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Tapio Suominen, Harri Tolvanen, Risto Kalliola. Surface layer salinity gradients and flow patterns in the archipelago coast of SW Finland, northern Baltic Sea. *Marine Environmental Research*, 2010, 69 (4), pp.216. 10.1016/j.marenvres.2009.10.009 . hal-00564778

HAL Id: hal-00564778

<https://hal.science/hal-00564778>

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Accepted Manuscript

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PII: S0141-1136(09)00135-4

DOI: [10.1016/j.marenvres.2009.10.009](https://doi.org/10.1016/j.marenvres.2009.10.009)

Reference: MERE 3384

To appear in: *Marine Environmental Research*

Received Date: 27 May 2009

Revised Date: 17 September 2009

Accepted Date: 12 October 2009

Please cite this article as: Suominen, T., Tolvanen, H., Kalliola, R., Surface layer salinity gradients and flow patterns in the archipelago coast of SW Finland, northern Baltic Sea, *Marine Environmental Research* (2009), doi: [10.1016/j.marenvres.2009.10.009](https://doi.org/10.1016/j.marenvres.2009.10.009)

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Surface layer salinity gradients and flow patterns in the archipelago coast of SW
Finland, northern Baltic Sea

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Abstract

The highly fragmented Archipelago Sea in the northern Baltic Sea forms part of a sill area between two large sea basins. In addition to the water exchange between the basins, its waters are influenced by runoff, and thus the sea area has both sill and estuarine characteristics. We studied surface layer salinity gradients and their applicability in defining water exchange patterns through and within the region. A broad scale salinity pattern was detected during two sequential years. The spreading of fresh water in the spring was succeeded by a gradual increase in salinity during the summer. Long term data revealed a non-seasonal salinity fluctuation and diminished salinity stratification in the central and northern parts of the study area. We concluded that temporally unrepresentative mean values of salinity alone are inadequate for the purposes of coastal management in this region. In addition, both the range of variation and persistence of the conditions define the character of the transitional and coastal waters.

Keywords: Archipelago; Baltic Sea; estuaries; GIS; interpolation; monitoring; salinity

1. Introduction

The horizontal and vertical gradations of the water properties are characteristic features of the Baltic Sea. The basin has a positive water balance, whose major components are the in- and outflows through the Danish straits (Fig. 1), river runoffs and net precipitation (von Storch and Omsted, 2008). The occurrence and intensity of the water exchange through the straits control much of the physical, chemical and eventual biological processes in the Baltic Sea (HELCOM, 2009). Further, the sea basin is divided by sills into multiple large sub-basins, which complicates the

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distribution of the Atlantic waters, along with a weak anti-clockwise surface layer circulation (e.g. Alenius et al., 1998; Stigebrandt, 2001; Maslowski and Walczowski, 2002; Myrberg and Andrejev, 2006).

Figure 1.

Surface water salinity in the Baltic Sea decreases from ~9 ‰ in the Arkona basin close to the entrance area to almost freshwater in the northern parts of the Gulf of Bothnia (Bock, 1971; Rodhe, 1998). In general, the less saline waters flow southwards in the surface layer, while the inflowing saline and dense water penetrates into the deeper layers. This results in a permanent stratification with the halocline at a depth of 60–80 metres in the largest basin of the Baltic Sea, the Baltic Proper. The gradient of the surface salinity is rather even in the open sea, with the highest variations occurring in the sill areas between the sub-basins (Rodhe, 1998; Stigebrandt, 2001). The mean surface salinity fluctuations of the Baltic are related to the fresh water input and show an approximate 1 ‰ variation over several decades with no long-term trends (Winsor et al., 2001; Fonselius and Valderrama, 2003). In the northern Baltic Sea salinity exhibits a seasonal cycle in near shore areas as in spring the snowmelt runoff diffuses from the mainland. In summer the water is temperature-stratified, while during spring, autumn and in mild winters the water column shows strong vertical circulation above the halocline.

In the coastal and estuarine regions of the northern Baltic Sea, the complex bathymetry associated with different geomorphic forms sets strong prerequisites upon coastal circulations, resulting in highly variable chemical and physical properties of seawater over space and time (e.g. Kirkkala et al., 1998; Hänninen et al., 2000; Weckström et al., 2002; Erkkilä and Kalliola, 2004). These kinds of transitional changes are ecologically significant with manifold implications for the living environment, fisheries and environmental planning (Anon., 2003; Schernewski and Wielgat, 2004; Nordic Council of Ministers, 2006). One of the most fragmented coastal areas is the Archipelago Sea between mainland Finland and the island of Åland, forming the eastern part of the sill between the Baltic Proper and the Gulf of Bothnia (Fig. 1). The western side of this sill, formed by the Åland Sea between Åland and Sweden, is relatively deep and wide, whereas the Archipelago Sea is a unique coastal area with a mosaic of islands.

