encountered.



Figur 4: TOPAZ-reanalysis temperature field from 5 m depth on 18 July with the two SailBuoy tracks overlaid, SB Iskant in black and SB Nexos in white and pink; pink marks the parts of the track along which the echo sounder was operating. The final position (point of recovery) of each SailBuoy is marked by a star.

Figure 8 shows the vertical temperature distribution in the upper 100 m along the XBT line, with the MLD overlaid. The MLD varied between 7 and 20 m with an average of 13 m (standard deviation 4 m). Shallow MLDs, ranging between 5 and 30 m, are not uncommon in the Arctic Ocean during summer (Peralta-Ferriz and Woodgate, 2015). The mixed layer depths from XBT profiles were compared with the depth of an object type found in echograms, classified as a layer of phytoplankton. The plankton layer depth was between 3 and 20 m and thus agreed rather well with the MLD (see Yamakawa et al., 2017, conf. proceedings).

In classical oceanography, temperature–salinity (T–S) diagrams are used to categorize water masses, since water masses of different origin will have characteristic combinations of temperature and salinity. The distribution of data points in “T–S space” can say something about how many different types of water of different origin are present, and how they are mixing with each other. For classification of water masses and comparison with literature we must keep in mind that the SailBuoy measurements represent only the top 0.5 m of the water column. Surface water differs from the subsurface water in that it is in direct contact with the atmosphere, and with sea ice if present, and thus undergoes changes such as heating or cooling, input of fresh water from melting ice, etc.

A T–S diagram of the data from SB Iskant is shown in figure 9a. Here, the points in the T–S diagram are in addition coloured by the partial CO_2 pressure (μatm). The T–S diagram in figure 9b is coloured by the O_2 saturation (%) in water.

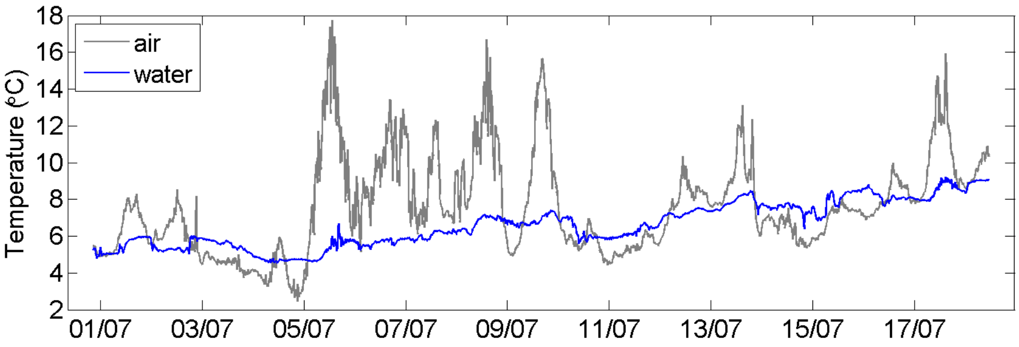
Most of the salinities measured were > 34.9 or even > 35.0, suggesting a relatively strong influence from the Atlantic Water carried by the West Spitsbergen Current. Since the measurements were made in the eastern part of the Fram Strait, the strong Atlantic Water influence is not surprising.

Apparently the SailBuoy encountered three types of water along its path:

