Geographical persistence of surface-layer water properties in the Archipelago Sea, SW Finland

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The Archipelago Sea in the Northern Baltic Sea has a complex water quality regime. The region consists of islands and underwater thresholds that separate interconnected sub-basins, where the waters from the adjacent sea areas and discharges from the mainland are mixed. Thus, the water properties in the region are exceptionally varying by season and location. We studied the seasonal developments of five surface-layer water variables – temperature, salinity, Secchi depth, chlorophyll and acidity – and the persistence of their geographical patterns in a network of 20 sampling stations in the eastern part of the Archipelago Sea during a period from May to October in 2007. Furthermore, the inter-annual persistence of the late summer observations of three of these variables were analysed within the same network. Although preconceptions about the general gradation patterns from the mainland towards the open sea were found realistic, we also identified geographically divergent seasonal developments and found out that the inter-annual persistence of the studied three variables were not geographically as strong as expected.

Keywords: water quality, monitoring, persistence, gradient, Archipelago Sea, Baltic Sea

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Introduction

Transitional coastal waters in the archipelago coasts of the northern Baltic Sea show temporally and spatially dynamic physico-chemical patterns (e.g. Kirkkala et al. 1998; Suomela 2001) that interact with the biota. It is important to understand these complex and often small-scale variations for both scientific and practical reasons. For example the European Union's Marine strategy (Anon. 2008) requires good knowledge-base about the seawaters, which can be achieved through a combination of *in situ* observations with adequate spatio-temporal coverage, remote sensing adapted to local conditions to present regional overviews (e.g. Härmä et al. 2001; Erkkilä & Kalliola 2004; Kratzer et al. 2008), various statistical analysis methods (e.g. Hänninen et al. 2000; Lundberg et al. 2005) as well as scientific knowledge to interpret the processes behind the observed patterns.

Water chemistry and cyclical biological processes are subjected to temporally biased and infrequent sampling (Carstensen et al. 2006; Carstensen 2007). Sampling all locations within the same period of successive years includes an assumption that the spatial distribution of water quality properties during a particular calendar week reflects the overall spatial water quality pattern of that region. This assumption ignores the fact that there are processes that do not occur simultaneously throughout the area. Therefore, the simultaneous sampling of non-simultaneous phenomena results in biased results *de facto*. However, such sampling designs are widely used, since a frequent enough sampling for studying seasonal cycles of water properties in high spatial detail would be impracti-

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cal, expensive to implement and out of the scope of monitoring. In Finland, the monitoring of the physical and chemical properties of the coastal waters is mainly based on standardised water sampling at fixed stations and subsequent laboratory analyses (Niemi 2009). The core of the coastal monitoring is made by 16 intensively monitored stations (20 visits/a) along the Finnish coast and approximately 150 stations that are sampled 2–4 times annually (Raateoja & Kauppila 2009). Added with some regional programmes, local pollution control monitoring and diverse short-term monitoring projects, these efforts have built up a large database of standardised water quality data (Manni 2009). These data provide valuable record considering monitoring, basic research and many applied purposes in research and coastal management. However, it is also criticised that the current data records are spatially and temporally inconsistent and thus not optimal for scientific applications (Erkkilä & Kalliola 2007). A sampling frequency of 2–4 times a year, also proposed in the Water Framework Directive (Anon. 2000), is regarded insufficient for operational purposes also in the later implementation guide of the directive (Anon. 2003) where biweekly or monthly sampling regimes are recommended. According to Carstensen (2007), a high number (>500) of observations are needed to characterise a single water body. However, the sampling could be divided into multiple stations and for several years, and eventually the required sampling frequency and the number of stations depends on the variability of the water properties in the water body in question.

The extremely fragmented Archipelago Sea in SW Finland is an especially challenging area from the viewpoint of spatial data analysis with its numerous islands and interconnected sub-basins. The area acts as a transitional system where continental runoff mixes with brackish seawater (Suominen et al. 2010). Many of the seasonal physical, chemical and biological processes are driven by the annual cycles of solar radiation, causing a wide temperature range and bi-annual vertical circulation of the water column. The biological activity is linked to the concurrent physico-chemical water property dynamics, particularly to temperature, incident light and the availability of nutrients. Consequently, the Archipelago Sea is a diverse marine environment whose water properties must be studied as a complex four-dimensional system.

Although the overall annual cycles of the surface-layer water properties in the Baltic Sea are well known and described (e.g. Wulff et al. 2001; Leppäranta & Myrberg 2009), their dynamics in the coastal areas may be different. Since the Archipelago Sea is a particularly complex coastal sea with high demand for reliable water quality data, we find it important to study its spatial and temporal water quality patterns and their persistence from a geographical perspective. In this region, sampling even in a spatially dense network may not yield sufficient detail for all the research purposes compared to the region's complex and ephemeral water currents (Erkkilä & Kalliola 2004). Furthermore, the gradation from the inner archipelago to the open sea results in a transitional water property regime, whose persistency is largely unknown. To overcome these uncertainties, we describe the seasonal developments of five surface-layer water quality variables – temperature, salinity, Secchi depth, chlorophyll and acidity – by using measurements made with an electro-optical sonde in the eastern part of the Archipelago Sea. Since we were interested in spatial differences in seasonal development, we compromised on spatial and temporal resolution and the sampling were carried out in a network of 20 stations sampled eight times from May to October in 2007. We use these data to analyse the geographical differences in the temporal patterns of these cycles through the summer, and apply robust time stability plot graphs to evaluate the persistence of the detected geographical patterns in order to identify areas of constantly higher or lower values, as well as areas with more varying character. Additionally, we will use national monitoring data from late summers of 2002–2008 in order to study the inter-annual persistence of the geographical patterns of temperature, Secchi and chlorophyll value distributions within the same sampling network.

Material and methods

Study area

Transitional archipelago coasts are typical geomorphological formations in the northern Baltic Sea (Frisén et al. 2005). The Archipelago Sea of SW Finland alone consists of 25 000 islands larger than 500 m^2, and 14 400 km of shoreline in an area of approximately 10 000 km^2 (Granö et al. 1999). Our study area covers the northern and eastern parts of this coastal region, including the entire transition from the shallow inner bays to the

