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 (N59º46.84, E21º22.13) 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, 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), 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 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 °C 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 have changed into a new phase, in which the sea-ice does not anymore reduce the local temperature increase caused by the global warming.

1 Introduction

Recently, average atmospheric concentration of carbon dioxide has exceeded 400 ppm (Kilkki et al., 2015) 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
5   changes (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. Seawater
10 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 Meteoro-
15 logical Organization, 2017). However, despite observations having started already in 1881, limited number of meteorological studies (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
20 1881-2016.

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 Atmospheric and Marine Research Station; 3) to study the long-term changes of sea water properties, ice cover and meteorology at Utö.

25 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, some future plans and an appendix with a short description of the current observations and the local bathymetry.

2 Measurement site and general characteristics

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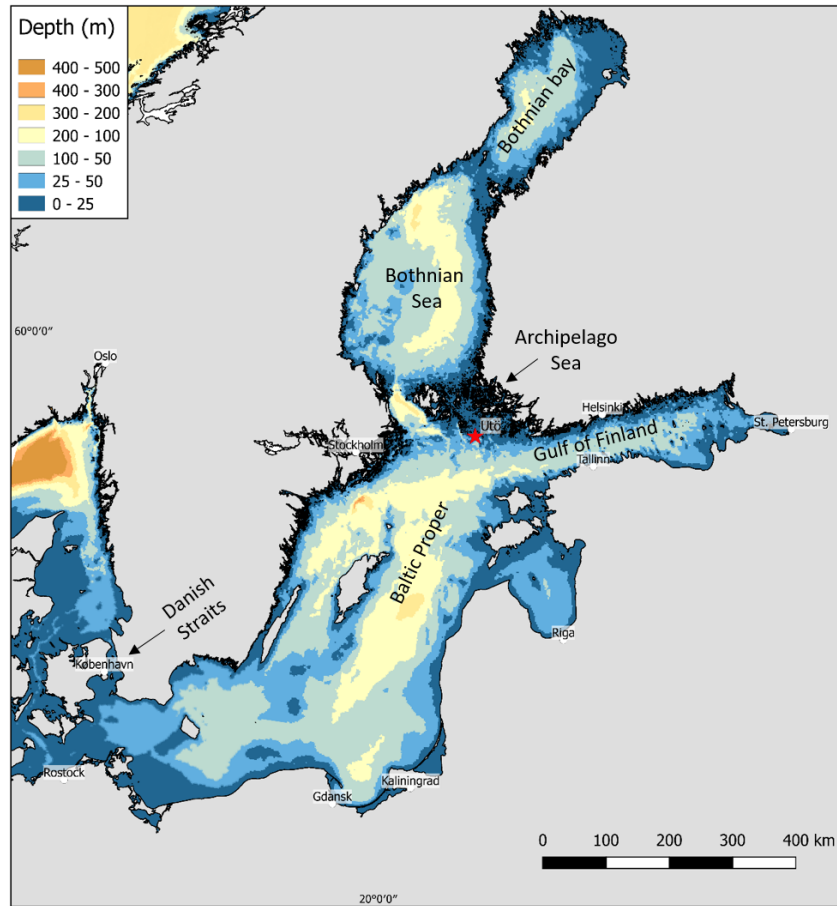
Figure 1. Map of Baltic Sea. Utö measurement site is indicated with a red star. The local bathymetry around Utö Island is shown in Fig. A2 in Appendix A.

cycle, which is also reflected 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

5 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; Väli et al., 2013) keep the stratification strong.

Utö Island (N59º46.84, E21º22.13) 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.

10 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 several generations of pilots living on the island. 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 west of Utö is relatively deep, 104 m, and is connected to the open sea through a deep channel (see

15 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. This is visible in e.g. seabed erosion (unpublished data). During the last decades, sea ice is observed at Utö 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

20 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 observations and the site description are given in Appendix A.

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

3 Observations and methods

30 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 uncertainties. Meteorological data for the period 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 seawater salinity and temperature have been measured at Utö deep (N59°46.96', E21°20.96') 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 – 2017/07.

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 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

5 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 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.