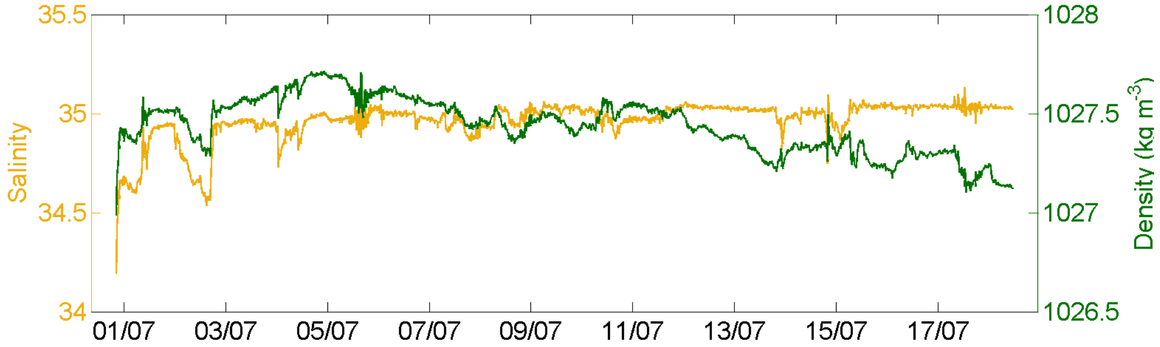
i Very warm and saline

ii Cool and somewhat less saline; low O_2 saturation

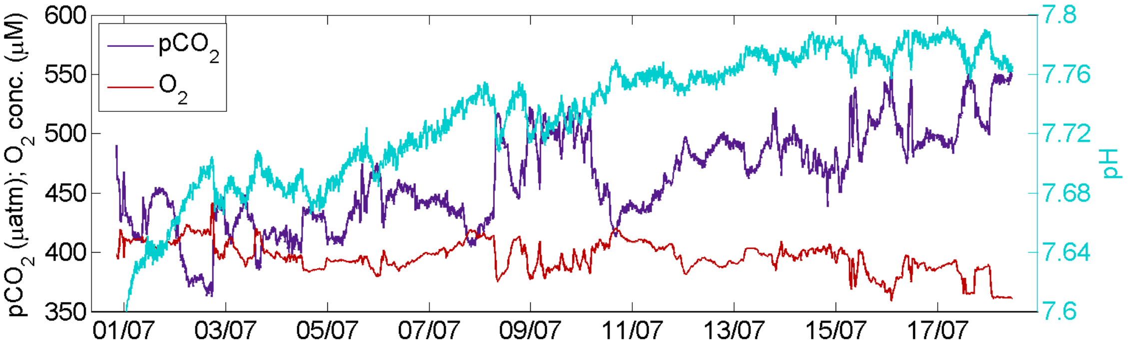
iii Fairly cool and much fresher; low pCO_2 pressure