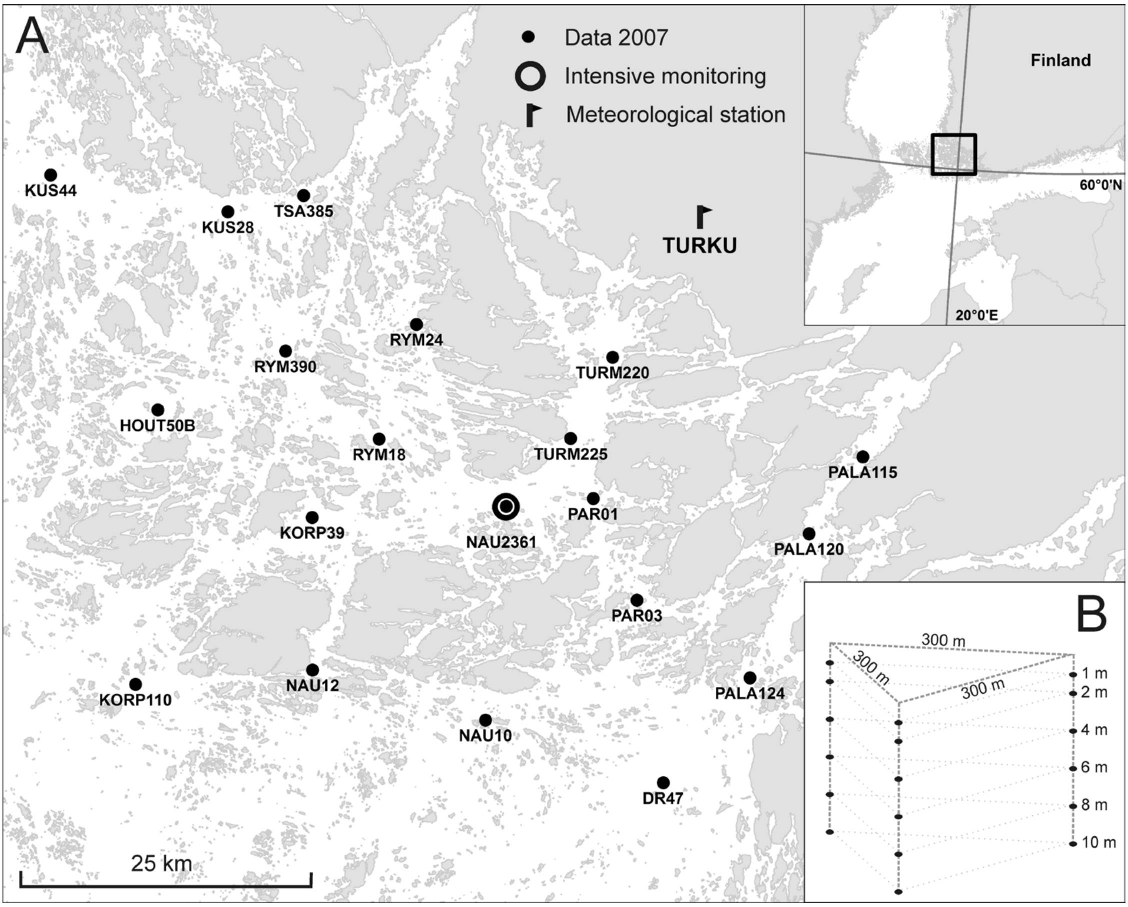

Fig. 1. A) The sampling stations in the Archipelago Sea, SW-Finland. B) Sampling pattern with three parallel depth profiles at a station.

outer archipelago zone (Fig. 1). The Archipelago Sea is structured by fragmented bedrock that has a local relative elevation range of about two hundred metres. The bedrock base is partially covered with till, glaciofluvial deposits and marine sediments. The mean depth of the Archipelago Sea is estimated to be only 23 m, typically ranging from 0 to 50 m with some deeps and fault lines exceeding 100 m. The deepest basins in bedrock faults provide channels for water currents through and within the area, whereas islands and underwater thresholds of the region form numerous local sea basins where the terrestrial runoff and offshore waters mix, resulting in a mosaic of water masses with different origins and properties. Water flow velocities are typically less than 10 cm s^{-1} (Virtaustutkimuksen neuvottelukunta 1979) and flow directions vary depending on the combined effect of the Baltic-wide water balance fluctuation, regional atmospheric pressure and wind patterns. Although the general anti-clockwise flow pattern of the Baltic basin, i.e. from south to north in the area of Archipelago Sea, is rather a statistical artefact than a physical phenomenon (Alenius et al. 1998; Myrberg & Andrejev 2006), the observed salinity fluctuations in the Archipelago Sea (Suominen et al. 2010) support its presence on a long-term.

The highest surface-layer water temperatures (approx. 20 °C) occur near the mainland in August. The annual permanent ice cover in the region extends up to 100 days on the average (Seinä & Peltola 1991) and in spring and autumn, vertical circulation interrupts the summer and winter stratification. Surface-layer salinity varies from the low levels at river mouths up to approximately 7.0‰ in the open sea (Viitasalo et al. 1990; Suominen et al. 2010). Optically, the Baltic Sea classifies into the Case-2 waters, indicating that the optical properties of the water are influenced not only by chlorophyll concentration, but also by suspended particulate matter (SPM) and coloured dissolved organic matter (CDOM) (Morel & Prieur 1977). The concentration of CDOM in the Baltic Sea is exceptionally high compared to other seas (Kratzer et al. 2003). The inner archipelago waters tend to be turbid throughout the year, while low turbidity prevails in the outermost regions. Human-induced eutrophication is a distinctive and commonly acknowledged environmental problem in the Baltic Sea (Bonsdorff et al. 2002; HELCOM 2009), including the Finnish coastal waters (e.g. Pitkänen et al. 2004), and it is one of the key agents that promote pelagic and littoral ecosystem change in the region (Rönnberg & Bonsdorff 2004).

There is one sampling station (NAU2361) in this region that belongs to the national intensive monitoring programme (for location, see Fig. 1). Like other intensively monitored stations, it is sampled nominally 20 times a year with a wide range of parameters and sampling depths. Fig. 2 shows an extract of such long-term data from five different parameters covering the years of 1989 to 2008, to characterise some typical physico-chemical cycles in the central Archipelago Sea. *Temperature* changes in the surface-layer are considerable in the northern Baltic Sea, and the highest temperatures in the study area occur in July-August. The diffusion of fresh melting waters from the terrestrial runoff and sea ice can be recognised as lower *salinity* readings in spring and early summer. The wide range of salinity measured in spring at NAU2361 is probably caused by melting sea ice and the stratification of the fresh water beneath it. *Chlorophyll-a*, indicating the abundance of phytoplankton in water, peaks in spring after the ice melt, when there is an excess of inorganic nutrients and incident light. The spring maximum is succeeded by a phytoplankton minimum in the early summer due to planktic grazing and lack of available nutrients. Another maximum follows in the late summer. The *Secchi depths* are affected by SPM, CDOM and the abundance of phytoplankton. Larger Secchi depths occur in the early summer during the phytoplankton minimum. *Acidity* reflects both the intensity of primary production and the diffusion of terrestrial discharges, both of which are high in the spring. More detailed descriptions of the overall water properties and their seasonal cycles in the Baltic Sea and in general can be found e.g. in textbooks by Leppäranta and Myrberg (2009), Wulff et al. (2001) and Wetzel (2001).

Seasonal water quality data 2007

In order to obtain geographically and temporally representative data for the season from May to October, we designed a field sampling regime that covers the transition from the inner archipelago close to the mainland to the outer archipelago. To enable comparisons with earlier data, we selected the stations among the ones sampled by the Southwest Finland Regional Environmental Centre (SFREC). We prioritised relatively open sea areas with no nearby point source pollution, and paid special attention to long and deep straits in fault lines and their crossings, i.e. flow channels from, to and within the area. Consisting of 20 stations located 6–15 km apart (Fig. 1), our network provides a good overall sample of the area. At each station, three parallel depth profiles were measured in a constellation of an isosceles triangle with sides of 300 m (Fig. 1B).

The measurements were made every third week from mid-May to early October in 2007. During the weeks of 29 and 31 in July, field measurements were synchronized with the simultaneous sampling of the SFREC routine monitoring schedule. Each of the eight sampling round was made in two to three days, depending on weather conditions. In one case the data are missing, because the southernmost station was inaccessible at the week 37 due to weather restrictions. The missing data were imputed using mean values from the preceding and subsequent measurement week.

The weather conditions of the monitored season were rather normal to the region (Fig. 3). Air temperatures were above the long-term averages in the beginning of the year, as well as in August, but otherwise they remained near the long-term averages. Precipitation was high in January and May, and there were also occasional heavy rains in July. From August to October, precipitation was below the average (Drebs et al. 2002; FMI 2008). Due to some warm periods during the preceding winter of 2006–2007, river discharges were high in January-February. However, the spring peak river discharges were below the average in the southern and