10 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 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

15 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

20 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

25 calculated with software package DLM for R statistical language described 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, 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.
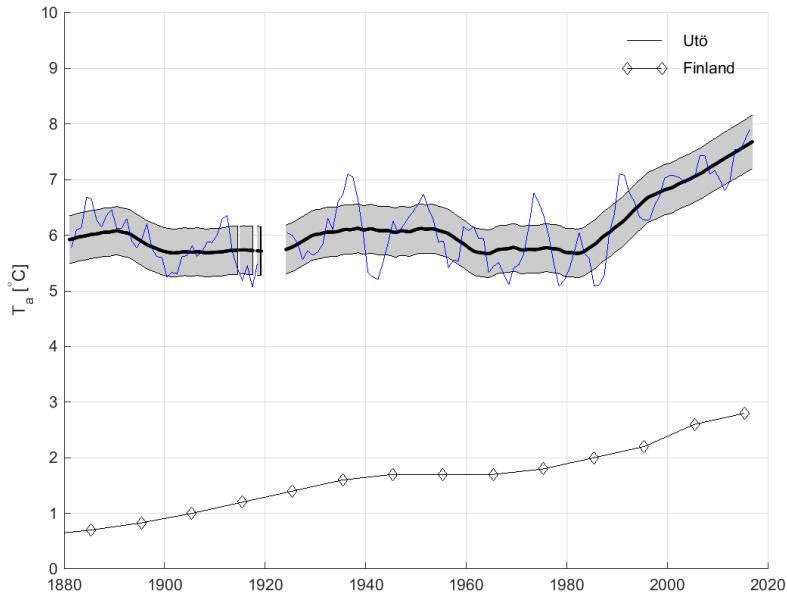
Figure 2. Average annual air temperatures at Utö during 1881-2016. Solid line represent temperatures calculated with DLM and the gray area shows the 95 percent confidence range calculated using bootstrap method. Blue line over the DLM curve is 5-years running mean of atmospheric temperature at Utö. Thin 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 °C 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
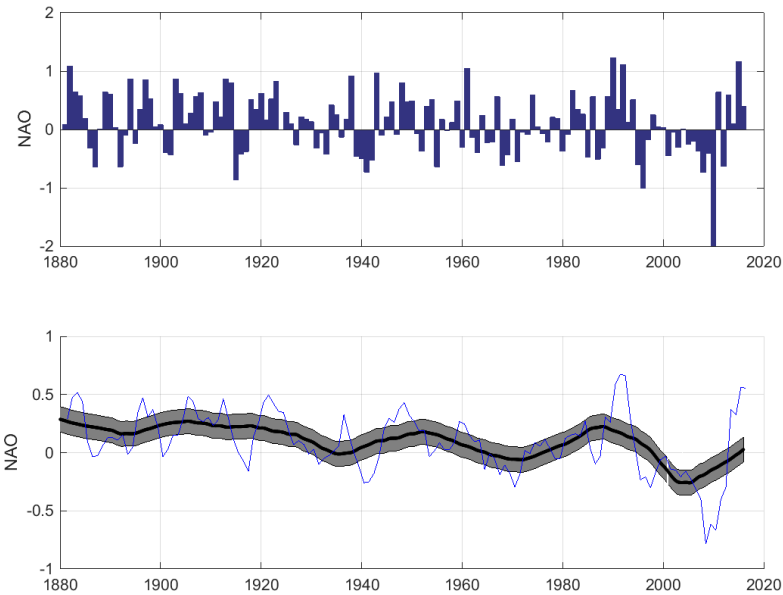
Figure 3. North-Atlantic Oscillation (NAO) during 1880-2016. Upper panel shows yearly NAO values and lower panel shows the trend of the NAO, together with 5-year running mean values.

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) (Hänninen et al., 2000; Osborn, 2004, 2006, 2011), and found that on average, lower temperatures connected to highest negative NAO values and vice-versa
5   (visible also in 5-years running mean shown in Figs. 2 and 3)(Lehmann et al., 2011). 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
10   temperatures during the winter and spring.

