Influence of landfast ice on the hydrography and circulation of the Baltic Sea coastal zone

Ioanna Merkouriadi
Matti Leppäranta

Department of Physics,
University of Helsinki,
P.O. Box 48 (Erik Palménin aukio 1), Fi-00014 Helsinki, Finland;

e-mail: ioanna.merkouriadi@helsinki.fi

e-mail: matti.lepparanta@helsinki.fi

Abstract

The influence of landfast ice on hydrography and circulation is examined in Santala Bay, adjacent to the Hanko Peninsula, Gulf of Finland. Three-dimensional electromagnetic current meters and conductivity-temperature-depth (CTD) sensors were deployed in winters 1999–2000 and 2000–2001 during the Finnish-Japanese 'Hanko 9012' experiment. In each winter, data collection started one month before the initial ice formation and lasted until one month after the ice had melted completely. Temperature and salinity are compared with long-term data from the Tvärminne Zoological Station, also located on the Hanko Peninsula. The water temperature was 2°C less than the long-term average. Ice formation and melting show up in the salinity evolution of the water body, which makes salinity a good indicator of ice formation and breakup in Santala Bay. The circulation under the ice became weaker by almost 1 cm s^{-1}.

1. Introduction

The Baltic Sea is located in the transitional area of the North Atlantic maritime and Eurasian continental climate systems, which determine the climatic conditions of this sea (Ojaveer et al. 2010). Most of its coastal

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

zone freezes over each year. The length of the ice season is 5–8 months; the maximum ice thickness is 50–120 cm and the maximum annual ice extent is 12.5–100% of the Baltic Sea area (Leppäranta 2012). This changes the nature of air-sea interaction dramatically. In particular, when the coastal zone is covered by landfast ice, the atmosphere-sea heat and moisture exchange is strongly reduced, and momentum flux is cut off. In addition, the ice acts as a buffer to atmospheric fallout, which accumulates in the ice sheet and is released into the sea water during the short melting phase. The extent of the landfast ice zone is dictated by the coastal morphology and topography of the sea bottom. This zone is especially wide along the coast of Finland owing to the large density of islands. In extreme cases, the whole Archipelago Sea between the Finnish mainland and the Åland islands, 200 km across, belongs to the landfast ice zone (Granskog et al. 2004) and the entire Gulf of Finland is covered with consolidated drift ice (Feistel et al. (eds.) 2008).

Hydrographic measurements in the Baltic Sea were initiated already in the nineteenth century, and regular offshore observations started in the early twentieth century (Fonselius & Valderrama 2003). However, in spite of the specific physical conditions obtaining during the ice season, very little research has been done on the Baltic Sea coastal zone in winter. Some sea ice studies have been done on the climatology (e.g. Jevrejeva et al. 2004) as well as on the onshore piling-up and ride-up of ice (Alestalo & Häikiö 1976, Girjatowicz 2004, Leppäranta 2013). Apart from these ice studies, winter oceanographic investigations have been limited. Long-term time series analyses have been performed on the hydrography of coastal stations (e.g. Granqvist 1938) but without any particular focus on the winter season. Lisitzin (1957) considered the water level variability in the winter season on the coast of Finland in comparison with ice-free conditions.

The Finnish-Japanese 'Hanko-9012' field programme was performed during four winters on the Finnish coast, at the mouth of the Gulf of Finland. The main study site was Santala Bay, on the north-western side of the Hanko Peninsula. This bay is located at the boundary of the Archipelago Sea and the Gulf of Finland. The 'Lotus' ice station, which gathered atmospheric surface layer, oceanographic and sea ice data, was deployed in the bay. The area freezes over annually, the ice season lasts for 3–4 months, and the maximum annual ice thickness is 20–60 cm. Further offshore, sea ice forms in the western Gulf of Finland in every three out of four years and drifts with the winds and currents.

'Hanko-9012' data have been extensively studied for the structure of sea ice and the influence of salinity on it (Kawamura et al. 2001, Granskog et al. 2004). The all-year heat budget of Santala Bay was examined by

Merkouriadi et al. (2013). In the present work, the oceanographic data are analysed in order to understand the seasonal behaviour of the Santala Bay hydrography and circulation and the interaction between the bay and the central basin of the Gulf of Finland. The data from before and after the ice season are used for seasonal comparisons. We begin by introducing the material and methods – this section contains information on the site and the research area, together with a short description of the weather conditions during the two measurement years. Then we present the results, and subsequently a discussion of the temperature, salinity and water circulation.