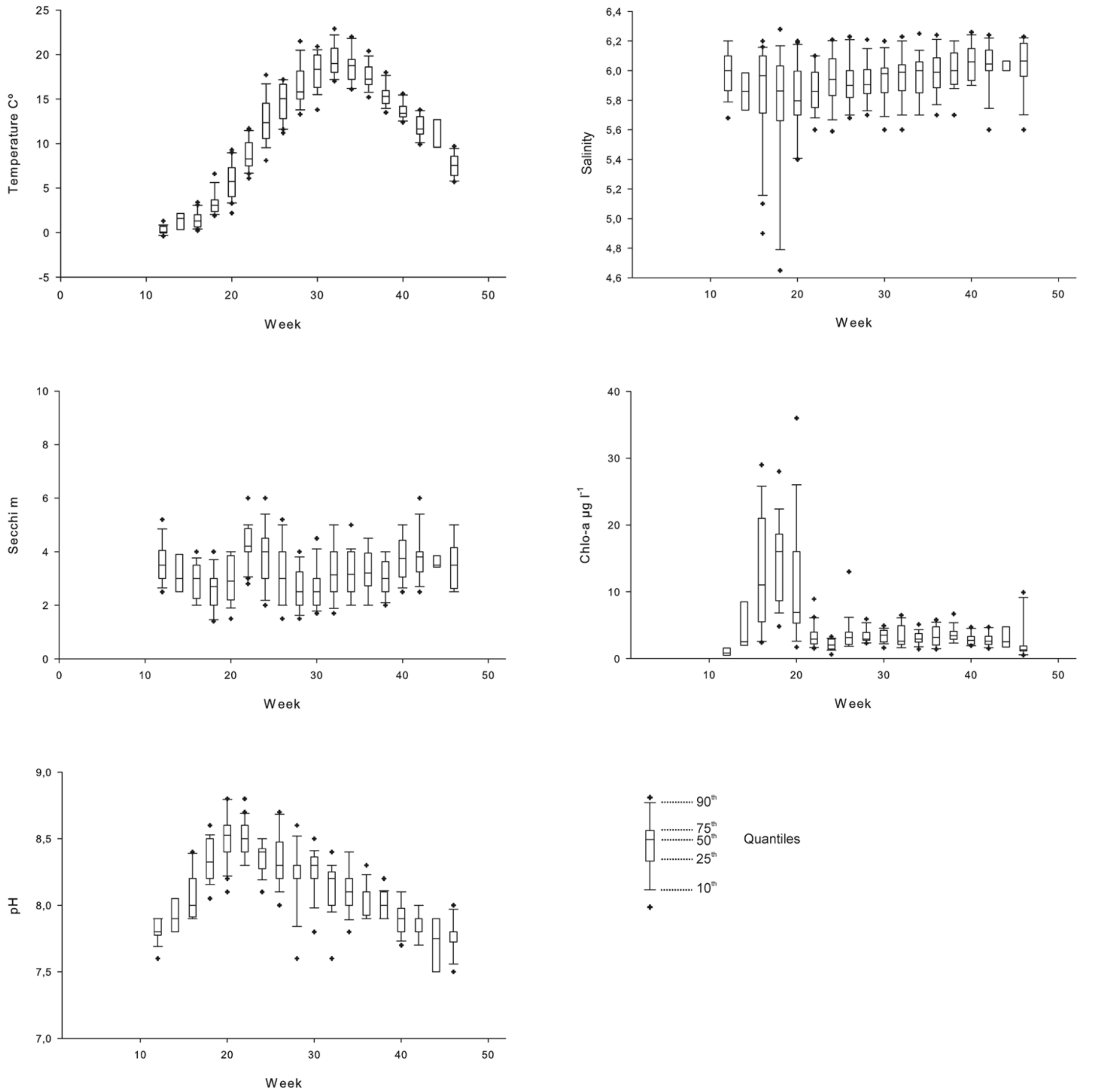

Fig. 2. Seasonal cycles of water property parameters measured at intensively monitored station NAU2361 in the middle Archipelago Sea (see Fig. 1). Each box plot represents observations collected during the same two-week period in 1989-2008.

western coastal zones. Summer discharges were mostly below the average although some heavy rains caused occasional high discharges. In the small rivers of the region, discharges increased at the end of the year to their highest values of the whole year, clearly exceeding the spring flood levels (FEI 2007).

The field measurements were made *in situ* using a multi-parameter sonde (YSI 6600 V2), equipped with sensors for conductivity and temperature (sensor model YSI 6560), pressure, chlorophyll (6025), pH and redox potential (6565), turbidity (6136) and dissolved oxygen (6150). The boat was stopped at a substation, usually within 10 m from

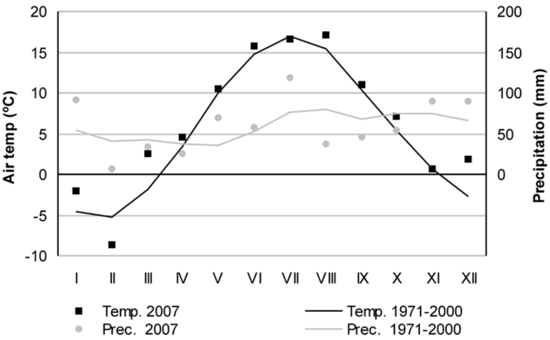

Fig. 3. Mean air temperature and precipitation in 1971–2000 and the monthly means in 2007 at the meteorological station of Turku airport (Drebs et al. 2002; FMI 2008).

the nominal GPS location, and the outboard engine was turned off during the near-surface measurement to avoid false readings due to water mixing or exhaust emissions. Drifting of the boat was not considered to be a problem, since the drift distance during one measurement was usually less than 50 m from the actual sampling point, and only rarely exceeded 100 m.

The sonde was connected to a handheld terminal with a 15 m cable enabling real-time examination of the measurement data. First, the sonde was held at 1 m depth until the sensor readings were stabilised (about 30 seconds), after which the readings were recorded at every two seconds for 20 seconds. This procedure was repeated in six sampling depths (1, 2, 4, 6, 8 and 10 m) at each substation. Secchi depth was measured using the white cap of a Limnos sampler.

Water samples were collected from 7–9 stations during each field sampling round to facilitate the post-calibration of the chlorophyll readings, and to inter-calibrate the sonde data with the national monitoring data. A Limnos 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 the readings were recorded for 1–2 minutes to get a control reading for the calibration.

Chlorophyll-*a*[1] samples were collected each week, conductivity[2] samples at the weeks 29–40, and pH[3] samples at the weeks 37 and 40. All water analyses were conducted by the laboratory of Water Protection Association of Southwest Finland. Drifts of the conductivity and chlorophyll sensor values were determined prior to and after every field trip by using distilled water as a standard. The measured values were corrected to correspond with the laboratory values with a linear regression model.

The conductivity values measured in the field were compensated to 25 ºC by an equation provided by the manufacturer; $\gamma_{25^\circ C} = \gamma/(1+TC(T\text{-}25))$ where $\gamma_{25^\circ C}$ is the specific conductance compensated to 25 ºC, 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 ($COND_F$) showed a good linear correspondence (r^2=0.98, n=48) with the laboratory results ($COND_L$) (Fig. 4). 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. An exceptionally high conductivity value at the station PAR01 in the week 26 was assigned as an outlier, and the mean value of the preceding and subsequent week were used instead.

The ranges of pH_F (field) and pH_L (laboratory) were narrow (pH 7.98–8.32 and pH 7.8–8.0, respectively). The pH sensor drift was determined at the week 35 with standards pH 7 and pH 10, and the results were also used in the comparisons (Fig. 4). The correspondence between the field measurements, laboratory analysis and standards was very good (r^2=0.99, n=14), but the field measures showed slightly higher values (approx. 0.2 units). The reported accuracy of the sensor is ±0.2 units. In analysis we used the estimated concentration of free hydrogen ions H^+, which was calculated from the logarithm of the reciprocals of pH.