The net water exchange through the Archipelago Sea is estimated to be low compared to the Åland Sea (Kullenberg, 1981; Omsted et al., 2004). The baroclinic flows combined with river runoffs and net precipitation are of major importance considering the water exchange between the Baltic Proper and the large gulfs as a whole (Omsted and Axell, 2003). Water exchange through and within the Archipelago Sea is further mixed by estuarine circulation with wind-driven surface currents. Islands and underwater sills form numerous local sea basins at various scales, resulting in a complex transitional system where the fresh water runoff mixes with the brackish sea water of the adjacent main basins.

The intermediate osmotic pressure of the brackish water of the Baltic Sea does not correspond to either a purely marine or limnic environment, with many of the aquatic organisms occurring at the edge of their ecological amplitude. Thus, the horizontal and vertical salinity gradients of the Baltic Sea strongly influence the species composition and abundance of flora and fauna (e.g. Remane and Schlieper, 1972; Bäck et al., 1992; Lappalainen et al., 2000; Hänninen et al., 2003; Gasiūnaitė et al., 2005). Generally, the lowest biodiversity in the Baltic Sea is reported to occur in conditions where the salinity ranges from 5 to 7 (von Storch and Omsted, 2008), corresponding to the conditions prevailing in the Archipelago Sea.

The aim of this paper is to provide detailed quantitative information about the surface salinity gradients and their temporal fluctuations in the Archipelago Sea – phenomena that create relevant dynamic ecological thresholds in the area. Further, we introduce an interpolation method modified for the archipelagial environment and discuss the applicability of salinity monitoring data in determining long term flow properties through the sill area of the Archipelago Sea.

We identified three main issues concerning the surface layer salinity: gradients, persistence and the magnitude of fluctuations. These issues were studied through three approaches. First, the general surface salinity patterns between the mainland and Åland Island were outlined using salinity data from different sources. The four salinity raster maps show the salinity gradients in July-August in 2007 and 2008. Second, the succession of the salinity gradients was followed from late spring to early autumn to study the intra-annual persistence of salinity in greater detail in the north eastern Archipelago Sea. Third, to attain an inter-annual perspective, salinity time series data from three intensively monitored stations representing the southern, eastern and northern Archipelago Sea were used.

2. Material and methods

2.1 Physical geography of the study area

Archipelago coasts are typical in the northern Baltic Sea (Frisén et al., 2005). The Archipelago Sea in SW Finland consists of 25 000 islands larger than 500 m² and 14 400 km of shoreline in an area of approximately 10 000 km² (Granö et al., 1999) (Fig. 1). The area is structured by fragmented bedrock that has a relative elevation range of about two hundred metres. The bedrock base is partially covered with till, glaciofluvial deposits and marine sediments. The deepest basins in bedrock faults provide channels for water currents through and within the area. The mean depth of the Archipelago Sea is estimated to be only 23 m. The depth is typically ranging from 0 to 50 metres, but some deeps and fault lines exceed 100 m. The Åland Sea in the west is an approximately 40 km wide strait between the Archipelago of Stockholm and the island of Åland. Its maximum depth is 301 m, but there is a sill at a depth of 70 metres at the southern end of the channel. In the Archipelago Sea, the highest surface-layer water temperatures (~20 °C) occur near the mainland in August, while the mean annual period of permanent ice cover extends to 100 days (Seinä and Peltola, 1991). According to the meteorological data from the island of Utö (close to the observation station S in Fig. 1), December is the windiest month with an average wind speed of 8.6 m s⁻¹, while May, June and July show the lowest average wind speeds (Drebs et al., 2002).