2. Materials and methods

2.1. Study site

The study site is Santala Bay, located at 59°55′N, 23°05′E on the north-west side of Hanko Peninsula, Gulf of Finland (Figure 1). The island of Byön gives the bay a rectangular shape. Santala Bay is shallow, with a maximum depth of 10 m. In the south-west, the bay is connected with the Gulf of Finland via a narrow strait, while in the north-east it is connected with the Archipelago Sea via a wider opening. The ice station was located in the centre of Santala Bay (Figure 1).
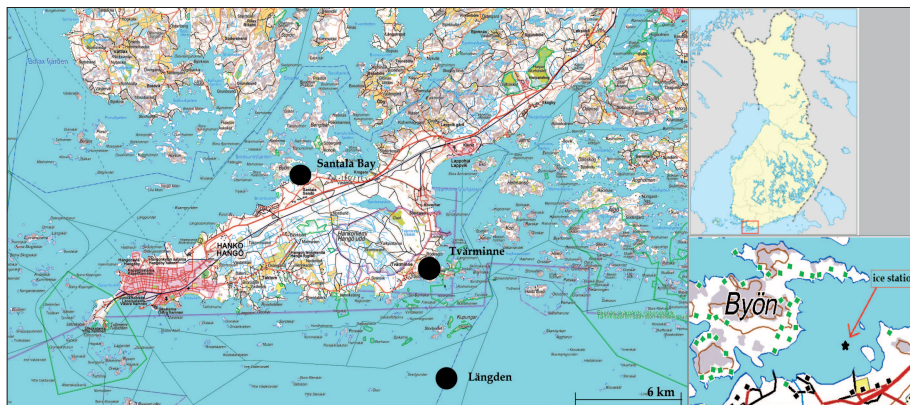

Figure 1. Hanko Peninsula with Santala Bay, Tvärminne and Längden (left) and the location of the ice station in the Santala Bay (right). North is upwards

The surface water salinity in the central Gulf of Finland varies from zero at the mouth of the River Neva in the east to 6 PSU (Practical Salinity Unit, equal to one part per thousand) at Hanko (Soomere et al. 2008). Off the Hanko Peninsula the salinity decreases towards the mainland as a result of small river inflows. There is a weak permanent counterclockwise

circulation in the Gulf of Finland (Palmen 1930). The mean surface current flows eastwards along the southern (Estonian) coast and westwards along the northern (Finnish) coast at an average speed of 1–5 cm s^{-1}.

Sea ice forms in the Gulf of Finland annually and it normally remains for 4–5 months (December–April). In mild winters only the eastern part freezes over but in a normal winter the whole basin is ice-covered (Jevrejeva et al. 2004, Leppäranta & Myrberg 2009). On average, the coastal region off the Hanko Peninsula freezes over between 21 December and 1 January, and the ice breaks up between 11 and 21 April (SMHI & FIMR 1982). The seasonal sea ice of the Baltic is a key factor in the Sea's physics, ecological state and climate variations; moreover, it plays a significant role in the North-European climate system (Leppäranta et al. 1998, Kawamura et al. 2001). Sea ice is both a sensitive and a good proxy for climate changes. The coastal zone is largely covered by landfast ice that effectively cuts off air-sea interaction.

2.2. Weather conditions

Winter 1999–2000

The air temperature was unusually high in October–November 1999 along the Finnish coast, due to strong low-pressure systems coming from the northern North Atlantic Ocean. The monthly average temperature was 8°C in October and 4°C in November. A shorter cold period in November initiated ice formation in the eastern part of the Gulf of Finland, after which the freezing front progressed slowly westwards. In Santala Bay ice started to form at the beginning of January (day number 93–100), which was about ten days later than average (Figure 2).

In mid-February and early March short cold periods occurred, both less than a week in duration (Figure 2). The sea surface lost heat and the sea ice gained in thickness. After mid-March the air temperature rose and the ice started to melt. Compared to the long-term winter climatology, the winter monthly average air temperatures in 1999–2000 were 3–5°C higher. The maximum thickness of the landfast ice was 28 cm in Santala Bay; the long-term average is 30 cm. Ice melting began in mid-March and continued slowly until the ice disappeared after mid-April in the Archipelago Sea, close to the average date. The eastern end of the Gulf of Finland became ice-free at the end of April, a week later than the average. All in all, the winter of 1999–2000 was a little milder than average in the central regions of the Baltic Sea, resulting in a three-week shorter ice season in the Archipelago Sea and a two-week shorter one in the Gulf of Finland.
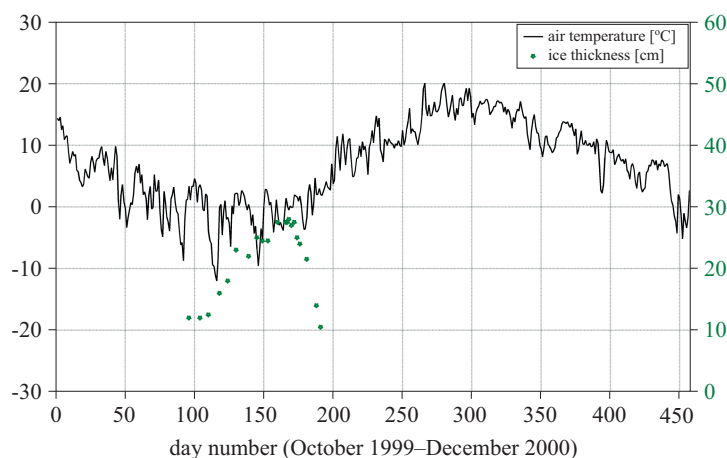
Figure 2. Daily averages of air temperature (scale on left, °C) together with weekly observations of ice thickness (scale on right, cm) in Santala Bay (1 October 1999–31 December 2000)