The chlorophyll sensor measures the total fluorescence of different chlorophyll pigments in the sample as relative fluorescence unit (RFU), which is regarded to be proportional to the quantity of phytoplankton. These results indicate the relative differences in phytoplankton biomass rather than the absolute concentrations of chlorophyll or phytoplankton biomass in the water column. This is because the intensity of chlorophyll fluorescence

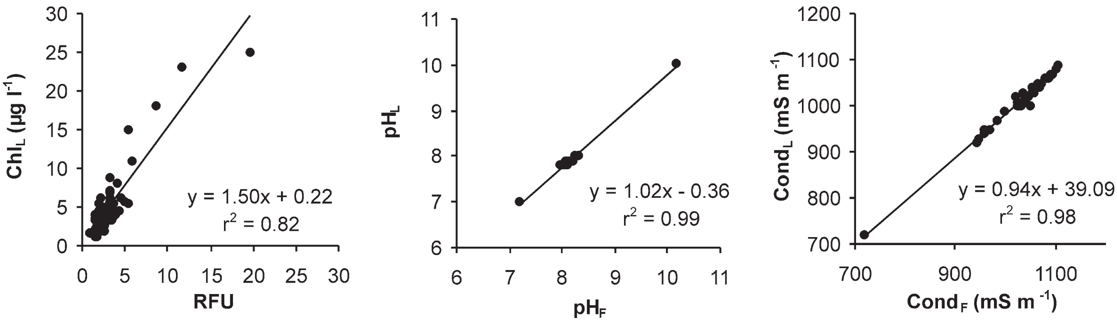

Fig. 4. The correspondence between the field measurements and laboratory results of chlorophyll-a, pH and conductivity.

depends, among other factors, on the physiological status of the phytoplankton and the level of photoinhibition that varies by the intensity of light during the measurements (Kirk 1994). Additionally, different phytoplankton species have different dominant photosynthetic pigments. This may bias the results, especially if the most common species in a sample are cyanobacteria containing phycocyanin and phycoerythrin as their dominant pigments. However, as the use of the fluorometer allows extensive sampling and reliable measurement of the relative differences in the vertical and horizontal distributions of phytoplankton, we considered it as an adequate instrument for this study. The correspondence between the field RFU values and laboratory analysed chlorophyll-*a* ($Chlo_L$) was moderate (r^2=0.82, n=69) (Fig. 4).

Late summer water quality data 2002–2008

Late summer (July-August) data from the national water quality monitoring, originally collected by SFREC, were derived from the Finnish Environment Institute's OIVA database (see Erkkilä & Kalliola 2007; Manni 2009). We used data from the years of 2002–2008 from the same network of 20 sampling stations, but since salinity and acidity are not sampled at all stations, only temperature[4] (1 m), Secchi depth[5] and surface-layer chlorophyll-*a6* were used. Water chemistry analyses of these data were done in the laboratory of the Water Protection Association of Southwest Finland.

Analysis of seasonal water quality data 2007

The observations of the three parallel profiles and the six sampling depths (1–10 m) were averaged to a single value for each station and for each week. We created quantile based box plot graphs for the parameters to illustrate the weekly (20–40) medians and 10^{th}, 25^{th}, 50^{th}, 75^{th} and 90^{th} quantiles, e.g. the overall variation of the measured water properties. The seasonal and spatial patterns of the measured parameters were further examined by visualising the values of each parameter weekly (20–40) in separate cartograms. The second cartogram indicates the deviation of the station's value from the median of all measurements at the same week, emphasising the spatio-temporal differences in the seasonal development of the water properties between the stations.

Methods for quantifying and visualising temporal stability have been developed for studies considering e.g. soil water storage (Vachaud et al. 1985; Starr 2005) and the fall of precipitation through forest canopy (e.g. Keim et al. 2005; Zimmermann et al. 2007). The implementations of the time stability plot differ, but the general idea remains. In our implementation we first calculated relative values of the variable, i.e. how much an observation deviated, relatively, from the median of the corresponding week

$$\tilde{\delta}_{i,j} = \frac{(\delta_{i,j} - Md(\delta_j))}{Md(\delta_j)} \qquad (1)$$

where $\delta_{i,j}$ is the value of an observation and $\tilde{\delta}_{i,j}$ is the relative value of the observation at the site i at the sampling week j, and $Md(\delta_j)$ is the median of the observations at week j. In time stability plot, the sites are then ranked by their median $\tilde{\delta}_{i,j}$ and plotted in a graph. The variation at a site between the observation weeks is visualised by adding a quartile based box plot showing 25th, 50th and 75th quartiles. Since there are eight observations per station, four of them are within the interquartile range. Temperature is not measured in a ratio scale and thus only their deviations from the global median of the corresponding week were calculated

$$\tilde{\delta}_{i,j} = \delta_{i,j} - Md(\delta_j) \qquad (2)$$

Vachaud et al. (1985) used mean values instead of medians in their first implementation of the time stability plot, and Keim et al. (2005) and Zimmermann et al. (2007) used standard deviation and median absolute deviation as the divisor, respectively. Further, in the time stability plot both ±1 standard deviation and 95 % confidence interval have been used as a measure of spread. In our study, neither the residuals, $\delta_{i,j} - Md(\delta_j)$, nor the relative values $\tilde{\delta}_{i,j}$ followed normal distribution. We wanted to use similar analysis methods for all the five parameters, and therefore we applied non-parametric methods and based our implementation in medians and deviations from it, and on the other hand, to quantile based box plot as a measure of spread in time stability graphs.

The time stability plots visualise temporal stability of the observations at the sites. To extend the time stability analysis by geographical dimension, the results were plotted over a map. For this, we classified the sites by their median of the relative values $\tilde{\delta}_{i,j}$ and the locations of the quantiles. White circles with a dot indicate the sites whose median $\tilde{\delta}_{i,j}$ are below zero, and the black dots indicate the sites whose medians are above zero. The size of the marker indicates the position of the quantiles compared to the zero level.

Analysis of late summer water quality data 2002–2008

The late summer data 2002–2008 consist of three annual observations for seven years. The time stability plots were constructed corresponding to the analysis in the previous section, but the higher number of observations facilitated the use of more quantiles. In addition to 25th, 50th and 75th quartiles, also 10th and 90th quantiles were used. Since there were altogether 21 observations from each station, the two lowest and two highest values were outside the quantiles. The classification of the sites according to the position of the median and the quantiles was different than in the seasonal data of 2007.

Time stability plots and their visualisations on a map characterise the stations' temporal behaviour, i.e. whether the values in the stations are higher or lower than the global median of the corresponding week. However, they do not quantify the stations' variation. Since there were only 21 observations and all three parameters were not normally distributed, we applied non-parametric median absolute deviation (MAD) to identify stability of the relative values at the stations

$$\mathrm{MAD} = Md(|\tilde{\delta}_{i,j} - Md(\tilde{\delta}_{i,j})|) \qquad (3)$$

where MAD is the median absolute deviation, $\tilde{\delta}_{i,j}$ is the relative value of the observation at the station i at the sampling week j and Md($\tilde{\delta}_{i,j}$) is the median of the relative values at the week j.

Results and discussion

Temperature

Surface-layer temperatures showed a steady seasonal increase in the spring and early summer of 2007 (Fig. 5, 6A). The highest surface water temperatures occurred at the week 34, when the temperatures varied between 17.9 ºC and 19.7 ºC. Spatially distinctive deviations were found especially in early and mid summer, whereas towards the late summer and autumn temperatures were geographically more constant (Fig. 6B). There was a gradation from the warmer waters in the inner archipelago to colder waters in the outer regions, but anomalies from this general setting were common. In the four stations that had the lowest temperatures, the median of the residuals was 0.4–1.2 ºC below the global medians of the corresponding weeks (Fig. 6C, 6D). Respectively, the four warmest stations near the mainland showed 0.3–0.8 ºC higher medians of residuals.