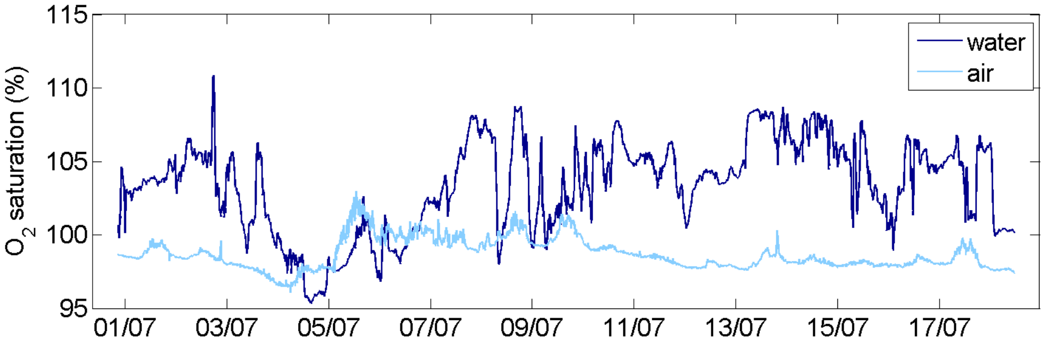
(a) Temperature in air and water



(b) Salinity and density

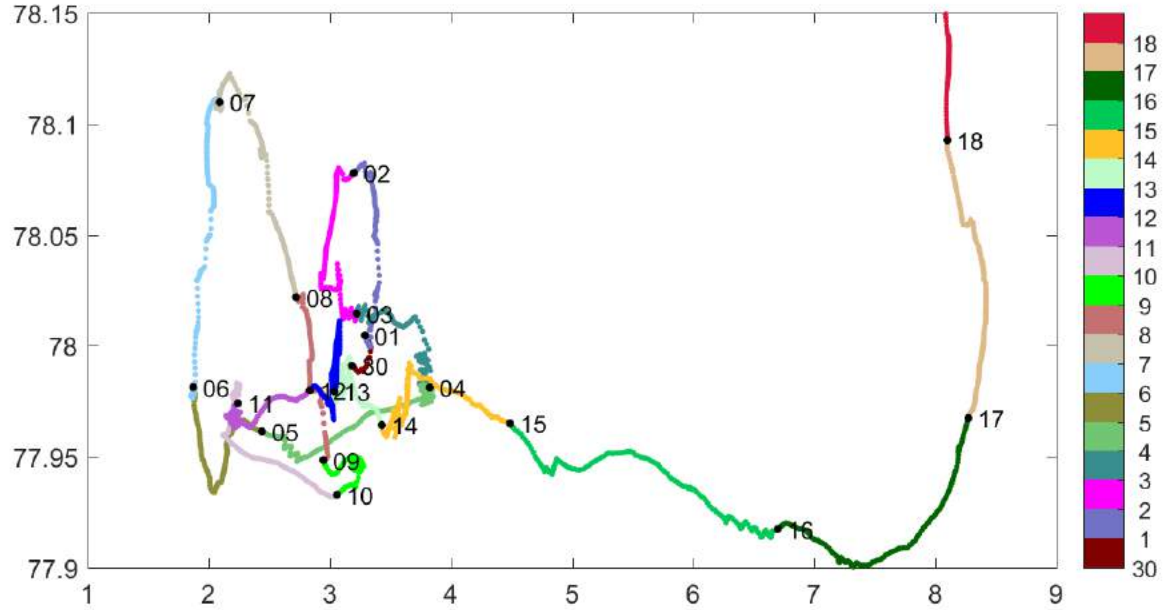


(c) pCO_2, O_2, and pH

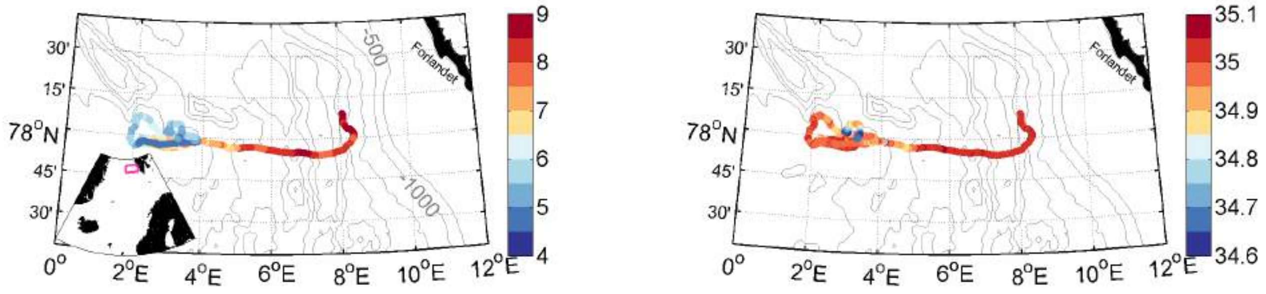


(d) O_2 saturation in air and water

Figur 5: Variation in time throughout the deployment of physical and chemical parameters measured by SB Iskant.

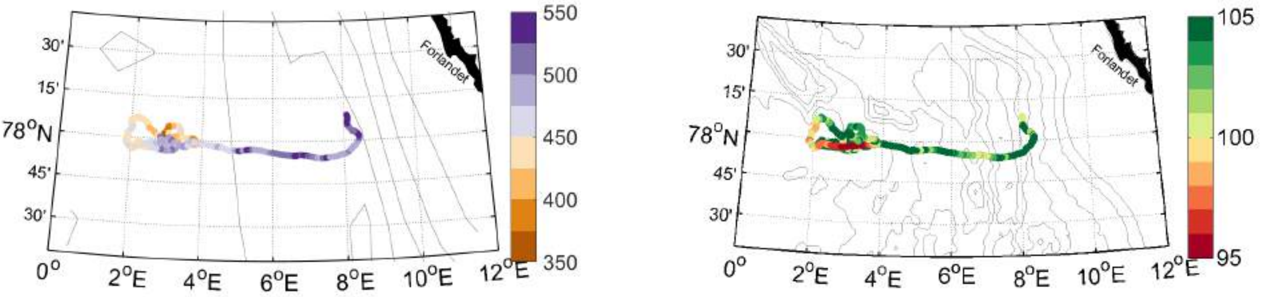


Figur 6: The route of SB Iskant with each calendar day shown in a different colour (see colour bar on the right). The start (00:00) of each day is marked by a dot and labelled with the date.



