Reply to referees Ver 19.6.2018

Anonymous Referee #1
Received and published: 26 February 2018

Laakso et al. One hundred years of atmospheric and marine observations at Utö Island, the Baltic Sea Ocean Sci. Discuss., https://doi.org/10.5194/os-2017-105

Review

RC1_1: The paper presents long-term meteorological and oceanographic data from the Utö station in the north-eastern part of the Baltic Proper (Archipelago Sea). It is a very valuable source of information for meteorologists, oceanographers, and climate researchers. I strongly recommend publication of the results.

The authors thank the anonymous referee 1 for his/her positive words on this manuscript.

RC1_2: However, the paper could be improved by adding more scientific discussion points. My main concern is that the statistical analysis results are presented, but not properly discussed. Much more can be done/analyzed that would help to put the results into a wider context.

We have added more discussion and compared the results with previous studies. All addition in the manuscript are written in red font.

RC1_3: Physical processes, which could cause the observed changes in stratification and deep layer characteristics are oversimplified in the analysis – mostly the changes are explained by vertical mixing. As shown in the Gulf of Finland, the stratification very much depends on wind conditions – winds from a certain direction tend to strengthen the stratification and opposite direction weaken it. Thus, bidirectional lateral transport is an important factor.

We added more discussion and references related to this topic.

RC1_4: I think, a look at the topography of the study area (and connections, sills between the Utö Deep and Baltic Proper) could be relevant.

This is a good an a relevant comment, which we further analyzed the following way:

1) We compared the available data between Utö and observation point LL15 (59°10.99'N;021°44.80'E, approximately 70 km SSE of Utö, max depth 130 m). Unfortunately, we do not have very well overlapping data period, but we made a short gif-animation (Figure R1) which clearly shows that the salinities start to deviate at 60 meters, indicating indeed that the water below this depth do not always represent the central Gulf of Finland.

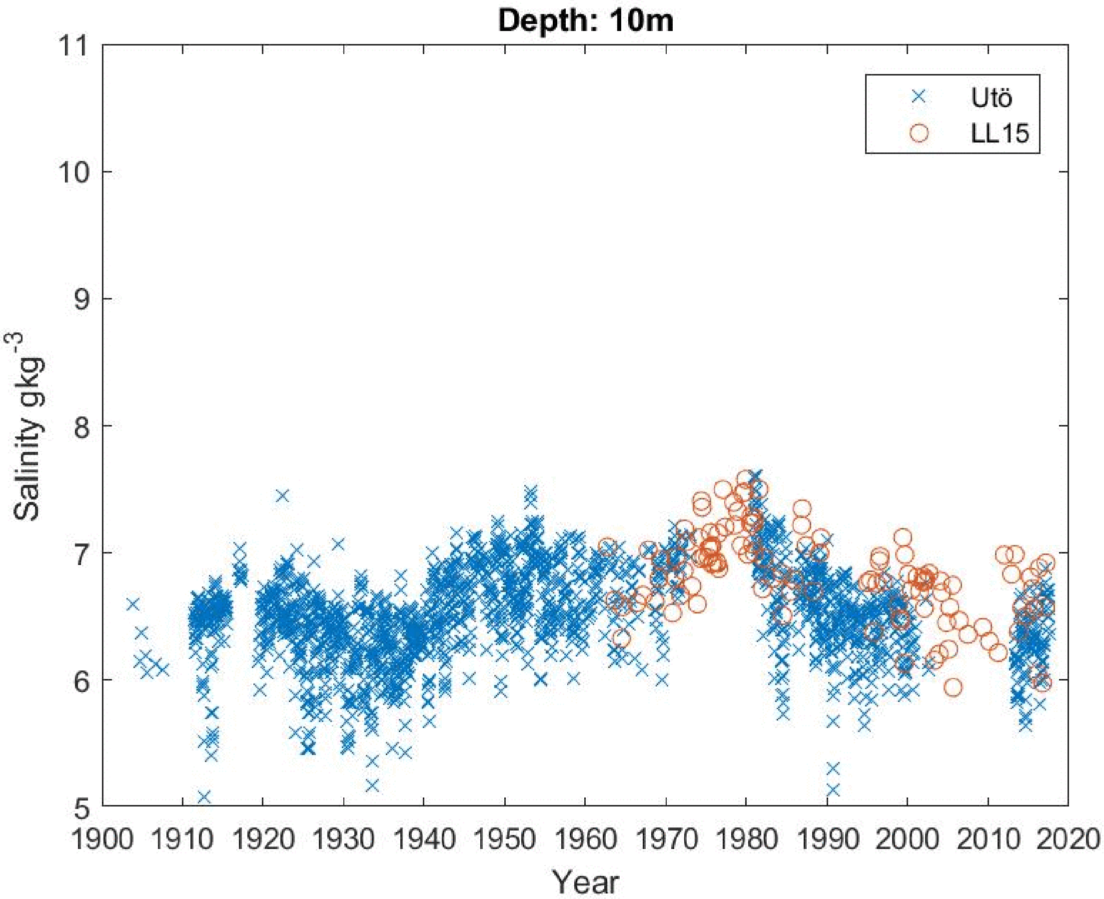

Figure R1: Time series of salinity at different depths in Utö and observing point LL15. This figure is also given as a separate file.

2) However, this is not always the case: we see sometimes saline bottom water reaching our measurement location and a halocline between 50 and 70 meters depth (Figure R2). Such periods may last for several months. These situations and reasons behind are interesting, and worth of another study.

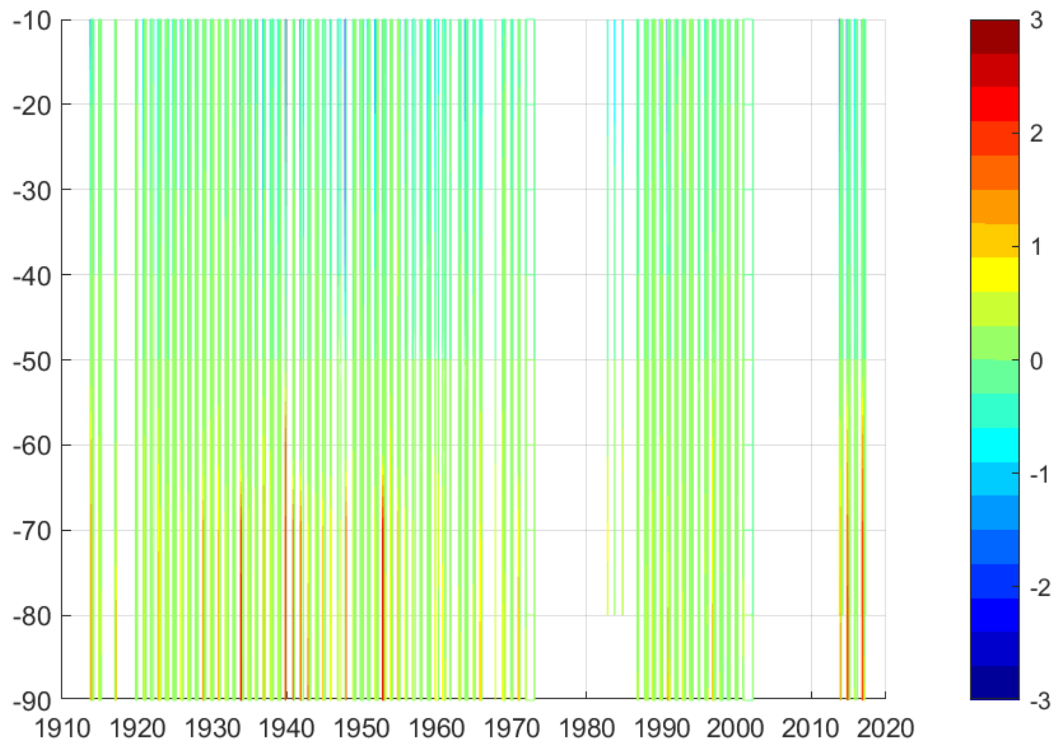

Figure R2: winter months (Oct - March) salinity difference between 50m and other depths (salinity at depth X divided with salinity at 50 meters).

We see that the saline water is sometimes able to reach Utö deep and there is a halocline between 60 and 70 m. However, it is observed only for short periods. This indicates in some cases, e.g. strong enough major Baltic Inflow or e.g. special situation with underwater currents, we have a halocline also at Utö deep.

Based on dataset used in this paper and the combined profiling buoy and ADCP-measurements started in April 2018, we may be able to understand this phenomenon better in the future.

3) The sea areas surrounding Utö are military areas and the depth maps publicly available do not necessarily represent the actual depths of the sea. Based on public data, we see (new Fig. A2 in the manuscript) that there is an area with depth of ~60 m on the western side of Utö and one further south, which may prevent the deep, saline water from entering the location of hydrographic observations. We composed a map based on public data, which is now attached in the appendix.

4) During the spring 2018, we have made some CTD-soundings (Figure R3) next to our new profiling buoy (Fig A2, location 6) and compared those with the observations on our long-term hydrographic observing location (Fig A2, location 1). The salinity profiles overlap between the surface and 60 m depth, while the salinity between 60 and 75 m is higher in the location South of Utö

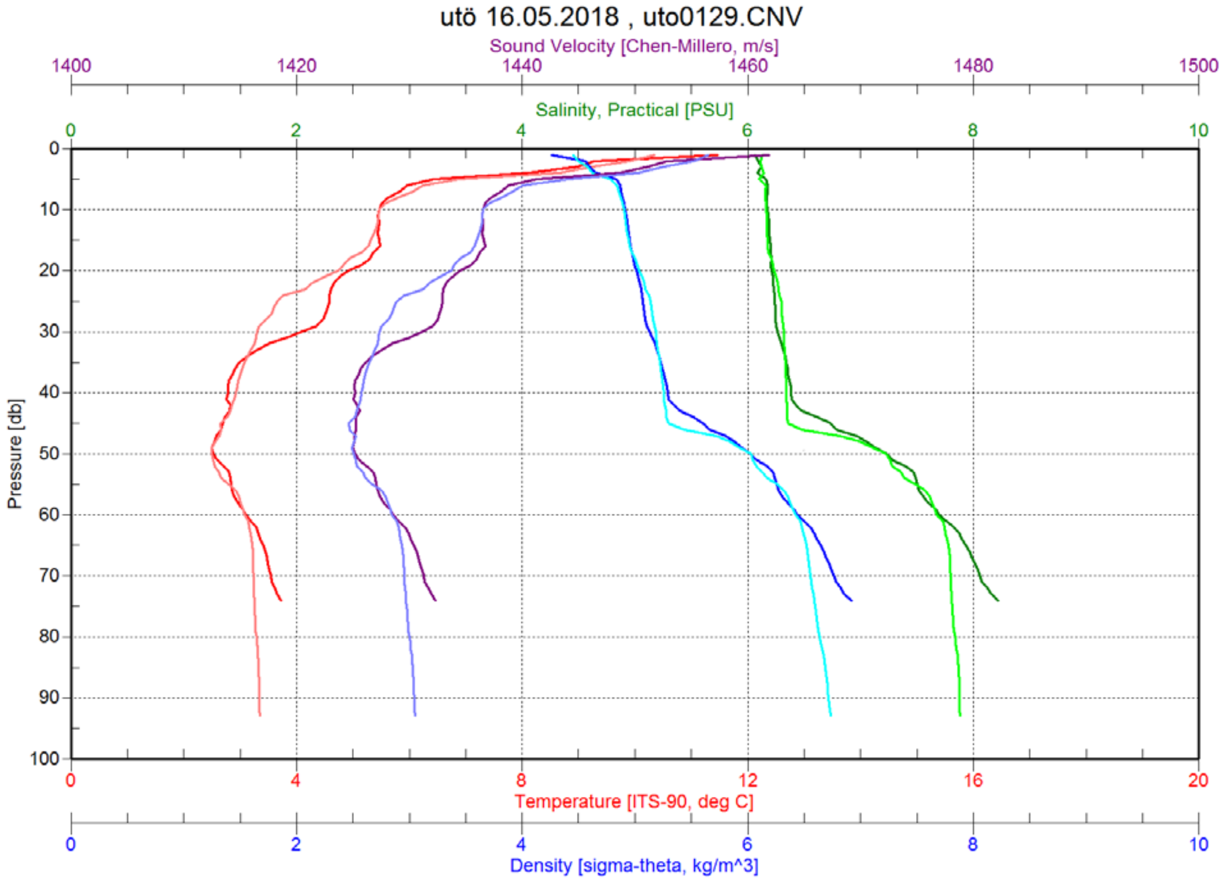

Figure R3: CTD profiles taken in the traditional measurement location (Figure A2, location 1: curves 0...94 m) and next to the profiling buoy (Figure A2, location 6, curves 0...75 m) in 16 May 2018.