Also the inter-annual late summer data indicate that the surface-layer water temperatures are higher in the inner archipelago (Fig. 7A). However, if the location of the interquartile range relative to the zero level is considered as a limit, only four stations showed constantly higher temperatures (Fig. 7A, B). In these stations the median of the residuals from the contemporary global median temperatures were 0.3–0.9 ºC higher. Respectively, only three stations in the western part of the study area showed relatively constant lower temperatures, with median residuals being 0.5 to 0.8 ºC

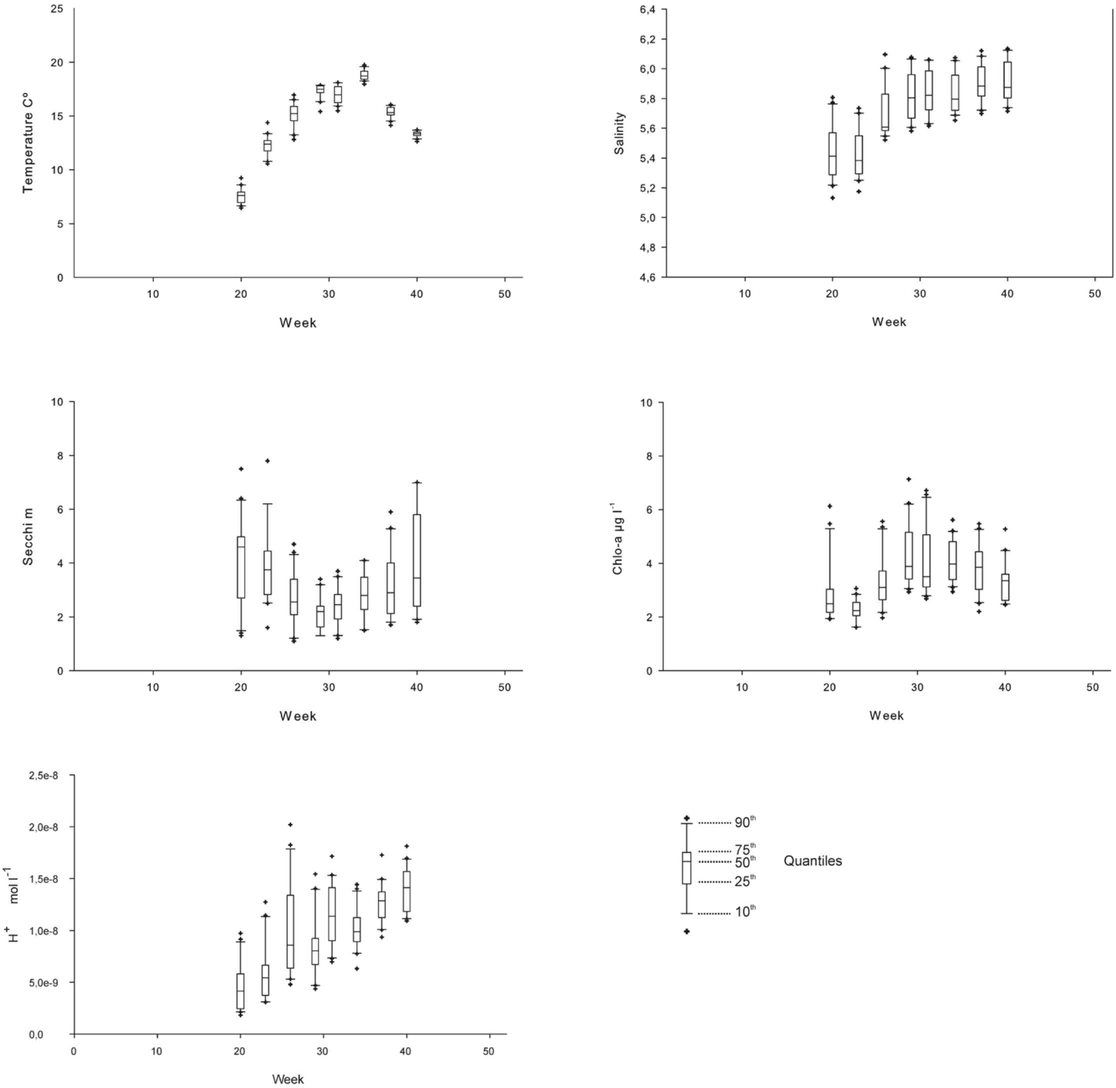

Fig. 5. Seasonal cycles of water property parameters measured at the 20 observation stations in the Archipelago Sea (Fig. 1). Each box plot represents observations collected during one of the eight one-week campaigns between May and October in 2007.

below the global median. Median absolute deviations from the weekly medians ranged at different stations from 0.2 to 0.75 ºC (median 0.35 ºC), and they did not show clear spatial pattern (Fig. 7C).

McKenzie and Schiedek (2007) compared multiple long-term temperature time-series measured in the North Sea and the Baltic Sea. They noted that the seawater temperature variations in the coastal monitoring sites reflect much of the variability in temperature at larger spatial scales. However, they also found significant differences in temperature variability between coastal sites and adjacent sea areas, and that the differences between the coastal and off-shore time-series and their seasonal amplitudes varied non-randomly with significant differences over time. In our study,

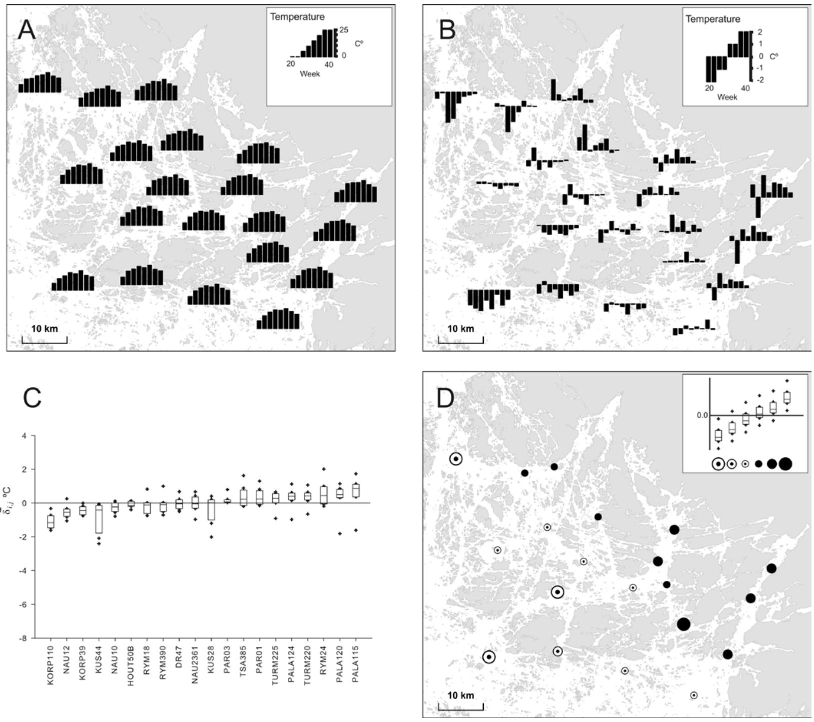

Fig. 6. Temperature in May-October in 2007. A) Surface-layer temperature, B) Temperature deviations from the median of the corresponding week, C) Time stability plot, indicating station-wise stability of temperature compared to the other stations, D) Classification of the stations according the location of the median, and 25th and 75th quartiles.

a gradation from higher temperatures in the inner archipelago towards lower temperatures in the outer regions was detected during the studied period in 2007, and in the late summers in general. Anomalies from this pattern were common, as in both cases only few stations showed constantly higher or lower temperatures than the contemporary global median. However at the same time the deviations from the contemporary global medians were relatively small and the temperatures were rather uniform throughout the area. Surface-layer water temperature is mostly affected by the solar radiation, which is an external and, in practise, evenly distributed factor. In the Archipelago Sea, the depths and volumes between adjacent sub-basins may differ, as well as the distribution of the surrounding land masses, affecting the rates of warming and the formation of thermal stratifica-

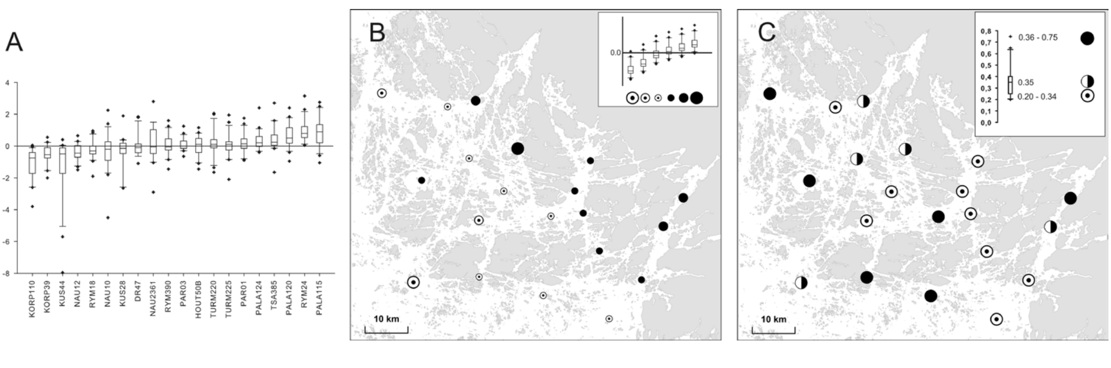

Fig. 7. A) Time stability plot based on the late summer temperature observations in 2002–2008 and B) station-wise classification according the locations of the median, and 10th, 25th, 75th and 90th quantiles. C) Station-wise median absolute deviations of the temperature residuals from the global median of the corresponding week.