4.2   Cloudiness and wind

The quality assurance for atmospheric temperatures 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 visual (manual) observations available. After October 2005, the cloud observations have been done with a ceilometer, and the results are not comparable
15   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
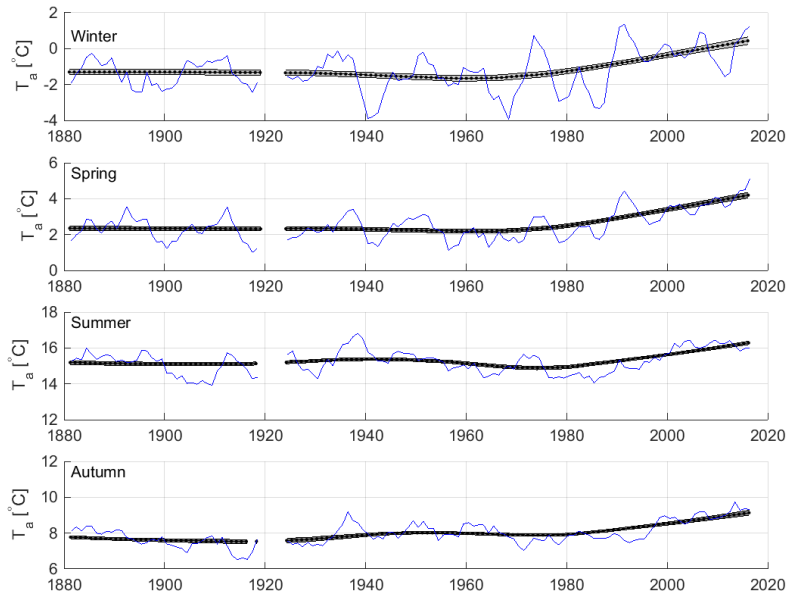
Figure 4. Average seasonal air temperatures at Utö during 1881-2016. Winter: Dec, Jan, Feb; Spring: March, April, May; Summer: June, July, August; Autumn: September, October, November. As in Fig. 2, Black line represent DLM-calculated trend, gray area error for the trend and blue line 5-years running average.

after that a decrease until the end of our 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 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, salinities and sea ice

Fig. 6 shows the monthly median 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 the winter while bottom temperature range is from 2 °C to 5 °C. Surface salinities vary between 6‰ and 7‰ , water being
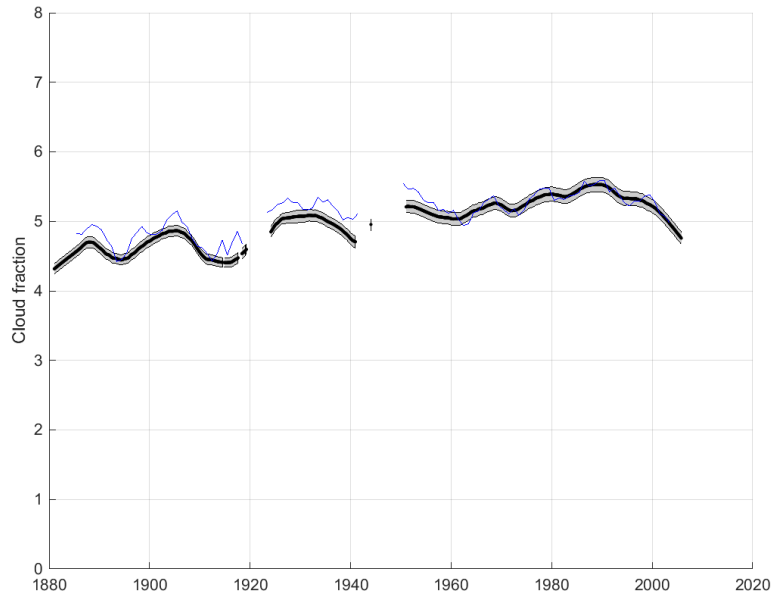
Figure 5. Cloud fraction during 1881 - 2005

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, wind-driven water transport (Liblik and Lips, 2017), upwelling (Myrberg and

5 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) in the average figure shown here. We investigated the reasons for this behavior by 1) comparing vertical salinity profiles at Utö with those observed at point LL15 (N59°10.99, E021°44.80, 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)

10 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.