This question is now shortly discussed in the paper

RC1_5: Also, as mentioned by the authors, this analysis sets the background for the further studies of biogeochemical changes. But no suggestions are made on this subject in the paper/discussion.

We added the following paragraph in the conclusions:

“An interesting study utilizing the time series presented in this paper together with the new observations will be to use the new cabled bottom profiler together with an ADCP (Fig. A2 and Table A1) to study the occasional inflows (briefly discussed in this paper) of saline bottom water which may have significant impacts on the Archipelago Sea ecosystem (Vuorinen et al., 2015).

Another planned study combining hydrographic observations with biogeochemistry and climate change is to use the profiler together with the flow-through system to analyze the thickness of biologically active layer and its connection to the marine carbon cycle.

Together with our new observations, the long data series represented in this paper will support better understanding of both the earlier observations and current, on-going physical, chemical and biological changes of the Baltic Sea."

Specific comments

RC1_6: Abstract
There are some spelling errors in Abstract. Please, correct them.

Corrected.

RC1_7: P1, L14-15: The last sentence of Abstract has to be rephrased. If I understand the results correctly, the ice does not cause large local effects anymore in this new phase. In the present form, the sentence has an opposite meaning that the ice does not reduce local effects. Did it reduce or cause the local effects earlier?

Clarified. The aim is to say that we see increase in local atmospheric temperatures at Utö only after the duration of ice cover has significantly decreased.

RC1_8: 1. Introduction
I miss a broader problem setting. Also, a scientific aim of the study could be formulated.

Clarified and better stated aims added.

2. Measurement site and general characteristics

RC1_9: P2, L29: I would avoid using the term "seasonal sea" which is not commonly used in the scientific literature.

Changed

RC1_10: P3, Fig. 1: It is quite empty. At least the sub-basins of the Baltic mentioned in the text should be shown (Archipelago Sea, Baltic Proper, Gulf of Finland, etc.). Also, consider presenting a local map where the oceanographic measurement site with the topography of the surrounding area could be seen.

Added to the map. We also added a local map around Utö in the appendix (Figure A2).

RC1_11: P4, L3-5: I agree that saline water inflows and freshwater input keep the stratification strong, but I do not agree that it causes the deep water to be anoxic. It could be opposite – saline water inflows could ventilate the deep layer. Moreover, the main reason for oxygen depletion is consumption of oxygen.

Removed

RC1_12: P4, L13-15: It is not obvious how the bottom topography and prevailing winds cause strong currents in the Utö Deep. Please, give a reference or explain it (also providing a map with topography if appropriate).

Finnish Geological Survey has mapped the areas close to Utö and found eroded areas at the bottom. We have access to this data, but are not able to publish it. The potential for strong flows is clearly visible in the canyon-like shape of the Utö deep (Figure A2).

In October 2017, we deployed an ADCP in the area, but unfortunately the acoustic releasers did not function, so we haven't been able to obtain the data yet (we try a ROV recovery later this year). We deployed a new ADCP in April 2018, so current data will become available in spring 2019.

3. Observations and methods

RC1_13: P4, L28-29: Please consider other options for sub-titles, e.g., "Observations and methods" instead of "Observations and methods used in this study"

Changed.

RC1_14: P6, L25-26: I do not understand the last sentence of this sub-chapter "In aim to keep the focus of this paper solid, we focus on a selection of the variables instead of all possible seasonal data." Please, rephrase it.

Removed. The aim is to simply state that with the available data set, we can calculate a lot of different things, but decided to focus on certain aspects only, to limit the length of this paper and keep it easier to read.

4. Results

RC1_15: P7, L9-13: Is the annual mean NAO index the best parameter to use here? For instance, Lehmann et al. (2011) did use NAO winter index (from December to March). Also, I do not see that the highest negative NAO values and low temperatures are connected (e.g., 2009 has far lowest NAO but not the lowest temperature).

We slightly modified the sentence as it was not accurate.

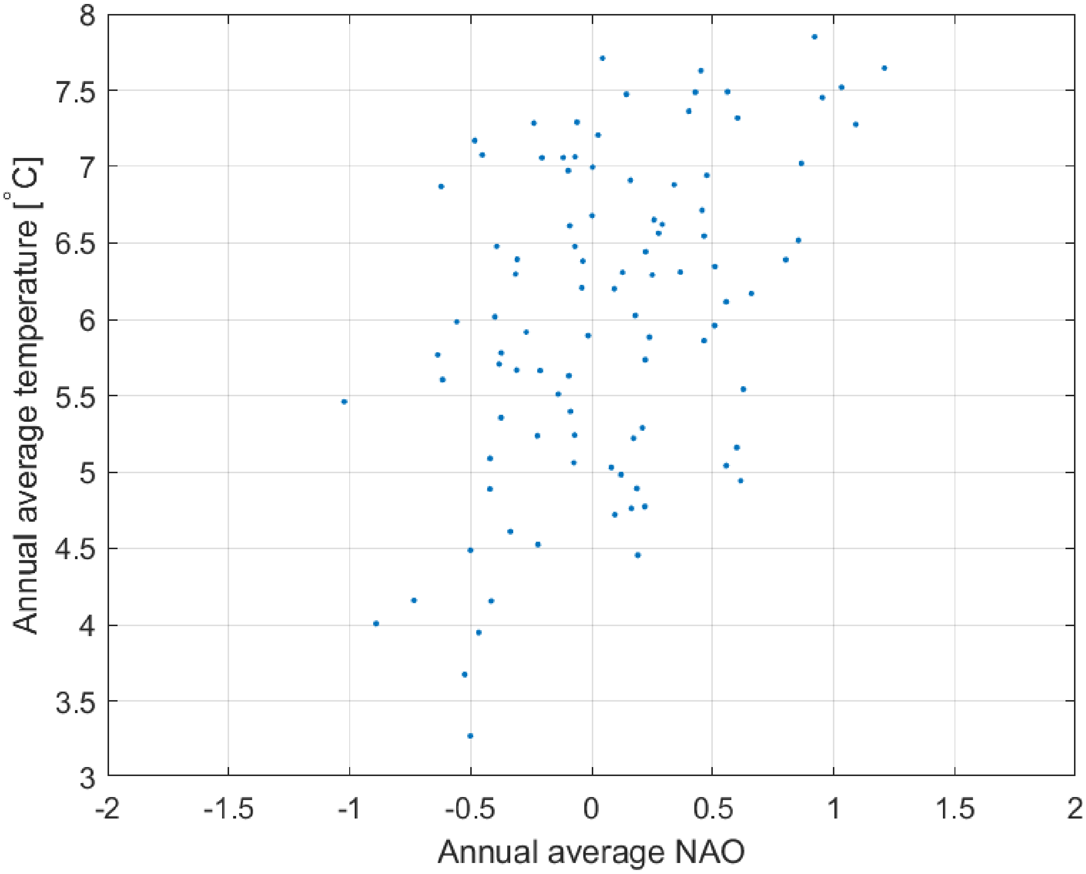

Figure R4: Annual average temperature as a function of annual average NAO. The average temperature for NAO < 0 is 5.7°C and for NAO>0 it is 6.3°C .

There is a lot of scattering in the data (Figure R4), but we see that the warmer years are typically with higher NAO index values and vice-versa. If we plot instead of annual average temperatures the winter time temperatures as function of winter time NAO, we see somewhat higher correlations.

RC1_16: P9, L9 and Fig. 6: Why median values are used here?

There was no particular reason to choose between mean and median. The resulting figure is not sensitive for this choice.

RC1_17: P9, L13-14: I do not agree with the suggestion that the relatively strong currents are the reason for the absence of the halocline. Could the bottom topography restrict saltier water transport into the Utö Deep?

We agree with the comment and have modified the article accordingly.

RC1_18: P11, L7-9: What do you mean by “we calculated the top and bottom of mixed layer depths”? I did not find a method in Lips et al. (2016) for that.

Reference left out and text modified.

What we actually did: We used a method inspired by the paper by Lips et al (2016) to determine the location of mixed layer. We basically described the top of the thermocline to be the location where the density had increased 0.25 kg/m3 from the density at 5 m and the bottom of thermocline the location where the density was 0.25 kg/m3 less than the density at 50 m. We also required the total density difference between 5 m and 50 m to be at least 0.5 kg/m3. Visually, this gave quite reasonable values. But this is now left out.

RC1_19: P11, L13-16: What could be these other phenomena responsible for deep water temperature increase in the 1980s and 1990s and recent decrease?

We do not know. In aim to see the potential effect of river runoff, we combined a data series for total Baltic Sea river runoff for the period 1900-2016. As we think these data will support the discussion in the paper, we included it as third panel in the Fig. 10.

We also added the following paragraph in the section 3.1 Observations and other data:

“River run-off data for the period 1900-2016 is a combination of observations for the period 1900-1995 (Hansson et al., 2011) and modeling for the period 1996-2016 (Johansson, 2018). The offset between the two data sets was corrected by calculating averages for both data sets for the overlapping period 1950-1995 and correcting the modeled data with the difference “

We also studied data by plotting e.g. monthly averages of sea water temperatures and salinities at different depths and tried to see if we can better figure out the differences. For example, we saw that during the period 1990-2000 the autumn time salinity difference between 90 and 50 meters was ~0.1-0.2 g/kg, while in 2013-16 it was almost 1 g/kg. As the the vertical mixing takes place during this period (Fig. 6), there is more resistant for the vertical mixing during the later period.

We will understand this phenomenon better in the future, when we have collected at least one year of high time-resolution data on sea water temperatures, salinities, underwater currents with the new instruments installed in April 2018.

RC1_20: P12, L3: Stratification should not be large and small, but rather strong and weak.

Corrected.

RC1_21: P12, L9-11: Do you explain the observed changes in deep water temperature by vertical mixing and stratification only, or is it possible that these changes are related to lateral exchange? Please, explain it because it is not clear what are “these changes... responsible for the increased water temperatures at 50 m and 90 m depths”.

There has not been significant changes in the wind pattern during the period 1960-2016, as seen from Fig. R5 below. Thus, while for individual periods the lateral exchange has definitely a strong impact, we do not assume it has influenced the trends.

RC1_22: P12, L14: What is meant by “We also see a rapid increase in 1940s”?

Added word “salinities”

RC1_23: P13, L7-8: Why these 30-year periods were selected for the comparison. It could be reasonable for the atmospheric data, but not for the oceanographic parameters which revealed a rapid change in the 1990s.

We decided to use the standard climate periods. However, we added a clarification in the text stating this.

RC1_24: P13, L14-15: Has this sentence (“However... ”) the meaning of the previous comment that the chosen periods hide the rapid change after the 1980s?

Sentence improved

RC1_25: P14, Table 1: How these averages and standard deviations were estimated?

Simply calculated from the data using standard Matlab functions. We found a small inconsistency in our calculations and re-calculated the values and updated the table accordingly.