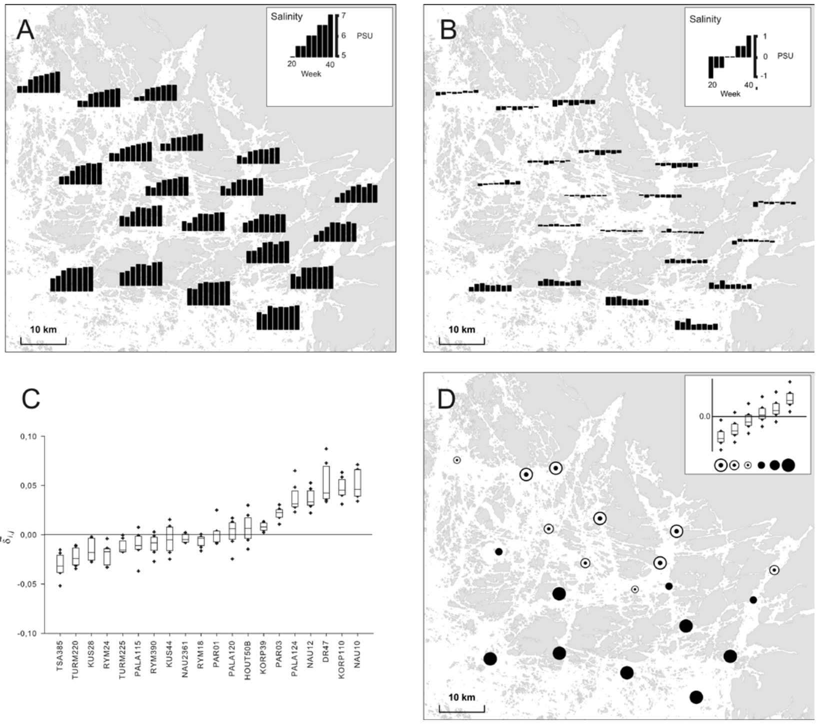

Fig. 8. Salinity in May-October in 2007. A) Surface-layer salinity, B) Salinity deviations from the median of the corresponding week, C) Time stability plot, indicating station-wise stability of the relative deviations from the global median of the corresponding week, D) Classification of the stations according the location of the median, and 25th and 75th quartiles.

tion. The vertical and horizontal water movements regulate the surface water temperatures, and also the ephemeral currents driven by weather and water level changes may induce momentary temperature patterns in the surface waters of the region.

Salinity

In 2007, salinity had a temporal pattern, in which the lowest values occurred in the early summer, followed by a leap in salinity between the weeks 23 and 26, and ending with a gradual steady increase towards the autumn (Fig. 5, 8A). The lowest median occurred at the week 23 in June (5.4, range 5.2–5.7), and the highest at the week 37 in September (5.9, range 5.7–6.1). The pattern of higher salinity in the southern parts of the study area and lower salinity in the north and north-east (Fig. 8B) remained geographically persistent through the summer. Salinity at the five most saline stations (Fig. 8C, D) was 3–5%, relatively, higher and in the five least saline stations 2–3% lower than the global median of the corresponding week.

According to Winsor et al. (2001) and Fonselius and Valderrama (2003), the mean surface salinity fluctuations of the Baltic Sea are related to fresh water input and they show ~1‰ variation over several decades with no long term trends. According Suominen et al. (2010) the salinity range in three intensively monitored stations in the middle and outer Archipelago Sea during a period of approximately ten years was 0.6, although these ranges were calculated from seasonally averaged data and the true ranges were somewhat wider. These types of variations may result from vertical or horizontal water exchange, local precipitation and evaporation or the influence of terrestrial runoff. An additional geographical factor in the Archipelago Sea is its location at the divergence of two larger sea basins with slightly different salinity, i.e. the more saline Baltic Proper in the south and the less saline Gulf of Bothnia in the north.

Secchi depth

In the outer archipelago region, the prevailing temporal trend in the water transparency in 2007

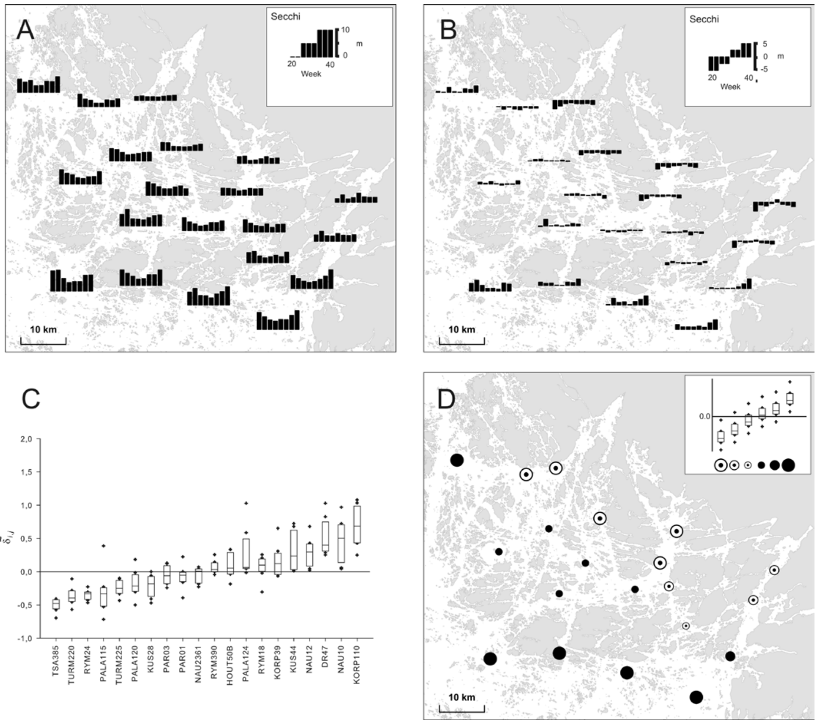

Fig. 9. Secchi depth in May-October in 2007. A) Secchi, B) Secchi deviations from the median of the corresponding week, C) Time stability plot, indicating station-wise stability of the relative deviations from the global median of the corresponding week, D) Classification of the stations according the location of the median, and 25th and 75th quartiles.

was from higher depths during the early summer to lower values in the mid and late summer, and a gradual increase towards the autumn (Fig. 9A). In the inner archipelago the Secchi depths remained more even through the entire studied period. The highest weekly median, 4.6 m (range 1.3–7.5 m), was measured in June at week 20, and the lowest median, 2.2 m (range 1.3–3.4 m), occurred in July at week 29 (Fig. 5). Although the temporal patterns differed in the outer and inner archipelago, and the Secchi depths were more similar throughout the area in the mid summer, the pattern of lower values in the inner archipelago and higher values in the outer areas was persistent through the summer (Fig. 9B, C, D). Secchi depths at the five stations that have the lowest medians of residuals were 26–49% lower than the global median of the corresponding week (Fig. 9C). Respectively, at the five stations with the highest medians, the Secchi depths were 23–67% higher than the median of the same week.