15 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.
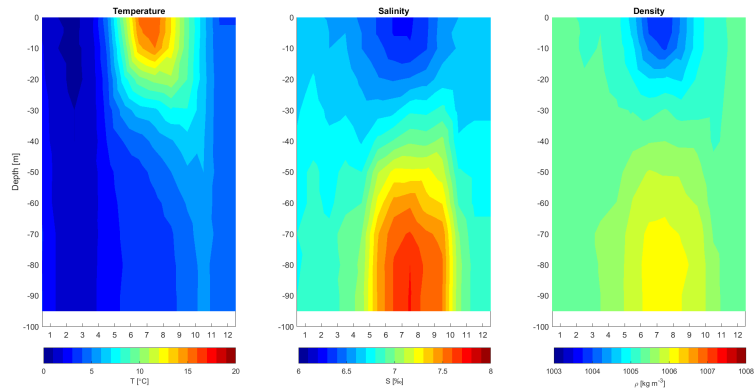
Figure 6. Monthly median seawater temperature, salinity and density in Utö during 1911-2016.

Exact measurement depths and the number of different observation depths have varied during the last one hundred years. 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

5   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 visual analysis of the temperature, salinity and density profiles: we inspected all profiles visually and found that during the summer months (June, July, 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

10   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

15   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. If we compare our salinity data (50 and 90 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.

20   In the salinity stratification, we see the following changes: the stratification was strongest in 1950's and weakest in 1980's and 1990's during the stagnation period when no major Baltic inflows occurred. The stratification increased again since 2013.
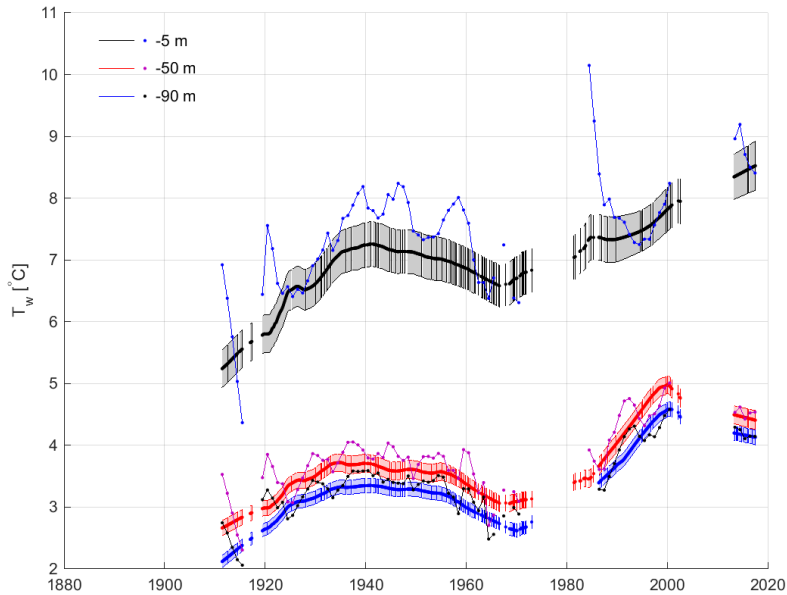
Figure 7. Average seawater temperatures in Utö at depths of -5, -50 and -90m. For better visualization, we have used a combination of black line and blue for -5 meters, red and magenta for -50 meters and blue and black for -90 meters as shown in the legend.

The seawater temperatures and salinities combine in the Fig. 9 as seawater density. As the salinity is a key factor (in layers where temperature variations are small) influencing 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.

5 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 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,

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.

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).

Utö is at the border between open Baltic Sea proper and the Archipelago Sea. The sea ice cover (Fig. 11) has thus varied