(a) Water temperature (°C)

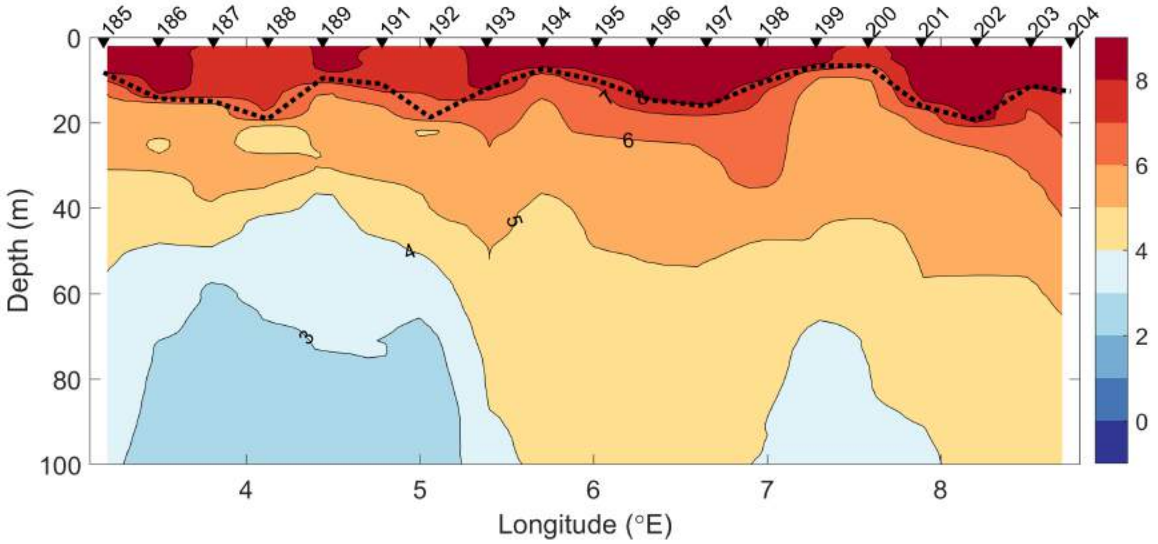
(b) Salinity



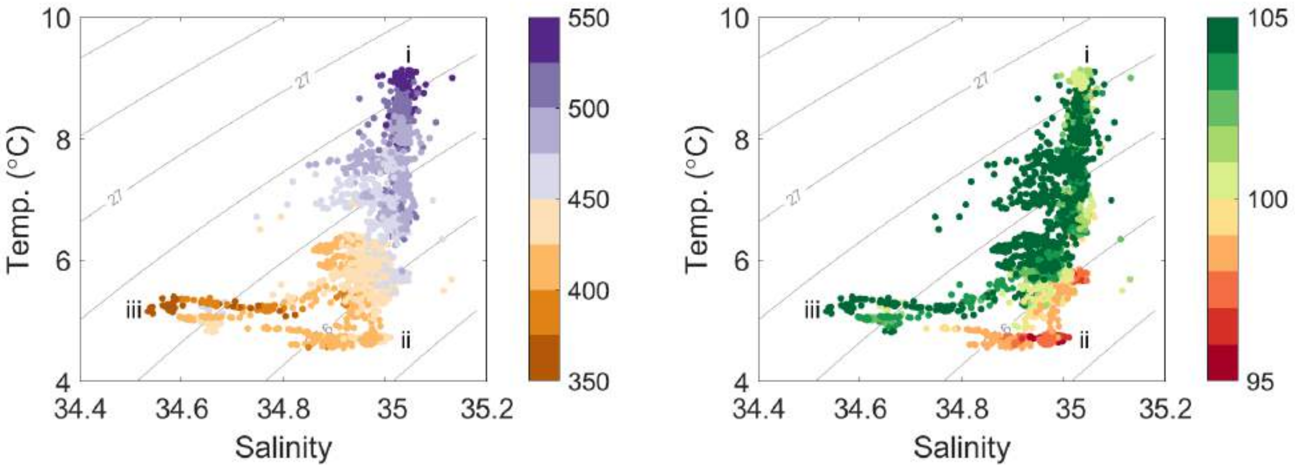
(c) pCO2

(d) O_2 saturation in water (%)

Figur 7: Along-track variation of physical and chemical parameters measured by SB Iskant. Small inset map in (a) shows the location of the study area in the wider Nordic Seas region.



Figur 8: Temperature section based on XBT profiles along a line parallel to the SailBuoy track (cf. figure 3b). The colour scale, see bar on the right, covers the same range as that of the surface temperatures in figure 4. The dashed black line marks the mixed layer depth (MLD).