The inter-annual late summer data from 2002–2008 showed that the six innermost stations had their interquartile range of residuals below zero, and their medians were 16–46% lower than the global median of the corresponding week (Fig. 10A, B). Respectively, six stations located mostly in the outer archipelago had constantly higher Secchi depths, with median residuals 15–54% higher than the global median. Median absolute deviations of the relative Secchi depths were highest in the outer regions, whereas in the middle and inner archipelago areas the variability was lower (Fig. 10A, 10C).

Both of the above analyses show a gradation in water transparency from the inner to the outer parts of the Archipelago Sea. In the outer regions, the main controlling factor to consider is phytoplankton, since the concentration of suspended particulate inorganic matter is low. In turn, in the inner parts, inorganic matter has a proportionally greater effect on the Secchi depth readings, which is seen as lower values and also more uniform seasonal development. It is noteworthy that the spatial patterns of the relative Secchi depths remain relatively even across the region through the summer even though the temporal changes in the measured Secchi depths are considerable. The late summer values showed higher variability especially in the outer regions. The large intra-annual and

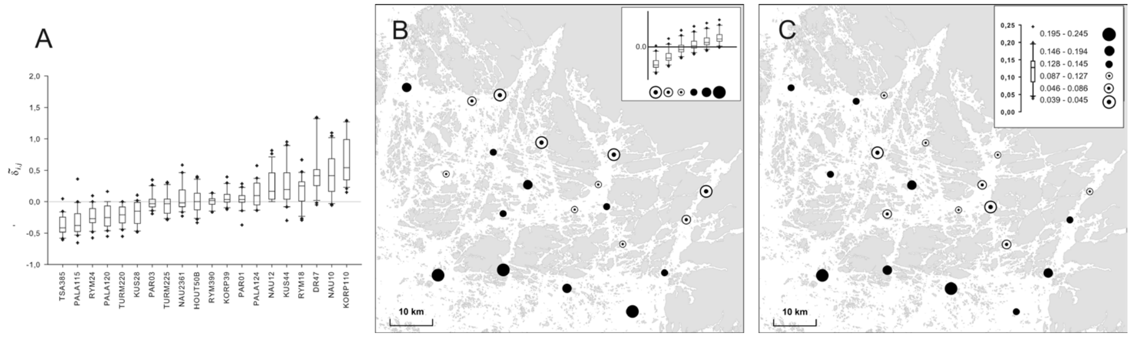

Fig. 10. A) Time stability plot based on the late summer Secchi observations in 2002–2008 and B) station-wise classification according the locations of the median, and 10th, 25th, 75th and 90th quantiles. C) Station-wise median absolute deviations of the relative Secchi depths.

inter-annual changes in the observed Secchi depths, or in light attenuation in the water column, call for more precise research of the effects of varying light conditions to littoral and benthic flora, phytoplankton and seafloor habitat distribution.

Generally, the Secchi depths in the Finnish offshore areas have shown a constant declining trend during the last decades (Sandén & Håkansson 1996; Lehtinen-Fleming et al. 2008). Increased eutrophication and as a consequence, the abundance of phytoplankton, is connected to decreasing Secchi depths (see Kauppila 2007), although there are substantial uncertainties regarding the relationships between the Secchi depth and the chlorophyll concentration of the seawater (Sandén & Håkansson 1996). In turbid coastal waters the high load of inorganic suspended matter, detritus and humic substances in river plumes may even depress primary production due to light limitation (Wasmund et al. 2001). In the southern Baltic Sea, phytoplankton biomass gave the strongest contribution to the Secchi depths during the summer and autumn, whereas in spring suspended matter gave the strongest contribution (Nielsen et al. 2002).

Chlorophyll-a

The first measurements of 2007 were made in mid May, after the phytoplankton spring maximum (Fig. 5). During the summer, the seasonal development of chlorophyll-a concentrations showed geographically slightly divergent temporal patterns. At the eastern stations, chlorophyll peaked between the weeks 26 and 34, but at the northern stations the concentrations increased through the summer with the highest values at weeks 34–40 (Fig. 11A, B). The lowest median of the chlorophyll-a concentration was 2.2 µg l^{-1} (range 1.6–3.1 µg l^{-1}) in June, and the highest median (3.9 µg l^{-1}, range 2.9–7.1 µg l^{-1}) at the end of July (Fig. 5). In general, the highest concentrations were found near the mainland and the lowest concentrations in the middle and outer archipelago, but temporally divergent developments indicate low overall geographical persistence in the patterns of chlorophyll-a concentration (Fig. 11C, D).

During the late summers of 2002–2008, the median residuals of the chlorophyll-a were positive at the stations near the mainland, and in the middle and western parts of the area the concentrations were lower (Fig. 12A, B). The three westernmost stations showed relatively constant lower chlorophyll-a concentration, median residuals being 20–33% lower than the global median. Also the variability of the relative concentrations was lower in the outer and middle regions, whereas towards the inner archipelago the variability increased (Fig. 12C). In all, there is a gradation from higher concentrations in the inner archipelago to lower values farther off the mainland, but anomalies from this pattern are frequent, and variability of the chlorophyll-a concentration within the seawaters of the Archipelago Sea is high.

Most of the Finnish coastal waters are eutrophicated compared to the off-shore areas due to the loads of nutrients and their effective cycling between water column and sediments, as well as the

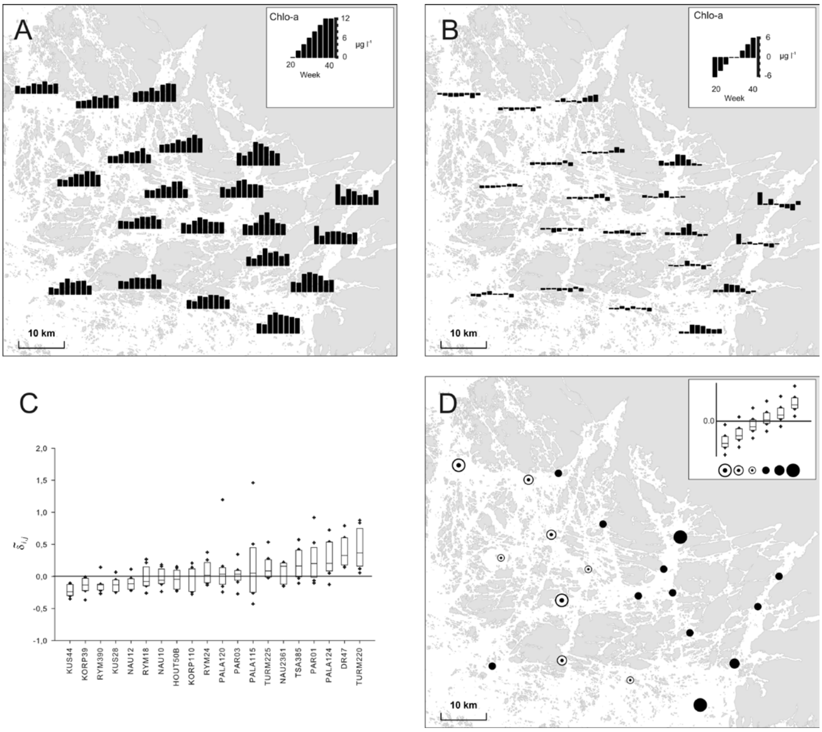

Fig. 11. Chlorophyll-a concentration in May-October in 2007. A) Chlorophyll-a concentration, B) Deviations of chlorophyll-a concentration from the median of the corresponding week, C) Time stability plot, indicating station-wise stability of the relative deviations from the global median of the corresponding week, D) Classification of the stations according the location of the median, and 25th and 75th quartiles.

limited water exchange of the archipelago areas (Pitkänen et al. 2004). In addition to the dispersion patterns of nutrients, their quantities and ratios, also other physical and chemical properties of water (Wasmund et al. 2001; Gasiūnaitė et al. 2005; Kauppila 2007) have an impact on the abundances and community structures of phytoplankton. Thus, numerous factors contribute to the phytoplankton communities, resulting in complex spatial, intra-annual and inter-annual variations.