5. Conclusions

RC1_26: P15, L15: The saline water inflows increase salinity in the deep layer, but they could cause either an increase (mostly) or decrease in temperature. This change is not directly connected to the reduced vertical mixing. Do you have any pieces of evidence that the observed decrease in deep water temperature was due to the reduced vertical mixing?

If we look Figs 7 and 8, we see that there is larger salinity gradients in 1910-1920, 1960-1970 and again after the last increase (2013→) in salinity. In all cases, the bottom water temperatures have been lower as well. It is not of course possible to definitely say this is the case, but based on the data, we think is may be the case. Please see also reply to RC1_19.

Referee 2, I. Vuorinen
Received and published: 3 May 2018

RC2_1: 1General comments:
The paper presents first time digitized and quality assured oceanographic data from the Northern Baltic proper in (semi) open sea conditions. Temporal range of the data is impressive, starting in 1881. Spatially the data is from one spot, which lies somewhat mid-way between open sea and coastal conditions, also between the Bay of Bothnia and the Gulf of Finland. Approach and methods are basic, which is okay for this type of paper (presentation of a new, significant data set).

The authors thank for the support for publishing this paper.

RC2_2:The discussion could be somewhat more extensive (see below in specific comments). Presentation of figures and tables is appropriate (with some exceptions which are commented below), and English is mostly okay. I suggest below some places where wording should be reconsidered.

I suggest publication with minor corrections.

Specific comments
RC2_2: Title: One hundred years of atmospheric and marine observations at Utö Island, the Baltic Sea. -There are several islands with that name in the Baltic. I know of one in Sweden and two in Finland. Consider adding the coordinates, the country, or other information in the title in order to avoid mixing at least with the Utö in the Stockholm archipelago.

We agree with the comment especially with the possible confusion to Swedish island Utö and changed the title to “One hundred years of atmospheric and marine observations at Finnish Utö Island in the Baltic Sea”

RC2_3: Abstract: I like the last sentence. It points out a possible tipping into a new phase. This idea should be discussed more thoroughly, considering a possible breakpoint, its temporal location and affecting mechanisms.

Our aim in this paper was to show the long tradition of observations at Utö, a station that will be even more important multi-scientific observation site in the future. We wanted to give background for the future studies by showing some trends and by quantifying changes that can be seen from those observations. In addition to that, we pointed out some potentials of our data sets. We agree that the datasets raise interesting questions, that should be studied further. However, such analyzes would need e.g. support from climate and hydrodynamic models.

RC2_4: I agree, that would be obligatorily speculative, but as at present this idea seems to be the only one outcome suggested by authors, it would be important to ponder it more deeply. I miss other conclusive sentences, such as what would be the best, or more appropriate way (instead of just assuming a linear model) to analyze the evidently non-linear change over time which is seen in many parameters, such as in the salinity. I agree that the linear analysis should be the one to start with, but I also expect the authors to show capability to go further. Seeing abrupt changes like temperature since the 1980s and salinity at Utö makes me look for possible explanations and coincidences. You could suggest a way forward, and the use of e.g. breakpoint equations in coming analyses, with other, non-linear, models.

We are using dynamical linear models (DLM) in the analysis, which does not correspond to traditional linear trend fitting. The trend estimated is not just a straight line but a function taking account the changes of the variables in time. See e.g. nice tutorial by Marko Laine in http://helios.fmi.fi/~lainema/dlm/dlmtut.html . DLM is actually a state-space model capable to model univariate or multivariate time series also in presence of non-stationarity, structural changes and irregular patterns.

RC2_5: Page 2 lines 10-12, you aim the paper to “analyse these time series in order to get information on typical atmospheric and marine conditions”, but reading the paper makes me think that several less typical phenomena are shown, such as a rapid increase of salinity, or a decrease and disappearance of the ice cover and a subsequent suggestion of a shift of balance in the climate of Utö into a new phase. So I suggest rewording these lines, for the reader not expect too much of “just typical” happenings being observed.

We have now improved the introduction and better described the aims of the paper. Please see also replies to Referee 1

RC2_6: Line 31, you give the coordinates and write about the observation site and about the Island. Are these coordinates for the midpoint of the Island or the lighthouse or coordinates for atmospheric observations? Compare to page 4, line 33, where you give coordinates for the oceanographic sampling point.

Coordinates for all measurement site on Utö island and surrounding sea areas added to the caption of (new figure) A2 in the appendix.

RC2_7: Page 3, the map should have two panels, one showing the location in the Baltic sea (the present one) and another to show local bottom topography, depth etc.

A new figure A2 added to the paper.

RC2_8: Page 4, line 1, “with permanent pilots living on the island for generations” this is repetition of the information of the first part of the sentence, and, besides, “pilots living for generations” sounds improbable. Remove the sentence.

Corrected

RC2_9: Line 5, you write that: especially the deep samples may be considered to represent conditions of the Baltic Proper. On the other hand you write (page 9, line 1-2): we do not see any permanent halocline (and comment that possible cause to the halocline missing could be mixing due to currents.) These two statements are contradictory, first one is by Ahlnäs in 1961. Have the circumstances changed between then and now? Lack of the deep halocline also puts the sampling station oceanographically more to the Bothnian Bay side than on the Northern Baltic Sea. Could you comment on that?

This is a good point, please see the detailed reply to comments by Referee 1. This discussion is also now reflected in the paper.

RC2_10: Line 7. I do not accept the phrase about biological characteristics. First: there is no information included in writing that "biological characteristics are typical for the outer archipelago" as this is anyway the basic assumption. Secondly, this kind of basic assumption is not valid for this location as biological characteristics point out to a eutrophic environment. Since the 1980′ s the cyanobacterial blooms have been observed in this area, but before that the area, as the whole Northern Baltic Proper was considered to be an oligotrophic environment. Same rapid change from oligotrophy to eutrophy is seen in, for example, in Secchi disc readings in the Gulf of Finland during the 1900. Please give appropriate information on biological change over at least the last decades, as you do for the sea ice in the next sentence.

We decided to remove the comment on typical biological characteristics None of the authors is a marine biologist / limnologist and we do not feel competent to discuss the biological characteristics on scientific level. We have a publication focusing on biological aspects in preparations and we will include better description of local ecosystem in that paper,

RC2_11: Page 6, lines 32-33, you write that you investigated the annual average temperatures against the NAO indices in Fig 3., but that figure only shows the NAO history, while temperatures are given in the Fig. 2. You also claim finding, for individual years, lower temperatures connected to highest negative NAO values, but in Fig. 2 there are no temperature values given for individual years at all. You refer also to Fig. 2 having lowest temperature values (5 year periods) in around 1980, while this period (1980) in the NAO figures just show mid values of the index. What are "highest negative NAO values" anyway? Are they just lowest values of the index, or something else? Rewrite this part.

Please see the comments to the referee 1 above. We improved the text for this part.

RC2_12: Page 7, line 9 and 12, you write about manual observations, you should write about visual observations.

We added word visual and put word "manual" in parenthesis. This is terminological issue, we normally call man-made observations "manual" and machine-made "automatic".

RC2_13: Page 8, line 3, you mention not to have found significant changes in wind speed. Okay, but my personal observation from Utö station when comparing wind observations before and after the 1970s was that there was a substantial reduction of completely calm days (see attached figure which is based in Finnish Meteorological Institute observations at the Island of Utö)). So the overall windiness has increased anyway. As you suggest, more analyses are needed. You could try and include also the data on calm days.

We calculated histogram of wind speed and directions (Fig. R5) for different periods and found no significant changes in wind directions or wind speeds. We do not have data prior to 1960 properly quality assured yet, so unfortunately it is not possible to see any longer term changes.

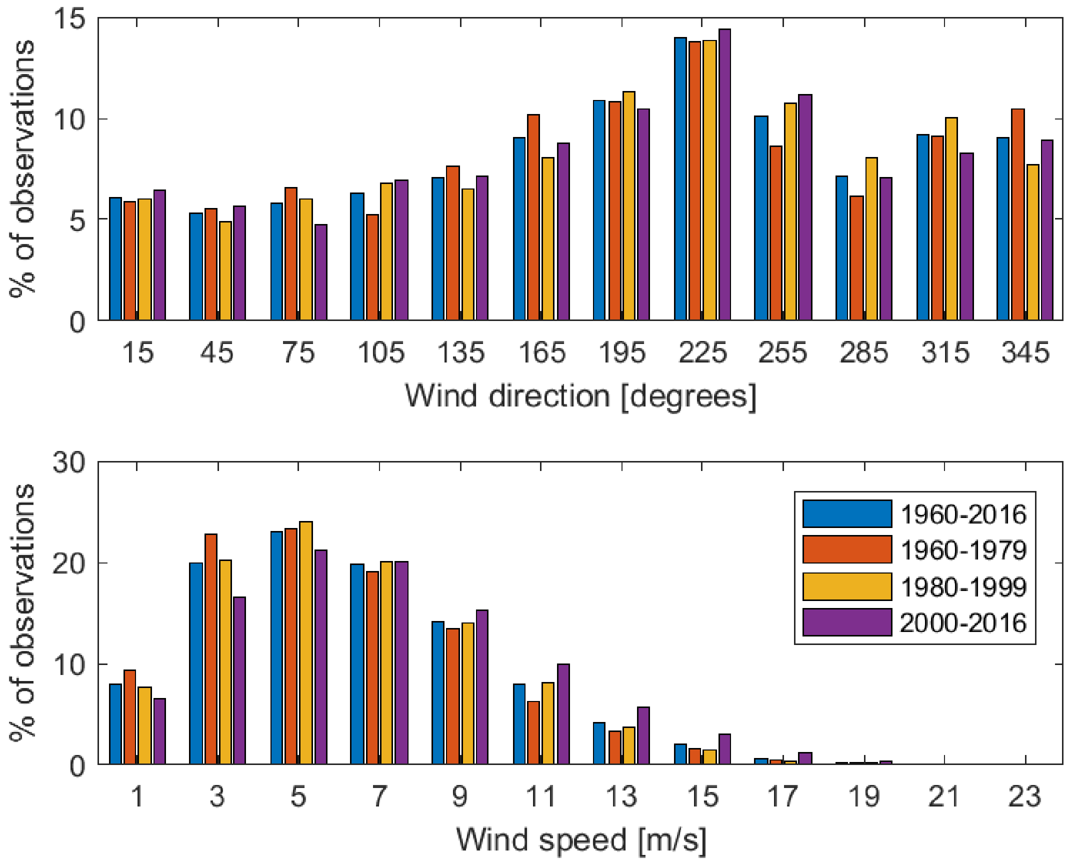

Figure R5: Histogram of wind directions and speeds for the period 1960-2016 and three shorter periods, 1960-1979, 1980-1999 and 2000-2016.

RC2_13: Page 9, line 4-5, remove the sentence: As our focus is..” and start directly from: We decided to... Lines 14-15 you write that: “the surface temperature follows the ... .atmospheric temperatures Fig. 2) ... with a rapid increase in 1980s, which is okay and correct, but then you write that: “and a warmer period from 1930 until 1960s” which, however is not seen at all in the Fig 2 which you refer to. Rewrite that part.

Beginning of the sentence removed. We do feel that there is a period with higher temperatures during this period, ~1930-1960 and it is visible in the top panel of Fig. 2

RC2_14: Page 13, line 10, “reduces the lowest temperatures” sounds strange. Consider rewording.