2.2 Description of the salinity data

2.2.1 The Archipelago Sea in July-August in 2007 and 2008

The Southwest Finland Regional Environment Centre (SFREC) collects annual water quality data from 61 stations in the eastern part of the Archipelago Sea (see Fig. 1, Table 1), comprising three sampling visits in the period between July and August. At most stations only the surface layer is sampled, and salinity is rarely measured, since the analyses are focused on indications of eutrophication. However, extended surface-layer (1 m) conductivity sampling was carried out from 27 and 56 stations respectively, in 2007 and 2008. Conductivity was analysed by the laboratory of the Water Protection Association of Southwest Finland, according to the standard SFS-EN 27888. The conductivity values were compensated to 25° C and the laboratory

results were given in mS m^{-1} to an accuracy of three significant figures. The algorithms presented by Fotonoff and Millard Jr. (1983) were used to convert conductivity into a practical salinity scale (PSS).

The Environmental Agency of Åland (referred to as ÅL) measures salinity in the western part of the Archipelago Sea, synchronising their sampling regime with SFREC to the same weeks each year. Salinity samples are collected from a depth of one metre at all stations. In this study we used the 38 stations on the eastern side of Åland Island (Fig. 1, Table 1). Conductivity was measured according to the standard SFS-EN 27888 using a WTW inoLab Multi Level 1 instrument, which converts conductivity to salinity. These results were given in per mil to an accuracy of two significant figures.

Table 1.

2.2.2 The 2007 summer season in the NE Archipelago Sea

To obtain spatially and temporally representative salinity data covering the period from late spring to early autumn, we carried out a sampling program in the north-eastern part of the Archipelago Sea. The sampling regime consists of 22 stations (Fig. 1, Table 1), a subset of the stations sampled by SFREC. In the sampling network design, we prioritised relatively open sea areas and paid special attention to long and deep straits and their crossings, i.e. flow channels to, from and within the area. At each station, three parallel profiles were measured in a constellation of an equilateral triangle with sides of 300 metres. The measurements were made every third week from mid-May to early October in 2007. One exception to this schedule was made to synchronise our data with the SFREC routine monitoring schedule during weeks 29 and 31 in July. Each station was visited eight times.

The field measurements were made using a multi-parameter sonde (YSI 6600 V2), equipped with sensors for conductivity and temperature (sensor model YSI 6560), and pressure. The readings were recorded at six sampling depths (1, 2, 4, 6, 8 and 10 metres) at each of the three parallel profiles, whose mean values were used. At two stations where the depth was less than 10 metres the measurements were made at one metre intervals until two metres from the sea floor.

To intercalibrate the sonde data with the monitoring program data, water samples were collected from 7 stations during the weeks 29–40. A Limnos water sampler was used to collect 5–10 litres of water to a plastic container, from which the laboratory sample bottles were filled. The sonde was subsequently immersed into the container and readings recorded for 1–2 minutes to get a control reading for the calibration. The conductivity values measured in the field were compensated to 25° C by an equation provided by the manufacturer; $\gamma_{25^{\circ}C} = \gamma / (1 + TC(T - 25))$ where $\gamma_{25^{\circ}C}$ is the specific conductance compensated to 25° C, γ is the measured conductance, TC is temperature coefficient 0.0191 and T is the sample temperature at the time of measurement (YSI 2007). The specific conductance values $\gamma_{25^{\circ}C}$ were calibrated to correspond with the laboratory values with a linear regression model. The field measurements of conductivity showed a good linear correspondence with the laboratory results ($r^2=0.98$, $n=48$). However, although the calibrations with distilled water and the standard solutions differed only marginally from the nominal values, the field readings were typically 20–25 mS m⁻¹ higher than the laboratory results. According to the manufacturer, the accuracy of the conductivity sensor is ± 0.5 % of the reading. The algorithms presented by Fotonoff and Millard Jr. (1983) were used to convert the inter-calibrated conductivity to PSS. The reference conductivity was analysed by the laboratory of the Water Protection Association of Southwest Finland according to the standard SFS-EN 27888. An exceptionally high conductivity value at one of the stations in week 26 was assigned as an outlier, and data are missing from the southernmost station in week 37. In these two cases the mean conductivity values from the preceding and subsequent week were used instead.