Acidity

The seasonal variations of the surface water acidity (expressed as hydrogen ion concentration, see methods) had distinct temporal patterns. At the

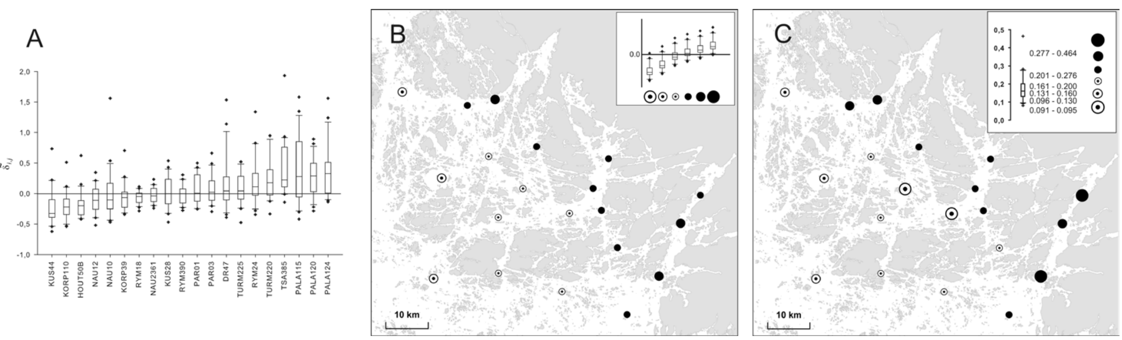

Fig. 12. A) Time stability plot based on the late summer chlorophyll-a observations in 2002–2008 and B) Station-wise classification according the locations of the median, and 10th, 25th, 75th and 90th quantiles. C) Station-wise median absolute deviations of the relative chlorophyll-a concentrations.

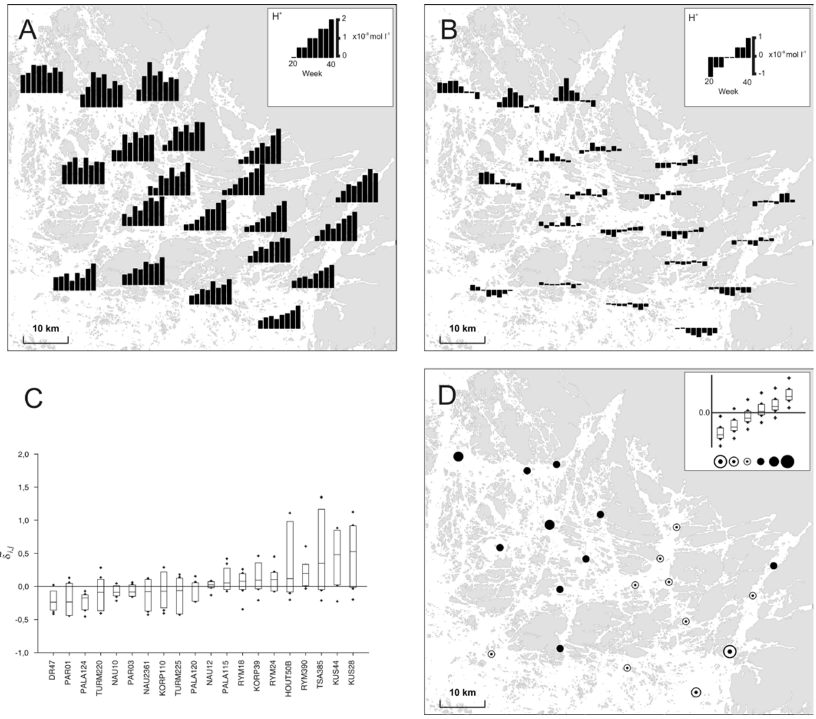

Fig. 13. Hydrogen ion (H^+) concentration indicating acidity in May-October in 2007. A) H^+ concentration, B) Deviations of H^+ concentration from the median of the corresponding week, C) Time stability plot, indicating station-wise stability of the relative deviations from the global median of the corresponding week, D) Classification of the stations according the location of the median, and 25th and 75th quartiles.

stations near the mainland, especially on the eastern side of the study area, the surface water H^+ concentration showed lower values at the beginning of the studied period, and a clear increasing trend during the summer (Fig. 13A, B). At the northern and western stations, H^+ concentrations were more even. The median of H^+ concentration was lowest in the beginning of the studied period, 0.41e-8 mol l^{-1} (pH 8.4), ranging from 0.18e-8 to 0.97e-8 mol l^{-1} (pH 8.0–8.7) (Fig. 5). At the end of the summer, the median was 1.4e-8 mol l^{-1} (pH 7.8) and the range was from 1.1-8 to 1.8e-8 mol l^{-1} (pH 7.7–8.0). Negative median of residual concentrations of H^+, i.e. on average less acid waters, were mostly found in the south-east, and the positive medians (relatively acid waters) at the stations in the north-west (Fig. 13C, D). However, this pattern is mostly caused by the differences in the concentrations at the beginning of the summer, since toward the end of the studied period the concentrations were more similar. For the same reason the persistency of the geographical pattern is low.

Water acidity is affected by the utilisation of dissolved inorganic carbon during photosynthesis, by respiration and decomposing of organic matter, and by river discharges carrying decomposed organic material. Weckström et al. (2002) sampled 45 shallow embayment in the northern coast of the Gulf of Finland, with pH values ranging from 7.3 to 8.7 (mean 8.2), highest pH values being usually recorded during the phytoplankton production peak in mid-summer. In larger scale, Omstedt et al. (2009) modelled the carbon cycle of the Baltic Sea and concluded that eutrophication effects may have damped acidification, but with increased seasonal pH variability and with low values occurring during winter season. The high pH values measured in this study during the early summer in the eastern and middle parts may be a consequence of the high rates of photosynthesis during the spring bloom, or it might indicate the influence of local river discharges in the area. However, both of these factors affect on the water quality also in the northern stations, where the pH is lower in the early summer and remains rather stable through the studied period. Thus, neither the rate of photosynthesis nor terrestrial runoffs appears to fully explain the detected geographical patterns in the seasonal cycle of acidity.

Conclusions

The results of this study mostly support the previously known geographical patterns of the seawater properties and their dynamics in the Archipelago Sea. However, we found geographically divergent seasonal developments and noted that the transitional patterns from inner to outer archipelago were in many cases prone to anomalies. The persistent and variable patterns of water properties that we found facilitate further evaluation of the water monitoring scheme in this area under high environmental pressures and social interests.

Intra-annual salinity and water transparency patterns were relatively persistent, although especially the Secchi depths appeared to change significantly over the year. Also the surface water temperature exhibits a relatively persistent geographical pattern at the general level, but occasional anomalies occur. The seasonal developments of chlorophyll-a and especially acidity are more variable and divergent in geographical terms. The long-term data for the late summer temperature, Secchi and chlorophyll-a support the above interpretations: these water quality variables have clear geographical patterns if measured as medians of relative values. However, only Secchi depth has rather persistent geographical pattern, while the geographical patterns of temperature and chlorophyll-a are prone to anomalies.

It is not only the simultaneous observations or observations collected during a fixed annual period that matter when physico-chemical or biological features and their spatial distribution are studied in a region where strong seasonal cycles are a dominant phenomenon. It is also essential to consider the spatio-temporal development as a whole, as fluctuations, for instance, in temperature (e.g. Hakala et al. 2003; Lappalainen et al. 2009) or in salinity (e.g. Ruuskanen & Kiirikki 2000; Westerbom et al. 2002) may have impacts on marine habitats. These needs have already been identified and monitoring programs are under evaluation. New techniques (see Rantajärvi et al. 1998; Huttula et al. 2009), such as automated buoys with sensors for collecting continuous water quality data, may partly help to overcome these challenges in the future.

NOTES

[1] spectrophotometrically from ethanol extract (SFS 5772 1993)
[2] SFS-EN 27888 1994
[3] SFS 3021 1979
[4] thermometer inside the Limnos sampler
[5] determined by using the white cap of the sampler
[6] spectrophotometrically from ethanol extract (SFS 5772 1993)

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