.. since open sea is a large source of latent heat, which leads to higher atmospheric temperatures than when the sea is ice covered

RC2_15: Typos: page 9, line 4 reads: one hundred year, should read one hundred years. Please also note the supplement to this comment:

Corrected

One hundred years of atmospheric and marine observations at Finnish Utö Island ~~,~~ in the Baltic Sea

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Abstract. The Utö Atmospheric and Marine Research Station introduced in this paper is located on Utö Island (~~59°46’50 N, 21°22’23 E~~N59°46.84 N, E21°22.13) at the outer edge of the Archipelago Sea, Baltic Sea towards the Baltic Sea Proper. Meteorological observations at the island started in 1881 and vertical profiling of sea water temperature and salinity in 1900. Since 1980 the number of observations at Utö has rapidly increased, with a large number of new meteorological, air quality, aerosol, optical, and greenhouse gases parameters and recently, with a variety of marine observations. In this study, we analyze long-term changes of atmospheric temperature, cloudiness and sea salinity~~and temperature~~ , temperature and ice cover. Our main dataset consists of 248367 atmospheric temperature observations, 1632 quality assured vertical seawater temperature and salinity profiles and 8565 ice maps, partly digitized for this project. We also use North Atlantic Oscillation (NAO)~~and~~ , Major Baltic Inflow (MBI) and Baltic Sea river runoff data from the literature as reference variables to our data. Our analysis is based on statistical method utilizing dynamic linear model. The results show an increase in the atmospheric temperature at Utö, but the increase is significantly smaller than on land areas and takes place only since early 1980’s, with a rate of 0.4 °C/decade during the last 35 years. We also see an increase on ~~sea water~~ seawater temperatures, especially on the surface, with an increase of 0.3 °C/decade for the last 100 years. In deeper water layers the increase is smaller and influenced by vertical mixing, which is modulated by inflow of saline water from the North Sea and fresh water inflow from rivers, and by wind-driven processes influenced by the local bathymetry. Date when air temperature in the spring exceeds +5 °C has become 5 days earlier from the period 1951-1980 to period 1981-2010 and date when sea surface water temperature exceed +4 °has changed 9 days earlier. Sea ice cover duration at Utö shows a decrease of approximately 50% during the last 35 years. Based on the combined results, it is possible that the climate at Utö ~~may have changed to~~ have changed into a new phase, in which ~~ice do not~~ the sea-ice does not anymore reduce the local ~~effects of global temperature increase~~ temperature increase caused by the global warming.

1 Introduction

Recently, average atmospheric concentration of carbon dioxide has exceeded 400 ppm (Kilkki et al., 2015) ~~, while~~ and the effects of climate change are getting continuously more visible throughout the Earth (IPCC, 2013; Mikkonen et al., 2015; Iles and Hegerl, 2017). The Baltic Sea, with shallow waters and variable ice cover rapidly responses to both annual and long-term changes ~~(HELCOM, 2013; Lehmann et al., 2011)~~(Lehmann et al., 2011; HELCOM, 2013). However, the responses are still slower than those observed over land areas, due to thermal inertia of the water body.

Previous studies from the Baltic Sea area show that during the 20th century, air temperatures have increased until 1930, decreased until 1960's and started to increase again since 1980's (HELCOM, 2013). Simultaneously, the sea surface temperatures have followed the atmospheric temperatures, with a clear increase due to recent decrease in duration of ice cover. ~~Sea water~~ Seawater salinities at the Baltic Sea follow both changes in fresh water inflow and Major Baltic Inflows (MBI). The MBI's increase stratification, leading to reduced vertical mixing.

In Finland, the longest observed data series containing sea temperatures and salinities together with meteorological variables are from the Island of Utö at the outer edge of the Archipelago Sea (Ahlnäs, 1961). Recently, Utö station was selected as one of the WMO long-term observing stations in the recognition of irreplaceable cultural and scientific heritage (World Meteorological Organization, 2017). However, despite observations having started already in 1881, limited number of meteorological studies ~~(Riihelä et al., 2015; Laapas and Venäläinen, 2017)~~ (e.g., Riihelä et al., 2015; Laapas and Venäläinen, 2017) and only few studies focusing on sea ice and hydrography (Ahlnäs, 1961; Haapala and Alenius, 1994; Haapala and Leppäranta, 1997; Jevrejeva et al., 2004) have been published. One reason for this is that significant part of the observation data has not been digitized or quality assured until the current study. In our study, we use the meteorological, hydrographic and sea ice observations carried out in Utö, Baltic Sea during the period 1881-2016.

~~One of the aims of our paper is to fill this gap and analyze these time series for getting information on~~ The paper has three aims: 1) to bring the data series digitized for this project in the scientific domain and available for other scientists; 2) to describe the observations and typical atmospheric and marine conditions and ranges of variability at Utö ~~. Another aim is to support and provide site characterization and background information for the future studies focusing on combined physical, chemical and biological processes at the recently developed~~ Atmospheric and Marine Research Station; 3) to study the long-term changes of sea water properties, ice cover and meteorology at Utö~~Atmospheric and Marine Research Station.~~ .

~~In this paper , we investigate meteorological, hydrographic and sea ice observations carried out in Utö, Baltic Sea for the period 1881-2016~~The paper has the following structure. First, we describe the general environmental characteristics of the measurement place. Next, we continue by describing the observations and supporting data sets, data quality assurance methods, and the tools used for statistical analysis of the data. The paper continues with time series of air temperature, cloudiness and seawater temperatures, salinities and densities. Paper is closed with conclusions, ~~while~~ some future plans and an appendix with a short description of ~~current observations at Utö research station is left as an Appendix~~the current observations and the local bathymetry.

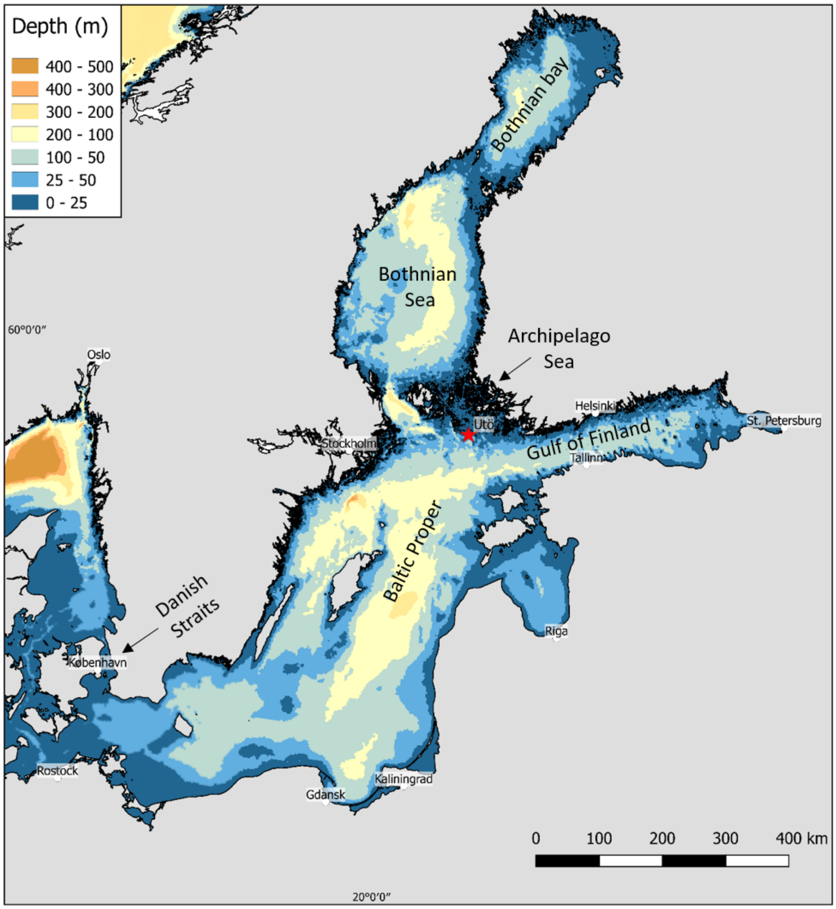

Figure 1. Map of Baltic Sea. Utö measurement site is indicated with a red star. The local bathymetry around Utö Island is shown in Fig. A2 in Appendix A.

2 Measurement site and general characteristics

The Baltic Sea is a shallow semi-enclosed ~~seasonal~~ seasonally ice-covered sea with average depth of 55 meters and maximum depth of 459 m (Leppäranta and Myrberg, 2009). In spite of the shallow depth, the vertical stratification is strong in summer in shallow areas and throughout the year in areas that are deeper than the mean depth. The upper layer of the sea has a strong seasonal cycle, which is also reflected ~~to the deep~~ partly to the deeper water. Parts of the Baltic Sea are ice covered every winter, so that the extent of the annual maximum ice cover varies among $50{\cdot}10^3$ and $340{\cdot}10^3$ km^2 (Seinä and Palosuo, 1996; Vainio, 2001) of the total area of $420{\cdot}10^3$ km^2. The salinity varies from more than 20 ‰ in Kattegat down to less than 2 ‰ at the ends of the large bays in the northern part of the Gulf of Bothnia and Gulf of Finland (Feistel et al., 2010). In deep areas of the Baltic Sea Proper, there is a permanent halocline somewhere between 60 and 80 meters depth. Occasional saline water inflows (Major Baltic Inflows) from the North Sea (Matthäus et al., 2008) and continuous inflow of fresh water from the rivers ~~(Ahlnäs, 1961; Hansson et al., 2011)~~ (Ahlnäs, 1961; Hansson et al., 2011; Väli et al., 2013) keep the stratification strong~~and cause the deep water to be anoxic in the Baltic Proper and western Gulf of Finland~~.

Utö Island (~~59°46'50 N, 21°22'23 E~~N59°46.84 N, E21°22.13) where the observations of this study are made, is located at the outer edge of the Archipelago Sea towards the Baltic Sea (Fig. 1). Utö is the southernmost permanently inhabited island in the Finnish archipelago. Its land area is approximately 0.8 km^2 and the average permanent population between 20 and 30 people. Utö Island has had a lighthouse and a pilot station since 18th century, with ~~permanent~~ several generations of pilots living on the island~~for generations~~. Due to its location and permanent population, local pilots and during the 20th century, military officers have carried out observations on daily basis except some short breaks during the WWI.

The sea area 1 km ~~northwest~~ hwest of Utö is relatively deep, 104 m, and is connected to the open sea through a deep channel ~~, so especially the deep samples may be considered to reflect the properties of Northern Baltic (Ahlnäs, 1961)~~(see Fig. A2). Due to the regional bottom topography, depth structure and prevailing wind direction from southwest, currents at Utö Deep may be relatively strong in comparison to typical values in the Baltic Sea. ~~Biological characteristics on the area are typical for the outer archipelago, with almost annual cyanobacterial algae blooms in July or August (Seppälä et al., 2007)~~This is visible in e.g. seabed erosion (unpublished data). During the last decades, sea ice is observed at Utö ~~only~~ every few years (Jevrejeva et al., 2004) while summertime cyanobacterial algae blooms are observed almost annually, in July or August (e.g. Kahru et al., 1994; Seppälä et al., 2007).

Finnish Meteorological Institute started meteorological observations at Utö already in 1881 and fixed oceanographic station has been in operation since 1900. Atmospheric trace gas and aerosol measurements were started on the island in 1980 in the framework of European Monitoring and Evaluation Programme (EMEP) (Ruoho-Airola et al., 2003; Laurila and Hakola, 1996). In 2012 Finnish Meteorological Institute (FMI) and Finnish Environment Institute (SYKE) started the construction of a marine research station on island, leading to a combined Utö Atmospheric and Marine Research Station (Finnish Meteorological Institute, 2017). The list of current ~~continuous observations at Utö is~~ observations and the site description are given in Appendix A.

~~Currently,~~ Observations at Utö ~~station is~~ are part of the HELCOM marine monitoring network, Integrated Carbon Observing System (ICOS), Finnish Marine Research Infrastructure (FINMARI) and Joint European Research Infrastructure ~~Network~~ network for Coastal Observatory ? Novel European ~~expertise for coastal observatories~~ eXpertise for coastal observaTories (JERICO-NEXT) (Puillat et al., 2016). It is also planned to become a part of European Research Infrastructure for the observation of Aerosol, Clouds, and Trace gases (ACTRIS).