2.2.3 Long term observations in 1999–2008

The Finnish Environment Institute (SYKE) has 14 intensively sampled monitoring stations in Finnish coastal waters, of which three, i.e. KORP 200, NAU 2361 and BRÄNDÖ 100, are located in the Archipelago Sea. They are referred to here as the southern (S), eastern (E) and northern (N) station, respectively (Fig. 1, Table 1). These stations are sampled nominally 20 times annually, but due to weather conditions some data are missing, especially during winter periods. The longest time-series, from 1983 to present, is available from station E (depth 52 metres). The time-series at stations S (78 m) and N (33 m) start in 1999 and 2000, respectively. In this study, we used data extending from 1999 (2000 at station N) to 2008. We used sample means collected from 1, 5 and 10 metre depths as the surface layer value. This range was found to be homogeneous and by using the mean of the surface

layer, we minimised the effects of individual erroneous values obtained as a result of incorrect sampling, analysis or registration. The near-bottom salinities were sampled approximately one metre above the sea floor. Here, salinity was analysed in the laboratory of SYKE with a Guideline Autosol 8400B salinometer and the laboratory results were given as per mil to an accuracy of three significant figures.

2.3 Analysis methods

2.3.1 The inverse path distance weighted interpolation

The archipelago conditions require sophisticated interpolation analyses, because the islands and straits restrict free water flow, resulting in an anisotropic distance configuration (see Little et al., 1997; Dunn and Ridgway, 2002; Løland and Høst, 2003; Krivoruchko and Gribov, 2004). We applied a procedure based on the inverse distance weighted (IDW) method (e.g. Longley et. al., 2001; Chang, 2002) to interpolate salinity values for the entire study area. The IDW weights the values of sample points linearly according to the inverse distance from the known data point to the raster cell to be estimated. The influence of the distance could be adjusted by raising the distance to a power and by limiting it to a given maximum value. Instead of using Euclidean distances, we calculated path distances along the water surface from each sampling point and named the method as inverse path distance weighted (IPDW). This calculation was made by applying a cost raster surface, in which the water areas have a value of 1, with land areas assigned a high value to prevent the path from crossing land surfaces. The script was written with Python programming language within ArcGIS and utilises GIS functions introduced in this environment. The execution of the script is described in Table 2, with some of the intermediate and resulting raster surfaces demonstrated in Figure 2.

Table 2.

Figure 2.

The cost raster originates from the shoreline vector data (1:20 000) of the National Land Survey of Finland, which was converted to raster format with a cell size of 100 metres. The cells whose centre points lie on land were assigned with the cost value 10 000, and other cells with the cost value 1. Thus, the cost raster allows unrestricted connectivity through narrow straits (<200 m), which does not correspond to the real

water exchange potential in such cases. To simulate a more realistic situation where the flow in shallow shores and narrow channels is limited, the cells retaining the cost value 10 000 were buffered by adding an extra row of cells around them.

The error assessment of the model was done with the UTU data (University of Turku, Table 1), which was sampled from 22 stations during the summer of 2007 (see section 2.2.2). The test was performed by omitting one station at time, interpolating a salinity raster surface with this incomplete set of known data points, extracting the interpolated value at the location of the omitted station, and by comparing the deviations of observed and extracted salinity from the observed mean salinity of the corresponding week (Fig. 3). This was done for each of the eight sampling rounds. However, all stations could not be used in this procedure: the stations at the outer limit of the interpolation area were excluded since they would have been extrapolated instead of interpolated. Thus, only 12 out of 22 stations were used. Since one measurement was regarded as an outlier, the total number of comparisons of modelled and measured salinity values was 95.

We compared the effect of the inverse path distance weighted interpolation (IPDW) against standard IDW by performing the above mentioned test with two cost surfaces. In addition to the cost raster described above, the test was performed with a constant cost raster in which all the cell values were set to value 1. This surface ignores the effect of land and the inverse path distance weighted simulation performs like a standard IDW. In both calculations, the influence of the stations were limited to a maximum distance of 20 km and the effect of the stations were set to decrease linearly according the increasing distance.

Figure 3.

The comparison revealed only minor differences in accuracy between the different interpolation methods. In both cases, the coefficient of determinations (Fig. 3) were $r^2 = 0.81$, while the mean deviations of the modelled from the observed salinities were also similar, i.e. MD = 0.04. This similarity occurs partly because the stations have initially been selected to represent open sea areas and they are usually connected through straight and wide waterbodies. The main benefits of the IPDW would occur in more complex and sheltered areas. The differences between IDW and IPDW methods were apparent in the straits and their ends (Fig. 4). The IPDW method was used to model continuous raster surfaces on the surface salinity of the Archipelago

Sea for the late summers of 2007 and 2008 and for the NE corner of the study area in the summer of 2007. The isohalines presented in figures 4-8 are generalised slightly to improve the cartographic presentation.

Figure 4.