15 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 Leppäranta, 2014). This
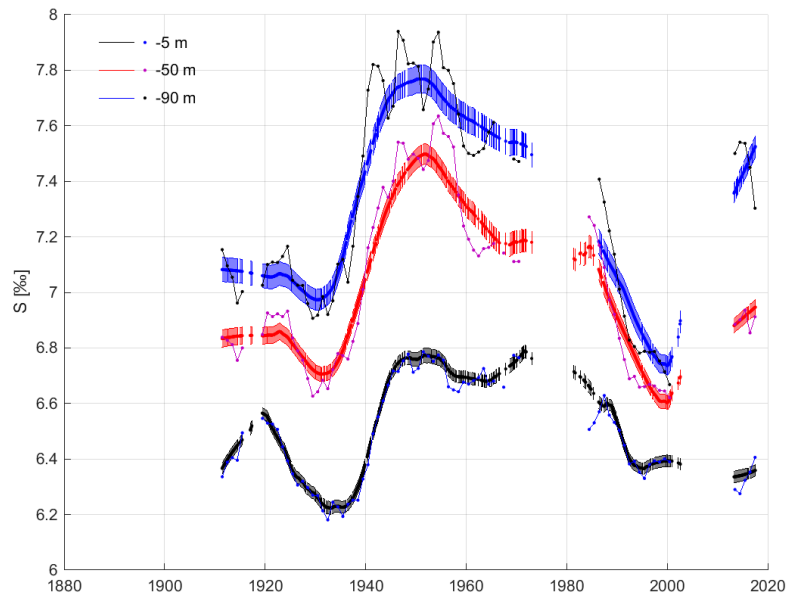
Figure 8. Average seawater salinities in Utö at -5, -50 and -90 m depths. For details, see Fig. 7
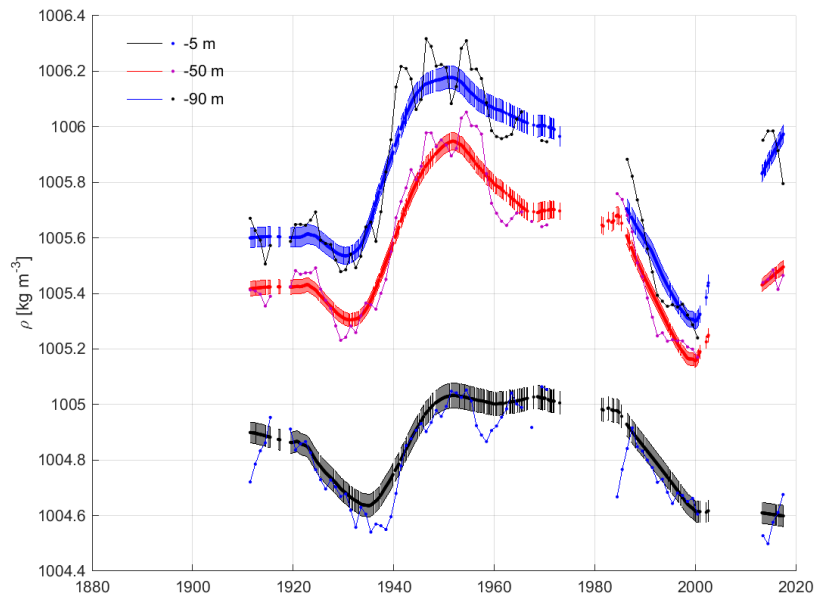
Figure 9. Average seawater densities in Utö at -5, -50 and -90 m depths. For details, see Fig. 7
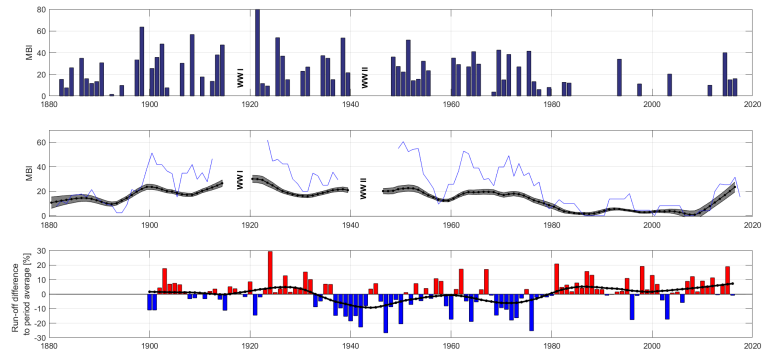
Figure 10. Major Baltic Inflows (MBI) during 1880-2016 (top and middle panel). There is no data available for the World War periods 1915-1920 (WWI) and 1940-1946 (WWII). The lowest panel shows the total river runoff to the Baltic Sea during the period 1900-2016. The unit is percent relative to the period average. Please see the text for details on data sources.
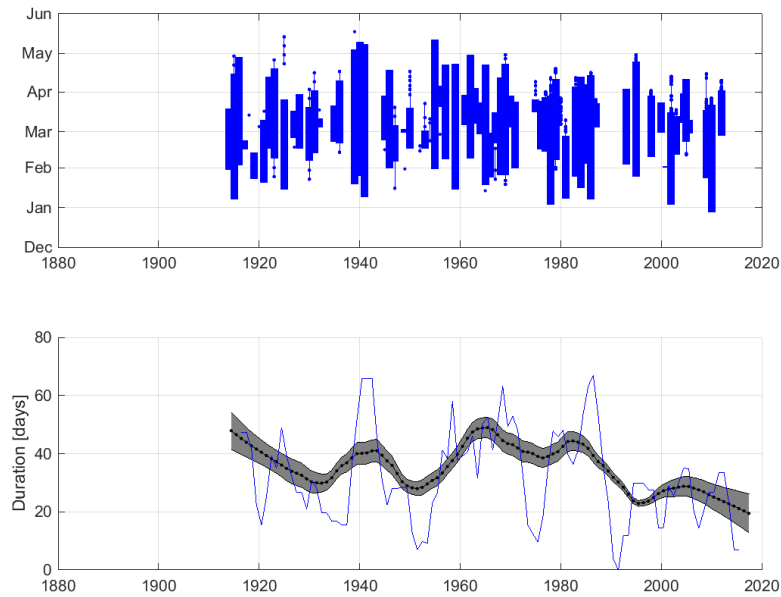
Figure 11. Winter time sea ice cover at Utö. The upper panel shows the yearly duration of the ice cover and the lower panel shows the DLM trend and five year moving averages of the length of the ice season.