3 Observations and methods~~used in this study~~

3.1 Observations and other data

In this study, we focus on long-term changes at Utö during the period 1881-2016. As we do not have all data available for the whole period, and there are gaps in the data, best coverage for combined data is for the period 1911-2016.

Meteorological observations including air temperature, wind speed and direction, cloudiness and sea surface temperature have been carried out with developing methods since 1881, initially three times a day and later on with increasing time resolution, currently with 10 minutes logging interval. As the methodology and exact observing places have changed during this long period and there is limited metadata from early measurements, especially the older data contains ~~some~~ uncertainties. Meteorological data for the period ~~1889-1959~~ 1881-1959 used in this study was manually digitized from annual written records; data since 1959 is taken from FMI electronic archives. These data were automatically checked from clear outliers and bad data, in addition to the original quality assurance done for all FMI operational meteorological observations. Our study focuses on air temperatures, but cloudiness and winds are also shortly discussed.

Vertical profiles of ~~sea water~~ seawater salinity and temperature have been measured at Utö deep (~~59°46’58 N, 21°20’58 E~~N59°46.97’, E21°20.78’) at standard depths down to 100 meters. The depth of the deepest measurement has varied, but was always more than 80m. The temperature observations started in 1900 and salinities have been measured since 1911. There were also some salinity records from the period 1900-1911, but due to poor data quality, they are excluded from our analysis.

The routine observations (until 2003) were done in fixed oceanographic stations in principle with ten days intervals, in every month?s 1st, 11th and 21st day. Because the observations from small boat are weather dependent, the exact observation days sometimes differ from the scheduled and also the number of winter observations is smaller than that of the summer observations. Thus, the results for winter months include higher uncertainties than for the other seasons.

There was a gap in the marine observations in 2003-2012, because of lack of observers at that time-period. Observations were started again in 2013, with an RBR XR-620 CTD with a RINKO-III Dissolved Oxygen sensor, measuring temperature, salinity and pressure with 0.5 db (~ m) intervals. The profiles have been measured once in every ten days when weather and ice conditions have permitted. These new data are combined with the earlier fixed depth data in order to obtain as long time series as possible.

Oceanographic profiles were visually inspected, specifically for this study, using a code written in MATLAB. All suspicious profiles, like those with clearly wrong salinities and/or temperatures ~~,~~ or impossible density profiles were rejected. After the quality check, we have 1520 good-quality full vertical profiles of temperature and salinity from the period 1911-2002 and 112 more profiles from the period 2013/04 - 017/07.

Sea ice data were obtained from ice maps done during the ice season for the Gulf of Finland. The ice charts are based on ice observations done in large number of locations, one of the observing sites being Utö. We used this generalized ice data instead of direct local ice observations from Utö, as there were few periods when we were not able to determine whether the sea ice observations at Utö were missing, or there were simply no ice. For the same reason, we also excluded from our analysis the ice thickness observations made at Utö during the period 1897-2015. The use of ice charts also provided us with better general understanding of the ice situation in the vicinity of Utö. The ice data used in this study are based on 8564 ~~manually-analyzed~~ manually analyzed ice maps from the period 1914 - 2016.

NAO data was taken from Jones et al. (1997) with updates from Osborn (2004, 2006, 2011). Major Baltic Inflow (MBI) data is taken from Matthäus et al. (2008), with latest updates from Mohrholz et al. (2015) and Nauman et al. (2016).

River run-off data for the period 1900-2016 is a combination of observations for the period 1900-1995 (Hansson et al., 2011) and modeling for the period 1996-2016 (Johansson, 2018). The offset between the two data sets was corrected by calculating averages for both data sets for the overlapping period 1950-1995 and correcting the modeled data with the difference.

3.2 Time-series analysis methods

A trend is a change in the statistical properties of the background state of a system (Chandler and Scott, 2011). The simplest case is a linear trend, in which, when applicable, we need to specify only the trend coefficient and its uncertainty. Natural systems evolve continuously over time, and often, it is not ~~always~~ appropriate to approximate the background evolution with a constant trend. Furthermore, the time series can include multiple time dependent cycles, and they are typically non-stationary, i.e., their distributional properties change over time.

In this work, we applied dynamic linear model (DLM) approach to time series analysis of multiple meteorological variables measured at Utö Island. Dynamic linear models are ~~linear~~ regression models whose regression coefficients can depend on time. DLM is a state-space model capable to model univariate or multivariate time series also in presence of non-stationarity, structural changes and irregular patterns. With a properly set-up and estimated DLM model, we can detect significant changes in the background states and estimate the trends. The magnitude of the trend in an individual model is not prescribed by the modeling formulation. This dynamic approach is well known and documented in time series literature (Chatfield, 1989; Harvey, 1991; Hamilton, 1994; Migon et al., 2005). The method is the same that was already applied in Mikkonen et al. (2015) for the Finnish mean temperature time series. DLM is used to statistically describe the underlying processes that generate variability in the observations. The method effectively decomposes the series into basic components, such as level, trend, seasonality, and noise. The components can be allowed to change over time, and the magnitude of this change can be modeled and estimated. The part of the variability that is not explained by the chosen model is assumed to be uncorrelated noise and we can evaluate the validity of this assumption by statistical model residual diagnostics.

The model provides a method to detect and quantify trends, but it does not directly provide explanations for the observed changes, i.e., whether for example natural variability could explain the changes in the background levels. The model construction procedure and equational formulation follows closely the one described in Mikkonen et al. (2015) and the results were calculated with software package DLM for R statistical language described in ~~in~~ Petris et al. (2009) and Petris (2010). Confidence limits for the trend estimates were calculated with Maximum Entropy Bootstrap for Time Series method (Hrishikesh and López-de Lacalle, 2009). The variables of interest in this study were air temperature, cloudiness, ~~water~~ seawater temperature in different depths, water salinity and density. Each variable was inspected in both manners: as total measurement series, where monthly variation is included in the model, and separately in different seasons of the year. ~~In aim to limit the length of this paper, we focus on a selection of the variables in stead of all possible seasonal data.~~

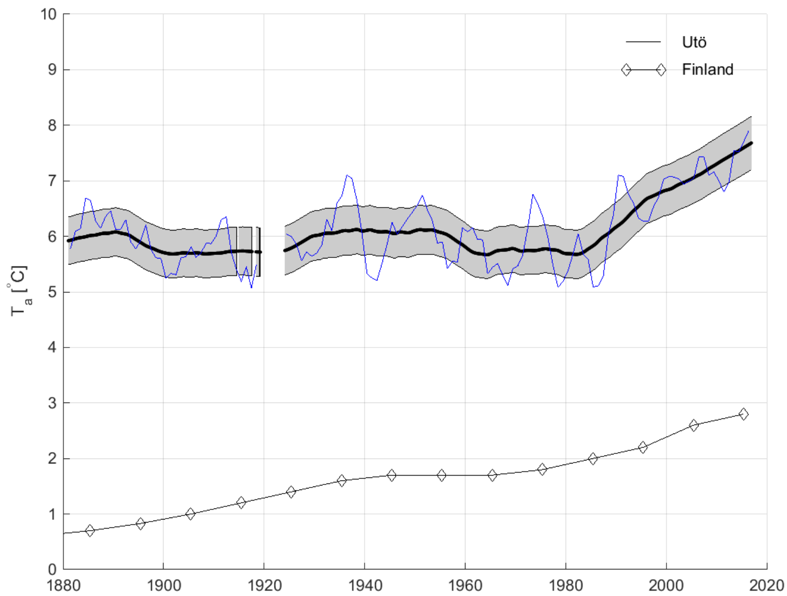

Figure 2. Average annual air temperatures at Utö during 1881-2016. Solid line represent temperatures calculated with DLM and the gray area shows the 95 percent confidence range calculated using bootstrap method. Blue line over the DLM curve is 5-years running mean of atmospheric temperature at Utö. Thin black line with diamonds shows the decadal average temperatures calculated for whole Finland (Mikkonen et al., 2015).

4 Results

4.1 Long-term changes in atmospheric temperatures

Fig. 2 represents the annual average atmospheric temperature at Utö during the period 1881-2016, together with the mean values for whole Finland. For illustrative purposes, we also included 5-years running mean (requiring at least 40% data coverage) in this and subsequent figures; however, quantitative results are based on DLM analyses only. According to DLM analysis, annual average temperature at Utö has increased from 6.0 °in 1881 to 7.5 °C in 2015. The total increase would have been 0.11 °C/decade if it were linear, which is lower than the average increase 0.14 °C/decade observed in Finland (Mikkonen et al., 2015).

While in Mikkonen et al. (2015) the temperature increase follows the pattern in global temperature time series (NASA, 2017), where the warming has taken place in two periods, before 1940's and after 1960's, in Utö the temperature increase has taken place only since 1980 without observable trend before that. This leads to an increase of 0.4 °C/decade during the last 35 years period, in line with results reported by Lehmann et al. (2011) and Almén et al. (2017), and the concluding remark of

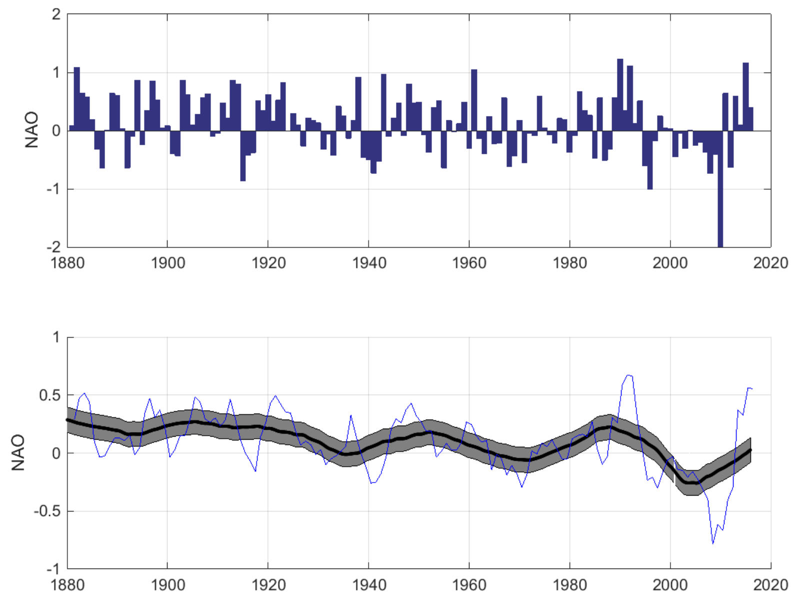

Figure 3. North-Atlantic Oscillation (NAO) during 1880-2016. Upper panel shows yearly NAO values and lower panel shows the trend of the NAO, together with 5-year running average values.

Mikkonen et al. (2015) stating that within the last 40 years the rate of temperature change in Finland has varied between 0.2 and 0.4 °C/decade.

We also investigated the annual average temperatures against the NAO indices (Fig. 3) ~~(Osborn, 2004, 2006, 2011)~~(Hänninen et al., 2000 and found ~~for individual years, as expected~~ that on average, (Lehmann et al., 2011), lower temperatures connected to highest negative NAO values and vice-versa (visible also in 5-years running ~~means~~ mean shown in Figs. 2 and 3). However, we were not able to explain the temperature trend or the longer (> 10 years) periods with higher and lower temperature with the NAO cycle.

In addition to overall temperature trend, it is of interest to look the changes in different seasons (Fig. 4). Using simply three calendar months as seasons, we see similar trends in each season as in the annual temperature (Fig. 2). Looking on individual seasons, we notice that the long-term increase in annual temperatures (Fig. 2) results especially from the increase of temperatures during the winter and spring.