2.3.2 Long term time-series analysis

We derived the long term data for the time series analysis from the OIVA database (also known as Hertta-PIVET, see Erkkilä and Kalliola, 2007; Manni, 2006) managed by SYKE. We divided the year into four 13-week quarters (quarter 1 = weeks 1–13, quarter 2 = weeks 14–26, quarter 3 = weeks 27–39, and quarter 4 = weeks 40–52). The winter observations in particular were occasionally clustered to either end of a given quarter. Since the salinity is considered to have a seasonal cycle, this clustering might lead to erroneous estimations, if the observed values only are used in calculation of quarterly means. Therefore, we calculated the salinity for each week of the year by linear interpolation before calculating the quarterly means.

We studied the long-term salinity patterns by creating two graphs for the period 1999–2008 (2000–2008 at station N): the mean salinity of each quarter at each station to show the general pattern of salinity fluctuations, and quarterly deviations from the mean of the corresponding quarter during 1999–2000 to emphasise non-seasonal long-term fluctuations. The temporal relations of the salinity fluctuations were studied by defining the cross-correlations between the stations with different time lags.

3. Results

The units and accuracy of the conductivity and salinity results differed according to the laboratories and instruments used, as indicated in section 2.2. In the following sections, the salinity values are given without units, an accuracy of two significant figures and are considered to correspond with PSS.

3.1 The Archipelago Sea in July-August in 2007 and 2008

The overall surface salinity patterns in the Archipelago Sea indicated similar gradients in mid-July (week 29) and mid-August (week 34) of 2007 (Fig. 5). The

highest salinity, 6.1–6.2, occurred in the southern reaches, from where the salinity decreased towards the shallow bays near the mainland. The large islands in the middle of the study area, surrounded by the dense and shallow archipelago, seemed to form a barrier for water exchange. In the more open parts of the archipelago, the isohalines bend northwards, but the salinity values decreased again towards Åland Island in the west.

Figure 5.

The general pattern of more saline waters extending northwards through the relatively open parts of the archipelago was visible also a year later (Fig. 6), although the isohalines of the year 2008 were rather differently shaped compared to the corresponding months of 2007. Although the salinity gradient more or less corresponded to the situation of 2007 in the southern archipelago, near the mainland the salinity was 0.3–0.4 higher, and the overall salinity range was distinctively narrower than in 2007.

Figure 6.

3.2 The 2007 summer season in the NE Archipelago Sea

The surface conductivity data from the summer of 2007 revealed more detailed patterns of salinity variation in the inner parts of the Archipelago Sea. In April and May (week 20 to 23), the isohalines first moved slightly southwards, but during the rest of the study period, the surface layer salinity increased in the inner archipelago (Fig. 7). A major leap in surface salinity occurred in June between weeks 23 and 26, when more saline waters intruded from the south-west and west to the inner archipelago. The large islands of the middle archipelago blocked the inflow of the saline waters, as interpreted also from Figure 5. The greatest salinity range was found in the inner bays near the mainland (~0.8) and in the western edge of the study area (~0.6), with the lowest range (~0.3) occurring in the south (Fig. 8).

Figure 7.

Figure 8.

3.3 Long term observations in 1999–2008

Station S had the highest overall salinity of the three intensively sampled sites (Fig. 9). The long term average at station S was 6.3 and 7.0 in the surface and bottom layers, respectively. At stations E and N, the surface/bottom layer long-term mean salinities were 5.9/6.1 and 5.9/6.0, respectively. At all stations, salinities were higher in the bottom layer than at the surface. However, at stations N and E the difference was on average only 0.1–0.2 and salinity varied simultaneously in the surface and in the bottom layer. At station S, the salinity difference between the surface and bottom was greater, i.e. 0.8 on average, and the salinities of these layers were not interlinked as at the shallower stations N and E. The salinity range in the surface layer was 0.6 at all stations. At station S, the salinity ranged from 6.0 to 6.6, and from 5.6 to 6.2 at both stations E and N. In the bottom layer, the salinity range was 0.7 at stations E and N (from 5.8 to 6.5, and from 5.6 to 6.3, respectively). The bottom-layer salinity showed more variation at station S, with a range of 2.1 (6.4 to 8.5).

Figure 9.

Although the deviations from the quarterly means revealed a similar pattern of non-seasonal surface layer salinity fluctuation at stations N and S (Fig. 9), the phase of this fluctuation was divergent. The broad scale temporal pattern was similar also at station E, but the short-term fluctuation did not follow the other two stations. In general, there was a period of higher salinity values starting either from the summer of 2003 (stations E and S) or from the beginning of 2004 (station N).