(a) T/S-diagram coloured by pCO$_2$ (μatm)

(b) T/S-diagram coloured by O$_2$ saturation in water (%)

Most data points are more or less on a line between the very warm and saline, ca 9°C, > 35.0, that we may refer to as Atlantic Water (marked by *i* in Fig. 9b), and less saline and cooler (ca 4.5°C, < 35.0) water that coincides with the only low O_2 saturations (*ii*).

The SailBuoy also encountered some water with significantly lower salinity. As mentioned above, salinities would generally be lower where one might expect more influence from water from the west (closer to the fresh East Greenland Current, and closer to the ice). However, the salinity did not only change gradually (or stepwise) from east to west - the minimum salinity was not encountered at the westernmost or northernmost points. Instead, the sharp jump in salinity in an area where higher salinities were found before and after, indicates that the SailBuoy passed in and out of a “blob” of fresher water, perhaps a small eddy. There was no difference in O_2 saturation between the surface water in that fresh feature and the surrounding water, but the pCO_2 pressure was lower than observed elsewhere.

6 Conclusions and recommendations

A successful 2.5 week deployment of two unmanned SailBuoys was made in the Fram Strait in 2016. A brief summary of findings so far:

- Three different water masses were observed, with distinct combinations of temperature, salinity, O_2 and pCO_2.
- The SailBuoy passed through a feature – possibly a small eddy – with low surface salinity.
- Water temperature and salinity varied over short distances and at time scales.
- When the wind speed increased, the buoys sailed faster; at the same time, satellite chlorophyll data were missing because of cloud cover, and the acoustic data got worse (presumably) because of waves causing in bubbles, and thereby noise. Increased wind speed can thus improve sailing ability, but may negatively impact measurement quality.
- A method of automatically identifying objects in echograms was developed. Objects seen in the echograms from the SailBuoy were categorized by their shape, and interpreted as plankton, individual fish or fish schools.
- The automatically identified and classified objects from the echograms were compared with satellite data and with the independently made measurements from the other SailBuoy. More work is needed to reliably interpret the relationships between the various observed parameters, but it is clear that using two SailBuoys with different instrumentation in tandem opens up interesting possibilities.

For similar work in the future, we recommend the collection of more ground-truthing data for all parameters, including net-hauls for validation of echo sounder observations. To avoid the challenge of disentangling meandering paths, one might choose to leave the SailBuoy to keep a position for longer (’virtual mooring’), or let it follow a longer straight paths, avoiding repeats.

The most important outcome of this technology-driven project is that the new sensor package appears to have worked well, and an interesting multi-parameter data set was collected. The interpretation of the results in terms of oceanography, biogeochemistry and marine biology needs more work. The oceanographic and biogeochemical data set from the project have been made publicly available (links to records below). The results of the acoustic data analysis have been presented at a conference in 2017 and published in the conference proceedings (see below).

Acknowledgements

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Communication of results

Contributions to conferences and workshops

- Echosounder observations from an unmanned surface vessel in the Arctic. Talk given by A. Yamakawa at the Underwater Acoustics Conference & Exhibitions, 4-8 September 2017, Skiathos, Greece.

- A voyage in the Fram Strait in summer 2016 with two small unmanned sailboats (SailBuoy). Talk given by J. Ullgren at the SSF Ocean Flagship 2nd Workshop, 4-5 October 2016, Osøyro, Norway.

- Observational studies of ocean circulation using mainly in situ measurements from moorings, sailbuoys, shipboard instruments, and gliders. Talk given by J. Ullgren, 2016 Aanderaa Workshop, 6-8 September 2016, Hardingasete, Norway.

Publications

- A. YAMAKAWA, J. ULLGREN, AND R. Ø YERHAMN (2017, SEPTEMBER). Echosounder observations from an unmanned surface vessel in the Arctic. In J. S. Papadakis (ed.). UACE 2017. Proceedings, 4th Underwater Acoustics Conference and Exhibition. Volume 38, part 4, p. 287 - 292. Paper presented at UACE2017, Skiathos, Greece.

Public data

- Metadata record on GeoNetwork for the physical and biogeochemical data from SB Iskant.
- The record can also be found by searching (e.g. by project name “Iskantseilas”) on the Norwegian Marine Data Centre (NMDC) web page.