4.2 Cloudiness and wind

The quality assurance for atmospheric temperatures ~~was~~ is relatively easy. For cloudiness and especially wind, the situation is more complicated. We analyzed the changes in cloudiness for the period 1881-2005 for which we had ~~manual~~ visual (manual) observations available. After October 2005, the cloud observations have been done with a ceilometer, and the results are not

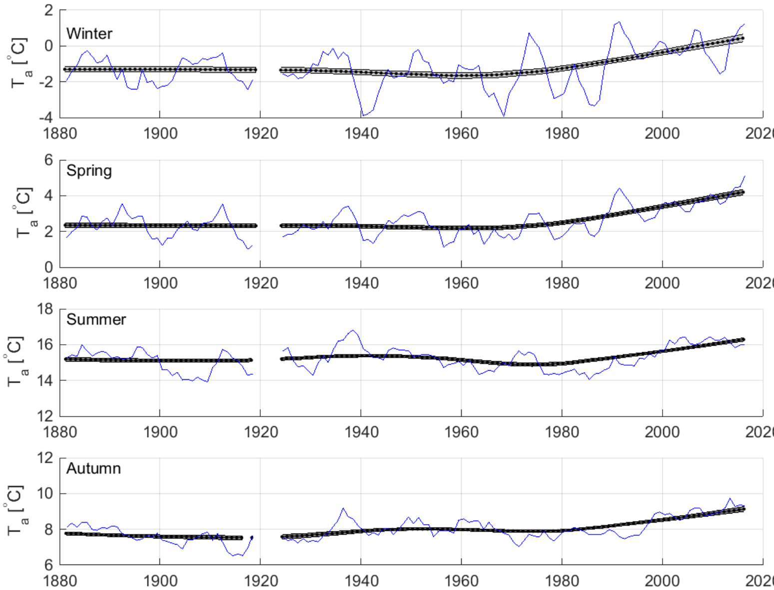

Figure 4. Average seasonal air temperatures at Utö during 1881-2016. Winter: Dec, Jan, Feb; Spring: March, April, May; Summer: June, July, August; Autumn: September, October, November. As in Fig. 2, Black line represent DLM-calculated trend, gray area error for the trend and blue line 5-years running average.

comparable with the previous data. Fig. 5 shows the time series of cloudiness on the scale from 0 to 8. We see increase till 1990 and after that a decrease until the end of our ~~manual~~ visual (manual) observations, 2005. Automated observations (not shown) since 2005 show again an increasing trend in cloudiness. Further investigations focusing on reasons behind the changes in cloudiness are, however, out of scope of this paper.

We also looked at wind ~~speed time series~~ time series (period 1959 - 2016) and found no significant changes neither in wind direction nor wind speed, in line with a recent study for the period 1979?2008 (Laapas and Venäläinen, 2017). However, because the wind observations are very sensitive to inhomogeneities in methods and location (Pryor et al., 2009; Wan et al., 2010; Feser et al., 2015; Laapas and Venäläinen, 2017), more analyses for observations done prior to 1959 are needed before further use of this part of the dataset.

4.3 Long-term changes in sea water temperatures~~and~~, salinities and sea ice

Fig. 6 shows the monthly median ~~sea water~~ seawater temperatures, salinities and densities in Utö deep during the period 1911-2016. From the figure, we see the annual cycle of the water body: strong vertical stratification in the summer, with mixed layer depths around 20 meters; vertical mixing throughout the whole water body in October; and the seasonal variation of salinity in all depths. Generally, at our site, average sea surface temperature varies between 18°C during the summer and 0 °C during

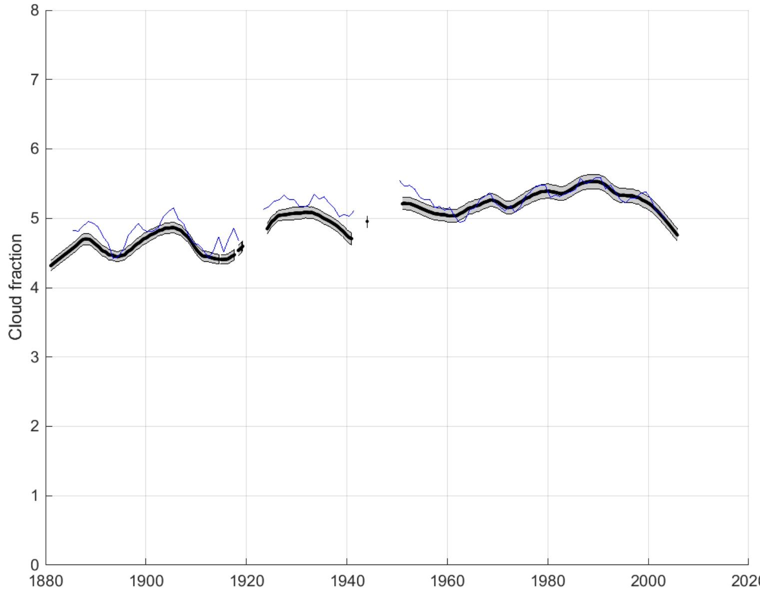

Figure 5. Cloud fraction during 1881 - 2005

the winter while bottom temperature range is from 2 °C to 5 °C. Surface salinities vary between 6‰ and 7‰ , water being less saline during the summer and more saline in winter. At the bottom, situation is opposite, with up to 8 ‰ in summer and around 7‰ in winter. Density follows the cycle of salinity in deep water. The values for individual years and months may be significantly different from these medians due to Major Baltic Inflows (MBI) bringing large amounts of saline water to the Baltic Sea, variation of annual temperatures, ~~river inflow~~wind-driven water transport (Liblik and Lips, 2017), upwelling (Myrberg and Andrejev, 2003), river runoff, and existence of sea ice cover. In contrast to the Baltic Sea Proper, we do not see a permanent halocline between 60 and 80 meters depth (Leppäranta and Myrberg, 2009) ~~. This may result from the relatively strong currents~~ in the average figure shown here. We investigated the reasons for this behavior by 1) comparing vertical salinity profiles at Utö ~~deep~~with those observed at point LL15 (59°10.99’N;021°44.80’E, approximately 70 km SSE of Utö, max depth 130 m) and few CTD profiles taken next to the new cabled bottom profiler 2 km south of Utö (Fig. A2, location 6); 2) studying the publicly available bathymetric maps (see Fig. A2) and; 3) investigating individual vertical salinity profiles.

Based on this analysis, we observed the following: 1) salinity profiles at Utö and LL15 correlate between the surface and approximately 60 m depth, but the salinities below 60 m are higher at point LL15; 2) the bathymetric map (see Fig. A2) shows two potential silts with depth of approximately 60 m in the channel between the observing site and open sea; 3) while the halocline between 60 and 80 m is not seen continuously, it is sometimes observed for shorter, few months periods.

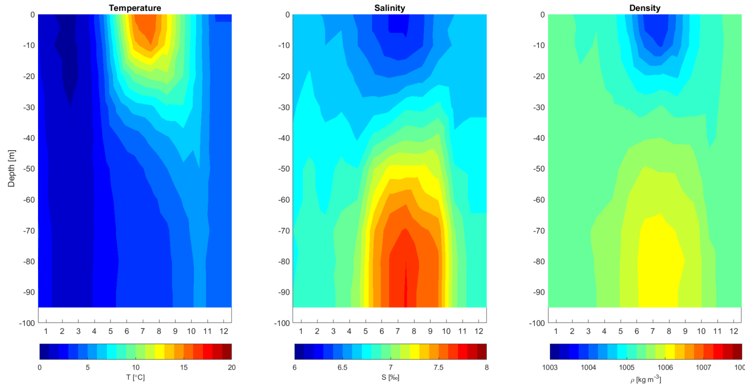

Figure 6. Monthly median ~~sea water~~ seawater temperature, salinity and density in Utö during 1911-2016.

Based on these observations, we may conclude that the statement by Ahlnäs (1961) "The trench-like gully opens into the open sea in the south and the deep samples may be taken to reflect the characteristics of the corresponding water layers in the Northern Baltic" may not fully capture all dynamic aspects of the observing site.

Exact measurement depths and the number of different observation depths have varied during the last one hundred years. ~~As our focus is on long-term trends, we~~ We decided to focus on three different depths where we have most data, while the depths have also physical meaning: 5 m represents the sea surface layer which is quite directly influenced by the atmosphere, but is most probable not influenced by measurement errors, 50 m depth which is at the old winter water layer that is not directly influenced by the surface processes in summer and that is also the middle point between the surface and bottom, and 90 m which is the closest point to the bottom, with high data coverage. While the decision to investigate 5m and 90 m depths was clear, selection of 50 m was also supported by ~~manual analysis of mixed depths: we calculated the top and bottom of mixed layer depths using similar method that ? utilized,~~ visual analysis of the temperature, salinity and density profiles: we inspected all profiles visually and found that ~~summer time~~ during the summer months (June, July~~and August) mixed layer was always above~~ , August) thermocline was almost always above the 50 meters depth.

Fig. 7 represents the trends in water temperatures at these three depths. We see that the surface temperature follows the behavior of atmospheric temperatures (Fig. 2), with a rapid increase since 1980's and a warmer period from 1930's until 1960's. The overall increase has been approximately 0.3 °C/decade during the last 100 years. For deeper layers, we observe partly different trends, with a faster increase in temperatures in 1980's and a drop or hiatus during the last few years. As the main heating to the sea water comes from the surface of the sea, the higher increase of deep water temperatures during the 1980's and 1990's, and recent decrease have to be influence by other phenomena than simply the increasing atmospheric temperatures.

Fig. 8 shows the changes in salinity at different depths. We see that the salinity has varied significantly during the observing period but there is no general trend in the data. ~~However, there are clear changes in~~ If we compare our salinity data (50 and 90

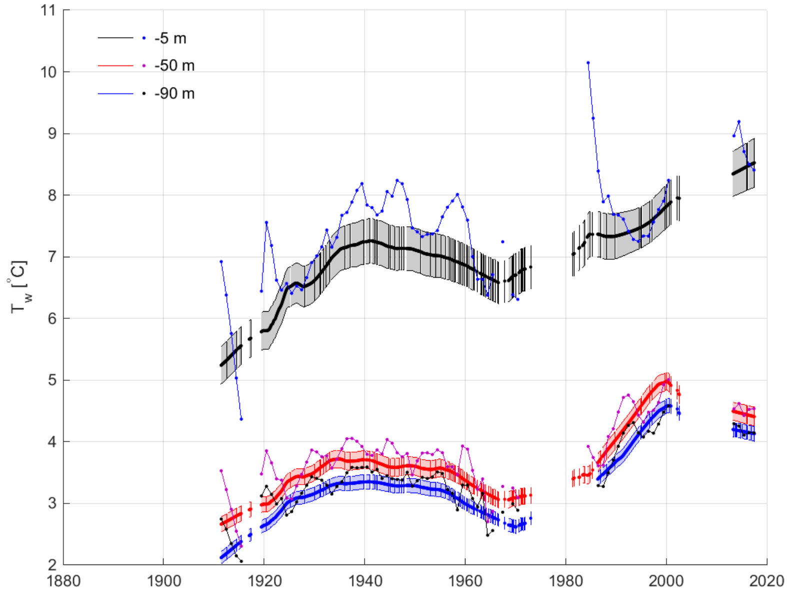

Figure 7. Average ~~sea water~~ seawater temperatures in Utö at depths of -5, -50 and -90m. For better visualization, we have used a combination of black line and blue for -5 meters, red and magenta for -50 meters and blue and black for -90 meters as shown in the legend.

meters depths) with those reported for 200 m depth in Gotland Deep (BY15) by Fonselius and Valderrama (2003), we see that the periods of maximum and minimum salinities are correlated between the two sites.

In the salinity stratification, we see the following changes: the stratification was ~~largest~~ strongest in 1950's and ~~smallest~~ weakest in 1980's and 1990's during the stagnation period when no major Baltic inflows occurred. The stratification increased again since 2013.