The cross-correlations of salinity between the stations were studied with time-lags of ± 8 quarters (Fig. 10). The cross-correlation between stations N and E showed that the fluctuations occurred simultaneously ($r = 0.64$ with no lag). The strongest cross-correlations between stations N and S occurred with lags of -2 or -3 quarters ($r = 0.58$, $r = 0.62$, respectively). In other words, station N followed the fluctuation at station S with a lag of 6-9 months. The cross-correlation pattern was unclear between the stations E and S.

Figure 10.

4. Discussion

The presence of a broad-scale surface water salinity gradient in the Archipelago Sea was identified. The general pattern of the gradient was from the lower salinity levels in the shallow inner bays near the mainland to the more saline waters in the open sea areas in the south, towards the Baltic Proper. The gradient was steepest in the semi-enclosed parts of the archipelago, behind a row of large islands and dense island concentrations. The straits that connect the adjacent sub-basins within the Archipelago Sea are usually narrow with shallow sills. This results in a filling-box effect that allows only the surface waters to flow onto the next basin, blocking the more saline waters in the bottom layer. In addition, the runoff of several small rivers leads to lower surface salinity levels within the inner archipelago. Another salinity gradient was detected in the area east of Åland Island, where it was assumed to be caused by southward surface flows of less saline waters from the Gulf of Bothnia. The terrestrial runoffs from Åland are hardly sufficient to maintain any permanent salinity gradients within this area.

The fingerprint of the anti-clockwise Baltic Sea circulation pattern was apparent. The northward net surface flow in the Archipelago Sea, portrayed as northward lobes of salinity into the middle parts of the study area, where the relatively open sea area allowed the most unrestricted surface flow. This wedge-like plume of more saline water was undisputed in all the spatial interpolations. A similar northward plume has also been recognised by other authors (Bock, 1971; Helminen et al., 1998; Rodhe, 1998; Erkkilä and Kalliola, 2004)

Some parts of the Archipelago Sea showed particularly changeable water salinity levels during a single summer season. The spring runoff was still spreading from the mainland until late May, but from June onwards, the inflow of the more saline surface water from the south compensated the decreased runoff. The dispersion of fresh water from the mainland runoff resulted in varying salinity regimes within the inner archipelago bays. A region of higher salinity variation also occurred on the western edge of the north-eastern study area (Fig. 7), which is occasionally influenced by both the northward flow of water from the Baltic Proper, as well as the westward dispersion of less saline water from the inner archipelago.

The long-term salinity measurements from the three intensively sampled monitoring stations confirmed the inter-annual fluctuations of the surface water salinity, while the deviations from the quarterly means revealed non-seasonal salinity fluctuations. The seemingly regular variation from 2000 to the end of 2003 was followed by a period of

elevated salinity levels at all the stations. In August 2002, January 2003 and August 2003, significant inflow events occurred through the entrance area of the Baltic Sea (Feistel et al., 2006). These saline pulses are likely seen in our data as a delayed impact of the increased salinity in the Archipelago Sea.

The stations N and E are characterised by rather identical salinity fluctuations. A halocline was not observed at these shallower stations during any season, although salinity was typically 0.1–0.2 higher in the bottom than in the surface layer. At the deeper station S, the average difference between the surface and bottom layer salinity was 0.8. The surface and bottom salinity values did not fluctuate simultaneously, indicating the presence of a halocline and an influence of the bottom layer water of the northern Baltic Proper. These findings further suggest that the underwater sills prevent the intrusion of the denser saline bottom layer waters into the inner archipelago area, allowing only the surface water layer to filter towards the north and the mainland.

Station N followed the fluctuation pattern of station S with a lag of 2–3 quarters, i.e. 6–9 months. Assuming that the surface salinity at these stations is an indication of northward surface water flow, the mean residual flow velocity can be defined: the distance between the stations is approximately 90 km, thus the northward flow component of the surface water flow through the Archipelago Sea is 0.4–0.6 cm s⁻¹.