Winter 2000–2001

This winter was colder in comparison with the previous one. However, October, November and December were among the warmest in the last 100 years in most of the Gulf of Finland. In addition, the amount of precipitation was higher than the year before. After mid-December, the air temperature dropped to normal levels, but since the autumn had been warm, freezing was delayed by more than a month in the western Gulf of Finland. Off the coast of the Hanko Peninsula, ice formation began after mid-January (Figure 3).

A cold period occurred at the beginning of February with temperatures falling to −20°C. This resulted in ice growth all along the Finnish coast. A milder, windy period in mid-February packed the ice up against the coast. Later in February the air temperature again fell and more ice was formed. In comparison to the previous year, March was a cold month, with temperatures approximately 1–3°C below average. The ice thickness off the Hanko Peninsula reached 41 cm (13 cm more than in the previous year). The largest annual ice extent of the whole Baltic Sea occurred on 26 March, the latest day ever recorded.

April was about 2.8°C warmer than average. The sea ice in the Archipelago Sea melted by mid-April, somewhat earlier than usual, and the Hanko Peninsula was ice-free by 23 April. On the whole, this winter was mild in terms of the length of the ice season; because of the warm autumn the ice season was more than four weeks shorter than the average. However, due to the short cold periods in mid-winter, the maximum annual
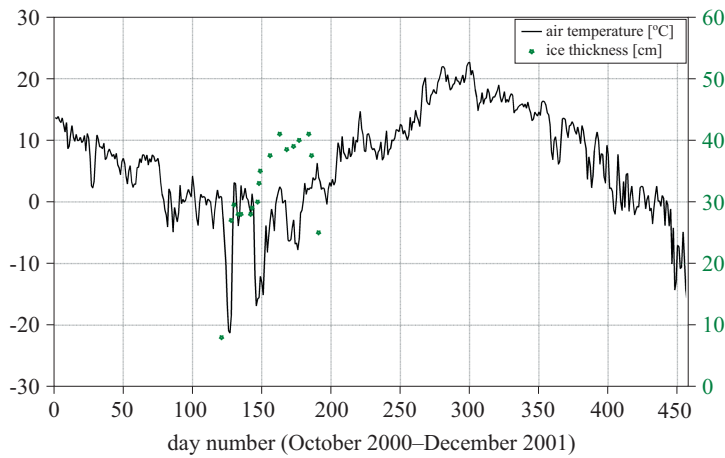
Figure 3. Daily averages of air temperature (scale on left, °C) together with weekly observations of ice thickness (scale on right, cm) in Santala Bay, (1 October 2000–31 December 2001)

ice thickness was more than the average and 13 cm more than in the previous year.

2.3. Methods

Water temperature, salinity, current and atmospheric surface layer data were collected on the 'Lotus' floating ice station during the 'Hanko-9012' experiment from 1999 to 2002. The first year was a pilot study with 'Lotus' active only in March, while in the last winter there were some problems with data acquisition. For this reason we focus primarily on the years 2000 and 2001.

The local hydrography and current velocity were recorded with a three-dimensional electromagnetic current meter with temperature, conductivity and depth sensors (Model ACM-32M, Alec Electronics Co., Ltd., Japan) and small conductivity-temperature sensors (Model MDS-CT, Alec Electronics Co., Ltd., Japan). They were deployed near the ice station, where the water depth was about 6 m. An additional temperature-conductivity sensor was deployed near the islet of Längden (59°43.6′N, 23°12.8′E) at the mouth of the Gulf of Finland in 2001. Längden is located south-east of Santala Bay at the edge of the open sea in the Gulf of Finland, and it serves as a good indicator for the open sea conditions (Figure 1). Moreover, the sea-ice in Santala Bay was sampled weekly for thickness, stratification, crystal structure and impurities. To measure the thickness, the ice was drilled at three sites near the ice station and the results averaged. The instrumentation available during the experiment is listed in Table 1.