The ~~sea water~~ seawater temperatures and salinities combine in the Fig. 9 as ~~sea water~~ seawater density. As the salinity is a key factor (in layers where temperature variations are small) influencing ~~sea water~~ seawater density, the density curves follow the changes in salinity. Fig. 9 shows smaller vertical density gradients in the 1980's and 1990's than earlier, and increase of density stratification during the last few years.

These changes, we assume, are responsible for the increased water temperatures at 50 m and 90 m depths during the period 1980-2000 and the recent decrease since 2012, and an explanation why there is a difference between the behavior (slope) of surface water being directly in contact with the atmosphere and the deeper water layers during this period, 1980-2000.

The observations at Utö are insufficient to ~~directly explain~~ explain directly the reasons for changes in the salinity stratification. However, the frequency and strength of Major Baltic Inflows (Feistel et al., 2008, update based on Nauman et al., 2016), shown in Fig. 10, clearly explain that the changes are related to major Baltic Inflows since 1980's. There have not been similar recent changes in the river run-off (Fig. 10, lowest panel) able to explain the observed salinity increase.

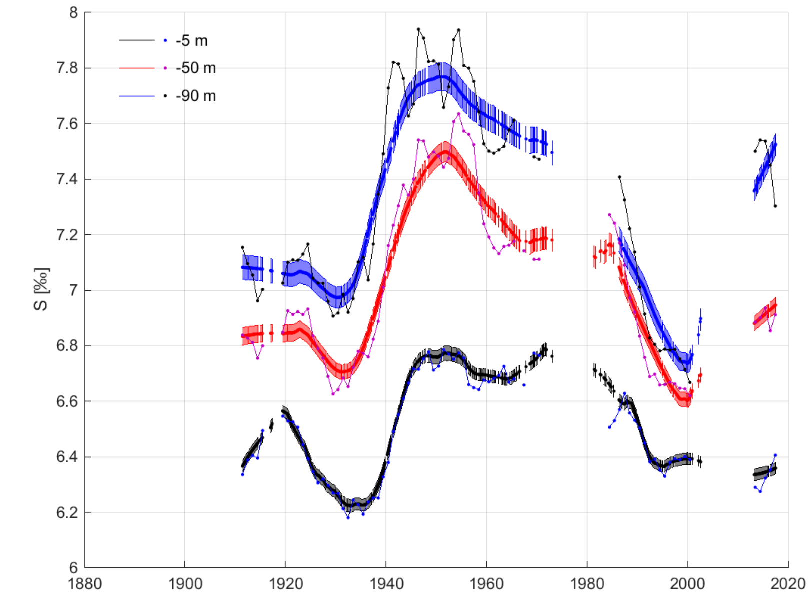

Figure 8. Average ~~sea water~~ seawater salinities in Utö at -5, -50 and -90 m depths. For details, see Fig. 7

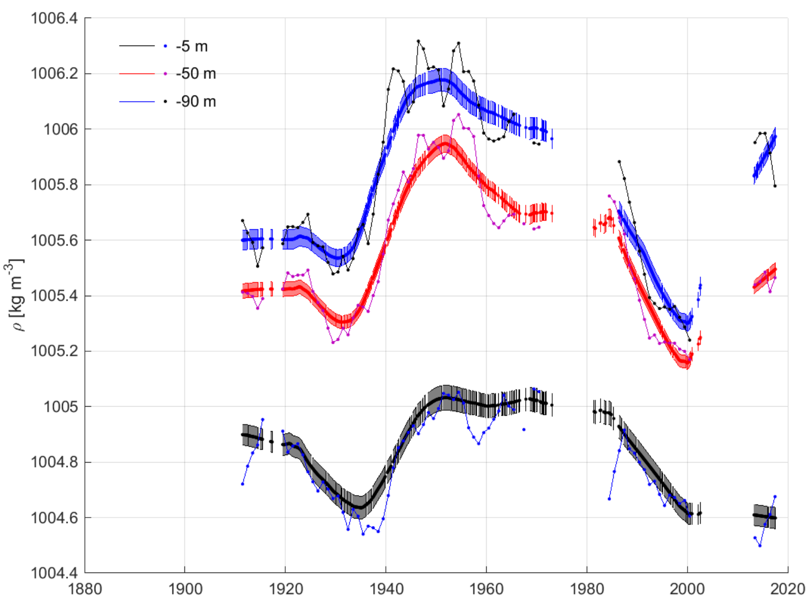

Figure 9. Average ~~sea water~~ seawater densities in Utö at -5, -50 and -90 m depths. For details, see Fig. 7

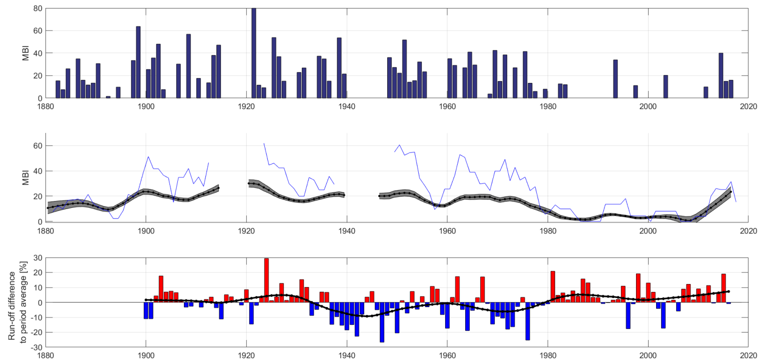

Figure 10. Major Baltic Inflows (MBI) during 1880-2016 (top and middle panel). There is no data available for the World War periods 1915-1920 (WWI) and 1940-1946 (WWII). The lowest panel shows the total river runoff to the Baltic Sea during the period 1900-2016. The unit is percent relative to the period average. Please see the text for details on data sources.

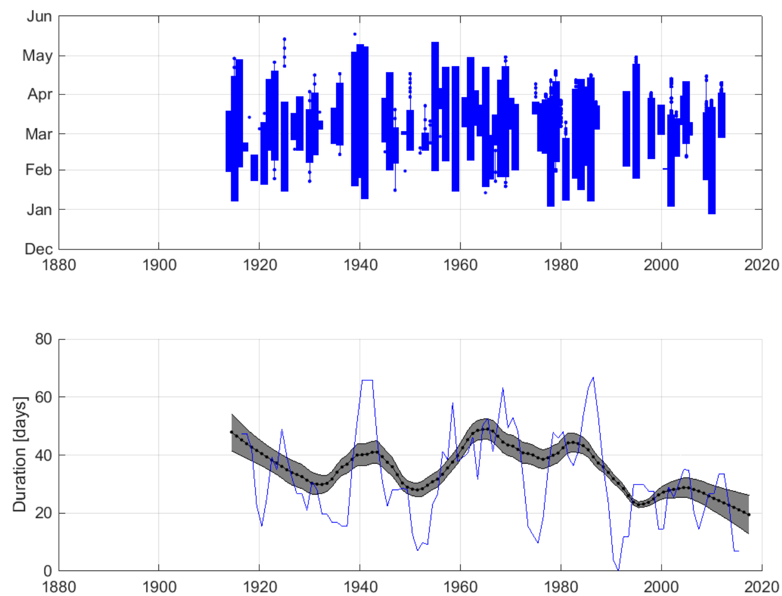

Figure 11. Winter time sea ice cover at Utö. The upper panel shows the yearly duration of the ice cover and the lower panel shows the DLM trend and five year moving averages of the length of the ice season.

We also see a rapid increase in salinities in 1940's. While there is no MBI data due to WWII (Matthäus et al., 2008), study by Ahlnäs (1961) supports strong MBI's during that period, combined with reduced river discharge (Hansson et al., 2011).

Table 1. Average values with standard deviations for the 30-years periods 1891-1920, 1921-1950, 1951-1980 and 1981-2010. As there have been gaps in observations, the uncertainties between variables and periods vary. Due to limited amount hydrographic and sea ice data during the first period (1891-1920), only values for air temperature and cloud fraction are shown.

		1891-1920	1921-1950	1951-1980	1981-2010
Air temperature (°C)		5.77 (7.56)	6.15 (7.91)	5.81 (7.64)	6.56 (7.33)
Cloud fraction (0...8)		4.73 (5.75)	5.20 (3.25)	5.24 (3.04)	5.33 (2.82)
Sea water temperature (°C)	-5 m	-	~~7.31 (5.47~~7.95 (5.67)	~~7.16 (5.47~~7.73 (5.52)	~~8.11 (5.59~~8.12 (5.49)
	-50 m	-	~~3.70 (2.08~~3.76 (2.04)	~~3.52 (1.94~~3.63 (1.90)	~~4.44 (2.56~~4.31 (2.52)
	-90 m	-	~~3.33 (1.63~~3.36 (1.61)	~~3.13 (1.48~~3.18 (1.39)	~~4.07 (2.11~~3.95 (2.06)
Sea water salinity (?)	-5 m	-	~~6.43~~ 6.40 (0.34)	6.72 (~~0.28~~0.29)	~~6.45 (0.29~~6.46 (0.30)
	-50 m	-	~~6.99 (0.48~~7.01 (0.50)	~~7.36 (0.48~~7.44 (0.54)	~~6.83 (0.35~~6.87 (0.37)
	-90 m	-	7.31 (0.69)	~~7.67 (0.63~~7.75 (0.66)	~~6.91 (0.36~~6.97 (0.38)
Sea ice cover duration	Days	-	31.8 (36.5)	37.5 (34.7)	27.8 (33.0)

Utö is at the border between open Baltic Sea proper and the Archipelago Sea. The sea ice cover (Fig. 11) has thus varied ~~a lot~~ greatly from year to year. We see that the average duration of sea ice cover has decreased with 50% since 1980, in line with the increased average temperature (Fig. 2) and previous studies (Jevrejeva et al., 2004; Merkouriadi and Lepparanta, 2014). This decrease in ice cover may have enhanced the recent rapid increase in air temperatures at Utö since open sea is a large source of latent heat~~and reduces the lowest temperatures observed in winter (Fig. 4)~~, which leads to higher atmospheric temperatures than when the sea is ice covered. Ice cover also increases albedo, which may have influenced the surface temperatures during the spring.

Finally, we calculated average monthly air and sea surface temperatures at Utö for four different 30-years reference periods, 1891-1920, 1921-1950, 1951-1980 and 1981-2010 (Fig. 12 and Table 1). ~~Comparison of those~~ The averages show the recent warming of winters and springs with a small increase in ~~spring-time sea water~~ springtime seawater temperature. In time, the date when average air temperature exceeds 5 °C has changed to 5.4 days earlier from the previous periods to 1981-2010. The date when seawater temperature at 5 m depth exceed 4 °C has changed even to 8.8 days earlier from the period 1951-1980 (and 1921-1950) to 1981-2010.

Average air temperatures, cloud fractions, sea water temperatures and salinities and durations of sea ice cover, together with standard deviations for the different 30-years periods are ~~summarized~~ given in Table 1. The data show clearly the high natural variability of environmental variables. However, these averages calculated stepwise for fixed 30-years climate periods also hide the rapid change which has taken place especially in temperatures since 1980, which ~~was~~ is clearly visible in figures showing the trends.