There are several studies considering the Baltic Sea circulation patterns based on either observations or modelling. Typical scalar current velocities in the upper layer of the Gulf of Finland are found to be 10 cm s⁻¹ (Alenius et al., 1998), and near the coast and in the open sea of the Gulf of Bothnia 5–7 cm s⁻¹ and 2–4 cm s⁻¹, respectively (Myrberg and Andrejev 2006). Further, in the NE Archipelago Sea, scalar current velocities were typically less than 10 cm s⁻¹ (Virtaustutkimuksen neuvottelukunta, 1979). During the BEVIS project (Kohonen and Mattila, 2007), flow measurements were made on the eastern side of Åland Island with moored instruments for three periods of seven weeks in four locations. They measured surface layer mean scalar velocities of 7–14 cm s⁻¹ (Forsius et al., 2007).

However, particularly in experimental studies periods of measurement are often relatively short. Thus, they do not reflect long term circulation and in moored experiment configurations, the results also depend on the local conditions, such as bathymetry. The circulation pattern of the Baltic Sea is not stable and currents

typically oscillate back and forth in different time-scales (e.g. Otsmann et al., 2001). Therefore, the mean residual flow velocities are significantly lower than the mean scalar velocities. In the early studies of Witting (1912) and Palmén (1930), the annual mean residual vector velocity in the Gulf of Finland and Gulf of Bothnia was reported to be less than 2 cm s^{-1} , while a similar mean residual flow velocity of $1\text{--}2 \text{ cm s}^{-1}$ was also presented by Alenius et al. (1998) for the Gulf of Finland. Forsius et al. (2007) reported the mean northward flow component velocities varying in the range of $-4.1 \text{--} 2.8 \text{ cm s}^{-1}$ in the sea area east of Åland, negative values indicating the southward flow.

Although the residual flow velocity (or mean circulation) is a statistical artefact rather than a physical condition in the Baltic Sea, it is usable when evaluating the distribution of substances (Myrberg and Andrejev, 2006; Alenius et al., 1998). The northward flow component indirectly derived in this study is low compared to the earlier studies in more pelagic areas. These results indicate that over a long term the Archipelago Sea acts as a relatively strong buffer and that the water retention time is long. This issue calls for further inspection, since it may impact, for instance, on the accumulation of nutrients and thus have implications to the development of the eutrophication process in the Archipelago Sea.

While the salinity gradients discussed above have been intuitively known, they have not been previously studied in such spatial and temporal detail in the Archipelago Sea. On the basis of our results, we argue that the Archipelago Sea can be considered both a transitional, estuary-like environment for its continuous mixing of continental and marine water masses, as well as a sieve-like sill system between two major basins of the Baltic Sea. These parallels may be embedded in the research of the biotic systems in these stress environments, where the local species assemblages constitute a mixture of salinity sensitive fresh water and marine species. The dynamic nature of salinity and other physical and chemical properties of the seawater should be thoroughly considered also in the planning of environmental monitoring in the region (Erkkilä and Kalliola, 2007). Water protection actions should find the most effective means to reduce nutrient dispersion and eutrophication. In this context, a multidisciplinary understanding of the water exchange dynamics as well as ecological gradients and limits within the Archipelago Sea are required (see Helminen et al., 1998, Kohonen and Mattila, 2007). It is also likely that the precipitation in the northern Baltic Sea drainage basin will increase during the century, which would lead to a decrease in the overall salinity of the Baltic Sea

(Graham et al., 2008) and changes in the ecosystem (Dippner et al., 2008). Further understanding of the Archipelago Sea's salinity dynamics in different spatial and temporal scales is needed for the prediction of the sea area's future development.

5. Conclusions

The combination of estuarine and sill characteristics creates spatially and temporally varying salinity conditions in the Archipelago Sea. Although the range of these fluctuations is narrow, the areas of volatile salinity need to be studied in higher detail, since the ecological implications of the salinity dynamics are manifold in these brackish waters. The highest variations occur in those areas that are influenced by both the occasional marine water intrusions through the area, as well as the runoff from the mainland. We extend the need of further research of spatial and temporal variation also to other key variables of aquatic environment. The predictive environmental modelling in the highly dynamic coastal and estuarine areas of the northern Baltic Sea should be based on the representative sampling and empirical mapping of the aquatic environment with its diverse physical, chemical and biological phenomena.

1 Acknowledgements

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3 The authors would like to thank the Southwest Finland Regional Environment Centre
4 for co-operation in sampling and laboratory analyses, and Husö biological station of
5 the Åbo Academy University and the Environment Agency of the Government of the
6 Åland Island for providing their field data. Simon Amelinckx, Anne Erkkilä, Jani Helin
7 and Andy Stock are acknowledged for field work assistance, and the Department of
8 Geography and the Archipelago Research Institute of the University of Turku for field
9 work facilities. The study was funded by the Academy of Finland (project 114083),
10 the Turku University Foundation and the Finnish Cultural Foundation.