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)	5.99 (7.73)	6.72 (7.46)
Cloud fraction (0...8)		4.70 (5.75)	5.20 (3.25)	5.32 (2.97)	5.46 (2.70)
Sea water temperature (°C)	-5 m	-	7.95 (5.67)	7.73 (5.52)	8.12 (5.49)
	-50 m	-	3.76 (2.04)	3.63 (1.90)	4.31 (2.52)
	-90 m	-	3.36 (1.61)	3.18 (1.39)	3.95 (2.06)
Sea water salinity (‰)	-5 m	-	6.40 (0.34)	6.72 (0.29)	6.46 (0.30)
	-50 m	-	7.01 (0.50)	7.44 (0.54)	6.87 (0.37)
	-90 m	-	7.31 (0.69)	7.75 (0.66)	6.97 (0.38)
Sea ice cover duration	Days	-	31.8 (36.5)	37.5 (34.7)	27.8 (33.0)

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, 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,
5 1891-1920, 1921-1950, 1951-1980 and 1981-2010 (Fig. 12 and Table 1). The averages show the recent warming of winters and springs with a small increase in 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
10 standard deviations for the different 30-years periods are given in Table 1. The air temperature averages for all periods are calculated based on three observations per day, which was the initial observing frequency. Based on later high time resolution data, we estimated that the average air temperature values given in Table 1 are approximately 0.17 °C larger than the true average values using high time resolution data, and correspondingly, the cloud fraction values are 0.14 larger than the true averages.

15 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 is clearly visible in figures showing the trends.
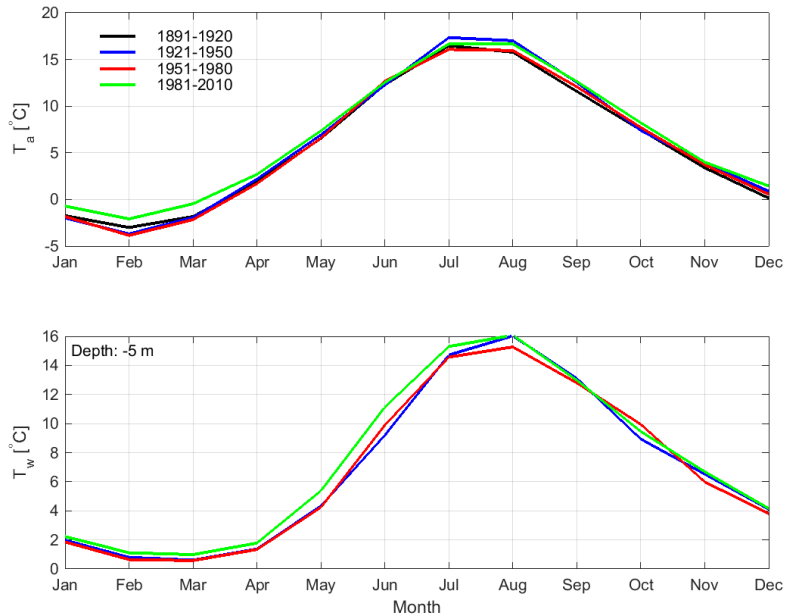
Figure 12. Monthly average air temperatures (upper panel) and sea surface water temperatures (lower panel) at Utö during the four 30-years reference periods

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 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 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. In the future, our aim is to continue the analyses of this dataset with other methods, and studies focusing more on individual changes and 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 in the Baltic Sea.