Tabell 1: For every day of the mission: the position of each SailBuoy at noon UTC (if not otherwise noted), some notes on their activity such as the given waypoint, and the wind observation taken at KV Svalbard at 10:00.

Date	Wind KVS (kn)	SB Iskant		SB Nexos		Activity/ Comments
		Lat (°N)	Lon (°E)	Lat (°N)	Lon (°E)	
2016-06-30	S 3	77.99	3.18	77.99	3.17	Deployment at 19:33 SB Iskant, 19:47 SB Nexos. (Position at 19:40, 19:50 respectively).
2016-07-01	S 4	78.06	3.38	78.00	3.63	WP 78.0 N, 4.0 E. Testing navigation.
2016-07-02	E 2	78.03	2.93	78.07	3.27	Keeping position until tested maneouvering in higher winds.
2016-07-03	N 3	78.01	3.68	78.00	3.94	— ” —
2016-07-04	N 6	77.97	3.55	77.99	3.78	WP 78 N, 2 E closer to ice (ca 40 km from ice edge). From there head north. Current towards west.
2016-07-05	NW 3	77.94	2.09	77.92	2.04	Plan to steer towards 78.5 N, 4 E, then to 79 N, 4 E.
2016-07-06	S 4	78.07	2.04	78.15	1.91	WP 78.5 N, 4 E. Slow progress, and SB Nexos a bit off track, due to current and little wind.
2016-07-07	N 2	78.08	2.43	78.30	0.89	Ice moving south, belt of ice down to 78.3 N, 3 E. Little wind; NW current. Steering SSE to avoid getting caught in ice.
2016-07-08	N 4	77.98	2.83	78.12	0.30	SB Nexos position at 12:30.
2016-07-09	N 3	77.94	3.24	77.83	1.17	WP 78 N, 2 E.
2016-07-10	NW 3	77.96	2.15	77.84	1.77	WP 78.5 N, 3 E to get closer to ice; slow progress because of weather.
2016-07-11	N 4	77.96	2.35	77.88	2.34	WP is mooring site UI2: 78.0 N, 3.8 E.
2016-07-12	N 4	77.99	3.02	77.94	3.05	— ” —
2016-07-13	NW 3	77.99	3.10	77.94	3.43	— ” —
2016-07-14	W 3	77.98	3.65	78.00	3.81	WP is mooring site UI1: 77.9 N, 8.75 E.
2016-07-15	N 5	77.94	5.83	77.95	6.11	Echo sounder battery out of power.
2016-07-16	NW 4	77.91	7.69	77.95	8.66	Higher velocity eastward. New WP: 79 N, 8.75 E.
2016-07-17	SE 2	78.03	8.40	77.98	9.08	— ” —
2016-07-18	N 3	78.15	8.08	78.23	9.22	Recovery: SB Iskant picked up at 10:00 UTC, SB Nexos at 14:00 UTC.

Tabell 2: List of variables output from the sensor package on SB Iskant. Variable names in bold are those saved in `sb_fs2016.mat`, used for most of the plotting and analysis. Numbers refer to the column numbers in the text file `sb_fs2016_full.txt`. Columns 1–6 are combined and converted to Matlab date format ('Day').

1 Year
2 Month
3 **Day**
4 Hour
5 Minute
6 Second
7 **Record Number**
8 **pCO$_2$ [uatm]**
9 **CO$_2$ [mg/l]**
10 **Temperature** [°**C**]
11 CalPhase [°]
12 Phase [°]
13 C1RPh [°]
14 C2RPh [°]
15 C1Amp [mV]
16 C2Amp [mV]
17 RawTemp [mV]
18 **Conductivity [mS/cm]**
19 **Temperature** [°**C**]
20 **Salinity [PSU]**
21 **Density [kg/m3]**
22 **Soundspeed [m/s]**
23 **O$_2$Concentration [uM]**
24 **AirSaturation [%]**
25 **Temperature** [°**C**]
26 **O$_2$Concentration [uM]**
27 **AirSaturation [%]**
28 **Temperature** [°**C**]
29 **pH**
30 **Temperature** [°**C**]
31 CalPhase [°]
32 DPhase [°]
33 C1RPh [°]
34 C2RPh [°]
35 C1Amp [mV]
36 C2Amp [mV]
37 RawTemp [mV]
38 Input Voltage [V]
39 Memory Used [Bytes]
40 **GPS Latitude** [°]
41 **GPS Longitude** [°]