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Figure 1. Location of the study area and the observation stations. For the abbreviations of the data provider, see Table 1. The intensive monitoring stations KORP 200, NAU 2361 and Brändö 100 are indicated with the letters S, E and N, respectively. The major rivers of the study area are indicated with their average discharge.

Table 1. Summary of the data sets.

Table 2. A step-wise diagram of the inverse path distance weighted interpolation procedure. The calculations are done locally for each cell separately and letters P, A, B, C, W, D and E refer to raster surfaces. The constant L set by the user defines the maximum distance of an influence. The value S refers to salinity measured in the field.

Figure 2. Examples of some of the intermediate raster layers in the inverse path distance weighted interpolation procedure and the resulting estimation of salinity. For explanation, see table 2.

Figure 3. Error assessments of the IDW and IPDW methods. $\bar{S}_j$ is the mean of observed salinities on week j , S_{ij} is either the observed salinity at the station i on week j (y -axis), or the modelled salinity at the location of the omitted station i on week j (x -axis).

Figure 4. Comparison of the isohalines on week 34 in 2007 produced by the IDW (A) and by the IPDW (B). The dotted lines on land are added for better readability. Field data provided by SFREC.

Figure 5. Isohalines on weeks 29 and 34 in 2007 (16.–19.7. and 20.–23.8.2007).

Figure 6. Isohalines on weeks 29 and 35 in 2008 (14.–17.7. and 25.–29.8.2008).

Figure 7. Isohalines in the NE Archipelago Sea on weeks 20–40 (from mid May to the beginning of October) in 2007.

Figure 8. The range of surface salinity in the NE Archipelago Sea during the weeks 20–40 in 2007.

1

2 *Figure 9.* The quarterly surface salinity (black) and the near bottom salinity (grey) at
3 the intensive monitoring stations N, E and S (left column) and quarterly deviations
4 from the mean of the corresponding quarter (right column).

5

6 *Figure 10.* Cross-correlations of surface salinity between the stations N, E and S with
7 time lags of ± 8 quarters.

1 *Table 1.*

2

Analysis	Year(s)	Weeks	Number of Stations	Data provider
The Archipelago Sea in July-August 2007	2007	29, 34	27	South-West Finland Regional Environmental Centre (SFREC)
	2007	29, 34	38	Environment Agency of Åland (ÅL)
The Archipelago Sea in July-August 2008	2008	29, 35	56	South-West Finland Regional Environmental Centre (SFREC)
	2008	29, 35	38	Environmental Agency of Åland (ÅL)
The NE Archipelago Sea in 2007	2007	20, 23, 26, 29, 31, 34, 37, 40	22	Department of Geography, University of Turku (UTU)
The long term observations in 1999–2008	1999/2000 - 2008	Variable	3	Finnish Environment Institute (SYKE)

1 *Table 2.*

2

Description	Equation	Resulting raster datasets
Calculate path distances from all sampled stations i along predefined cost surface		Path distances P_i ($i = 1...n$)
If the path distance from the station i is less than distance limit (L), preserve the cell value, otherwise set the value to distance limit	$A_i = \begin{cases} P_i & ,if\ P_i < L \\ L & ,if\ P_i \geq L \end{cases}$	Limited path distances A_i ($i = 1...n$)
Calculate the inverse path distance by dividing the distance limit by the limited path distance from the station i	$\frac{L}{A_i}$	Inverse path distances B_i ($i = 1...n$)
If the inverse path distance is greater than 1, preserve the cell value, otherwise set the value to zero	$C_i = \begin{cases} B_i & ,if\ B_i > 1 \\ 0 & ,if\ B_i \leq 1 \end{cases}$	Inverse path distances C_i ($i = 1...n$)
Calculate the weight of each station in each cell by dividing the stations i inverse path distance with the sum of the stations $i = 1...n$ inverse path distances	$\frac{C_i}{\sum_{i=1}^n C_i}$	Weights of stations W_i ($i = 1...n$)
Calculate the weighted salinity in each cell by multiplying the weight of a station by measured salinity value of the station (S_i)	$W_i \times S_i$	Weighted salinities D_i ($i = 1...n$)
Calculate the estimated raster surface for salinity by summing the weighted salinities	$\sum_{i=1}^n D_i$	Estimation of salinity

3