Data availability. Meteorological data digitized and 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/). Please cite this article when using the data.

Appendix A: Observations at Utö Atmospheric and Marine Research Station

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Table A1. Continuous atmospheric and marine observation at Utö. Site refers to numbers and coordinates in Fig. A2.

	Variable	Site	Start (year)	Reference
Meteorological observations	T, p, WS, WD, RH	5	1881	(Laapas and Venäläinen, 2017)
	Precipitation, cloudiness	5	1881	
	Global, diffuse and UV-radiation	3	1998	(Riihelä et al., 2015)
	Visibility	5	2002	
	Cloud cover and height	5	2006	
	3-D wind profile (Doppler lidar)	5	2012	(Hirsikko et al., 2014; Tuononen et al., 2017)
	Weather camera	4	2014	
Aerosol and trace	Aerosol mass (PM_{10})	5	1980	(Ruoho-Airola et al., 2003)
	SO_2	5	1980	(Ruoho-Airola and Salmi, 2001)
	Aerosol chemical composition (PM_{10})	5	1980	(Ruoho-Airola et al., 2003)
	NO_x, O_3	5	1986	(Engler et al., 2007)
	Aerosol mass ($PM_{2.5}$)	5	2003	
	Aerosol size distribution	5	2004	(Engler et al., 2007; Hyvärinen et al., 2008)
	Aerosol absorption	5	2007	(Hyvärinen et al., 2011)
	Aerosol scattering	5	2010	(Hyvärinen et al., 2011)
	Aerosol chemical composition ($PM_{2.5}$)	5	2011	
	Phosphorus deposition	5	2014	(Makkonen et al., 2015)
	Radon	5	2015	(Vesterbacka, 2017)
Atmospheric greenhouse measurements	CO_2, CH_2 and CO-gas concentrations	3	2012	(Kilkki et al., 2015)
	CO_2- flux	2	2012	(Honkanen et al., 2018)
Marine observations	Sea ice observations	1	1897	(Seinä and Palosuo, 1996)
	Temperature and salinity profiles (0...-90 m)	1	1900	(Ahlnäs, 1961)
	Nutrient and chlorophyll profiles (0...-70 m)	1	2001	(Suomela, 2003)
	Sea Ice radar	4	2013	
	Temperature, salinity, O_2, turbidity, chlorophyll (5 m)	2	2014	
	Currents (0...-23 m) and surface waves	2	2014	(Haavisto, 2015)
	Automatic Identification System (AIS)	2	2015	
	Bottle sampler	2	2015	
	Spectrometric observations of phytoplankton	2	2016	
	pCO_2	2	2016	(Honkanen et al., 2018)
	pH, DIC	2	2016	
	Cabled bottom profiler (-5...-70 m) Temperature, salinity, O_2, turbidity, fluorescence (3 wave lengths)	6	2018	
	Currents (0...-75m) and surface waves	6	2018	
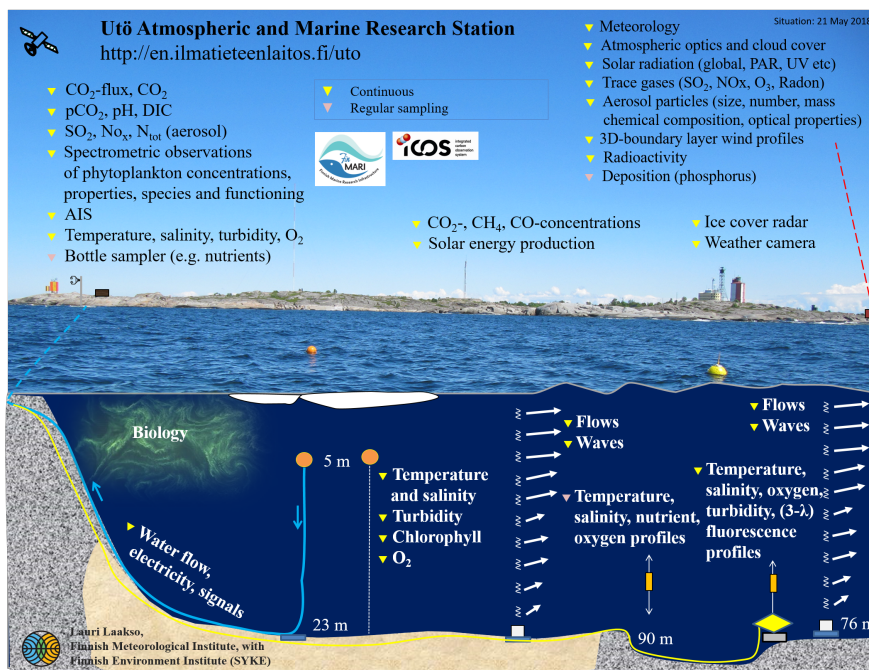
Figure A1. A schematic picture showing the observations at Utö. For a list of current observations, please see Table A1