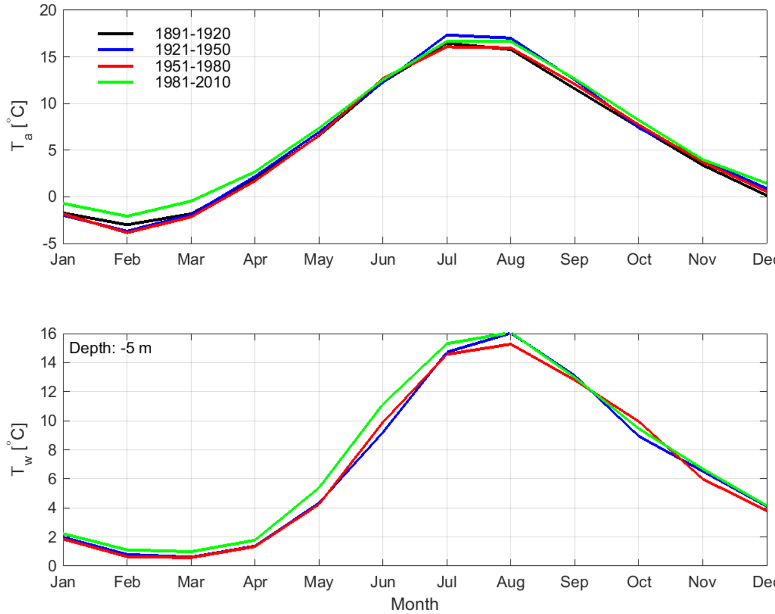

Figure 12. Monthly average air temperatures (upper panel) and sea surface water temperatures (lower panel) at Utö during the four 30-years reference periods

5 Conclusions

In this study, we used about 100 years long time series of atmospheric and marine observations carried out at Utö. The focus was on long-term changes and potential impacts of warming climate to the Baltic Sea hydrography. In an earlier study by Mikkonen et al. (2015), a clear increase of atmospheric temperatures was observed throughout continental Finland. On the sea areas, however, changes are dampened by the large heat capacity of the sea. In winter, the sea ice influence albedo, and sensible and latent heat fluxes between the sea and the atmosphere.

In our study, we saw an increase in the atmospheric and sea (surface) water temperatures only since 1980's, which is different from the Finnish average air temperature increase observed throughout the 20th century. As the increase observed at Utö is mostly due to the warmer spring and winter months, we assume that the impact of warming climate is visible especially after the reduction of ~~winter time~~ wintertime sea ice cover.

We also found that there was a clear reduction in the vertical stability of the water column during the ~~so called~~ so-called stagnation period 1980-2010, when there were less Major Baltic Inflows than before. This enhanced mixing, together with increased air temperature may have been responsible for the increased deep water temperatures during this period. Latest observations since 2013 show again an increase in vertical stratification due to recent MBI's, which have increased the bottom salinities and decreased the temperatures, we assume, due to reduced vertical mixing.

Our results are in line with previous studies on climate and hydrographic changes on the Northern Baltic Sea region. ~~The analyses shown in this paper are only the first step to analyze dataset we have digitized and combined.~~ In the future, our aim is to continue the analyses of this dataset with other methods, and studies focusing more on individual changes and ~~variability in frequency domain using wavelet methods~~processes.

The data and analysis represented in this study also forms a solid base for detailed process and biogeochemical studies which are an integral part of the JERICO-NEXT concept of integrated coastal observatories (Puillat et al., 2016). An interesting study utilizing the time series presented in this paper together with the new observations will be to use the new cabled bottom profiler together with an ADCP (Fig. A2 and Table A1) to study the occasional inflows of saline bottom water which may have significant impacts on the Archipelago Sea ecosystem (Vuorinen et al., 2015). Another planned study combining hydrographic observations with biogeochemistry and climate change is to use the profiler together with the flow-through system to analyze the thickness of biologically active layer and its connection to the marine carbon cycle.

Together with our new observations, the long data series represented in this paper will support better understanding of both the earlier observations and current, on-going physical, chemical and biological changes of the Baltic Sea.

Data availability. Meteorological data used in this article is be available through Finnish Meteorological Institute open data portal (https://en.ilmatieteenlaitos.fi/open-data). Hydrographic data used in this study is available through SeaDataNet (https://www.seadatanet.org/).

Appendix A: Observations at Utö Atmospheric and Marine Research Station

Acknowledgements. First of all, the authors want to thank the five generations of observers, pilots and soldiers of keeping the observations running. Especially we thank our recent observers Ismo and Brita Willström who have done and maintained the measurements used in this study. It is a privilege to work with this unique dataset obtained by their invaluable efforts. This project was partially funded by H2020-project Jerico-Next (grant agreement No 654410) ~~,~~ and BONUS Baltic Blue project Bonus-Integral (funded ~~by BONUS Blue Baltic~~jointly by the EU, the German Federal Ministry of Education and Research, the Swedish Research Council Formas, the Academy of Finland, the Polish National Centre for Research and Development, and the Estonian Research Council). Santtu Mikkonen acknowledges funding from Nessling Foundation and Finnish Academy (project No. 307331). MSc Sakari Äärilä is acknowledged for drawing the map of Figure 1. The authors also want to thank the referees for their comments which improved the manuscript.

Table A1. Continuous atmospheric and marine observation at Utö. ~~Last column include some of he relevant references for specific observations~~Site refers to numbers and coordinates in Fig. A2.

	Variable	Site
Meteorological ~~observations~~ observations	T, p, WS, WD, RH	5
	Precipitation, cloudiness	5
	Global~~radiation 1998 (Riihelä et al., 2015)Diffuse radiation 1998~~ , diffuse and UV-radiation	3
	Visibility	5
	Cloud cover and height	5
	3-D wind profile (Doppler lidar)	5
	Weather camera	4
Aerosol and trace ~~gas observations~~	Aerosol mass (PM_{10})	5
	SO_2	5
	Aerosol chemical composition (PM_{10})	5
	NO_x, O_3	5
	Aerosol mass ($PM_{2.5}$)	5
	Aerosol size distribution	5
	Aerosol absorption	5
	Aerosol scattering	5
	Aerosol chemical composition ($PM_{2.5}$)	5
	Phosphorus deposition	5
	Radon	5
Atmospheric greenhouse ~~gas~~ measurements	CO_2, CH_2 and ~~CO concentrations~~ CO-gas concentrations	3
	CO_2- flux	2
Marine observations	Sea ice observations	1
	Temperature and salinity ~~profiling 0-90m~~ profiles (0...-90 m)	1
	Nutrient and chlorophyll profiles ~~0-70m~~ (0...-70 m)	1
	Sea Ice radar	4
	Temperature, salinity, O_2, turbidity, chlorophyll (~~from~~ 5 m~~depth~~)	2
	Currents (0...~~-23m~~-23 m) and surface waves	2
	Automatic Identification System (AIS)	2
	Bottle sampler	2
	Spectrometric observations of phytoplankton	~~2016 properties~~ 2
	pCO_2	2
	pH, DIC	2
	~~DIC~~ Cabled bottom profiler (-5...-70 m)	6
	Temperature, salinity, O_2, turbidity, fluorescence (3 wave lengths)	~~2016~~
	Currents (0...-75m) and surface waves	6

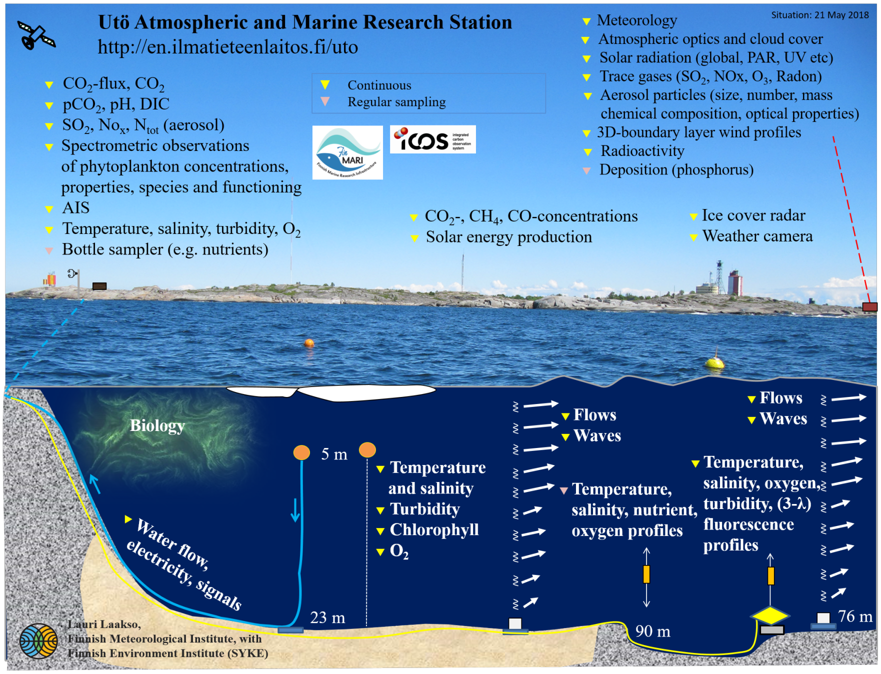

Figure A1. A schematic picture showing the observations ~~made in~~ at Utö and ~~described~~ listed in Table A1

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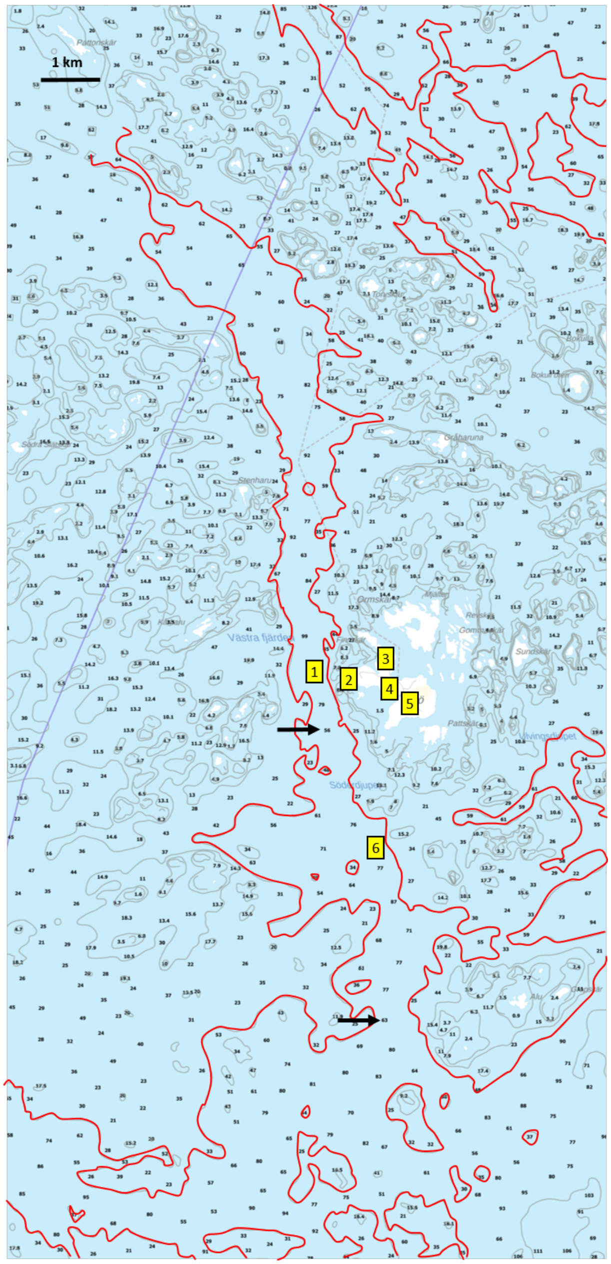

Figure A2. Bottom topography around Utö Island. 1: Hydrographic observations (N59°46.97', E21°20.78'); 2: Marine research station (N59°46.90', E21°21.45'); 3: GHG's and solar radiation (N59°47.12', E21°22.04'); 4: Radar (N59°46.84', E21°22.13'); 5: Meteorological and air quality station (N59°46.76', E21°22.51'); 6: Cabled bottom profiler and ADCP (N59°45.41' E21°22.13'); Red line: 50 m contour; Black arrows: possible silts (60 m depth). Map source: National Land Survey of Finland (2018).

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