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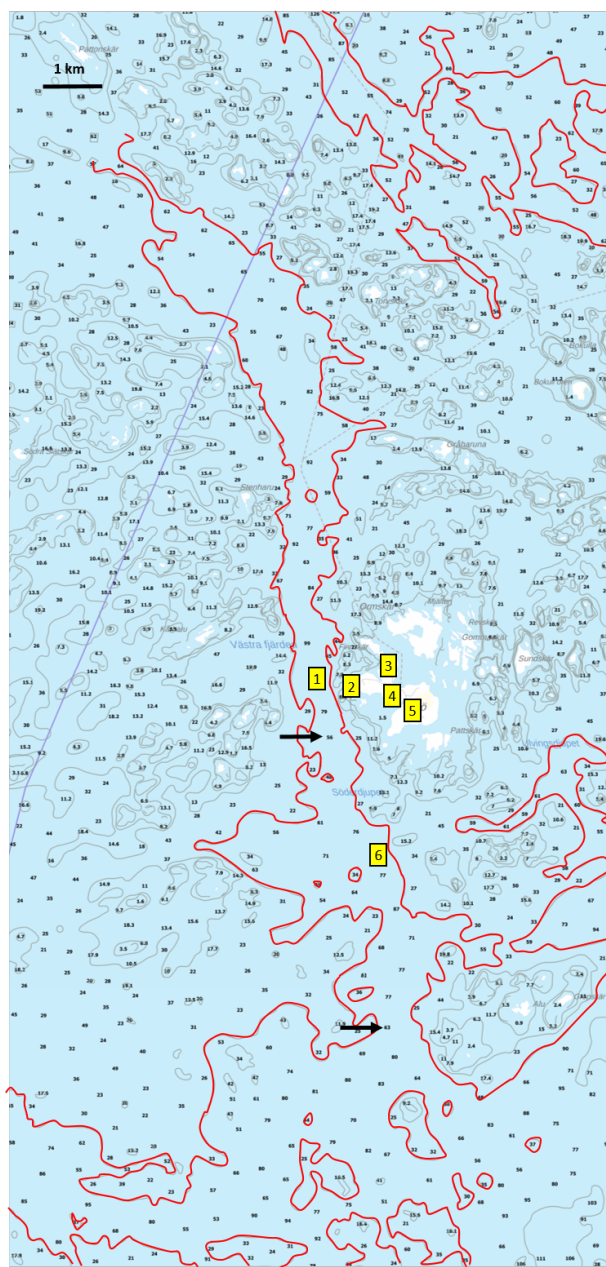
Figure A2. Bathymetry close to Utö Island. 1: Hydrographic observations (N59°46.96', E21°20.96' until 2002; currently N59°46.97', E21°20.78'); 2: Marine research station (N59°46.90', E21°21.45'); 3: GHG's and solar radiation (N59°47.12', E21°22.04'); 4: Radar (N59° 46.84', E21°22.13'); 5: Meteorological 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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