Table 1. Oceanographic sensors and their positions during the 'Hanko-9012' sea ice experiment, Santala Bay

Location	Sensor	Depth	Start time	End time	Sampling interval
next to the ice station (6 m depth)	CTD (Conductivity-Temperature-Depth)	3.0 m 3.0 m	14.12.1999 13.12.2000	29.07.2000 31.01.2000	10 min
	3D-ECM (Current meter with Conductivity-Temperature sensor)	2.5 m 2.0 m	14.12.1999 13.12.2000	24.05.2000 07.05.2001	30 min
Längden lighthouse (59°43.6′N 23°12.8′E)	CTD (Conductivity-Temperature-Depth)	10 m	29.01.2001	03.07.2001	20 min

First, we examined the impact of the weather conditions on the local hydrography. The data from Längden assisted in the comparison between the open Gulf of Finland and the inner archipelago Sea. To calculate the sea water density, we used the international thermodynamic equation of sea water-2010 (TEOS), where density is obtained from the absolute salinity S and potential temperature Θ.

In addition, we constructed a box model for Santala Bay based on the salinity changes and the water mass conservation,

$$\frac{d\xi}{dt} + \frac{H}{\overline{\rho}}\frac{d\overline{\rho}}{dt} = P - E + \frac{V_r + V_i + V_0}{A}, \tag{1a}$$

$$\frac{dS(H+\xi)}{dt} = \frac{S_i V_i - S_0 V_0}{A}, \tag{1b}$$

where ξ is the sea-level elevation, H is mean depth, $\overline{\rho}$ is mean density, P is precipitation, E is evaporation (and sublimation), V_r is river runoff, and A, V_i and V_0 are the surface area, inflow and outflow respectively. During the ice season we can assume that sea ice formation and melting correspond to evaporation and precipitation respectively. Precipitation data were available from the weather station at Tvärminne, 6 km south-east of Santala Bay. The latent heat fluxes from Merkouriadi et al. (2013) were used to determine evaporation and sublimation. Our purpose was to apply a local model of salinity in the case of no horizontal water mass exchange (i.e. the last

terms in equations (1a,b) are neglected), and to compare the results with the salinity observations. Then, the horizontal water mass exchange was obtained as a residual and in this way we were able to examine the main circulation pattern in Santala Bay.

In addition, we estimated the cross-correlation between the wind and the current velocities. We did this separately for the ice-covered and the ice-free conditions with a time lag of 1 hour. Finally, we analysed the frequency spectra of the current velocity components in order to examine the periodicity of the water motions.

3. Results

Time series of temperature and salinity

Temperature, salinity and precipitation time series from Santala Bay are presented below (Figures 4, 5).
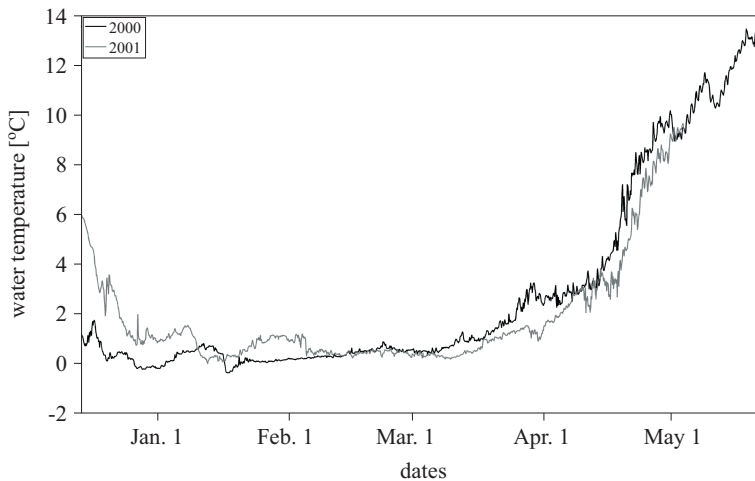

Figure 4. Water temperature records in 1999–2000 (2.5 m depth) and 2000–2001 (2.0 m depth), Santala Bay. The data is averaged over 3-hour periods

In December 2000, water temperature was 2–4°C lower compared to December 2001. This cooling delay in 2001 is explained by the warmer autumn season. After ice formation, the water temperature was less than 1.5°C with variations due to water exchange with the Gulf of Finland. In 2000 the water temperature increased slowly through the winter. In March and April 2001 water temperatures were lower (by 0–1°C), as we had anticipated from the ice and weather conditions. In both years temperature began to rise in March, when the snow was melting and there was still ice on the surface. This was the result of solar radiation penetrating through
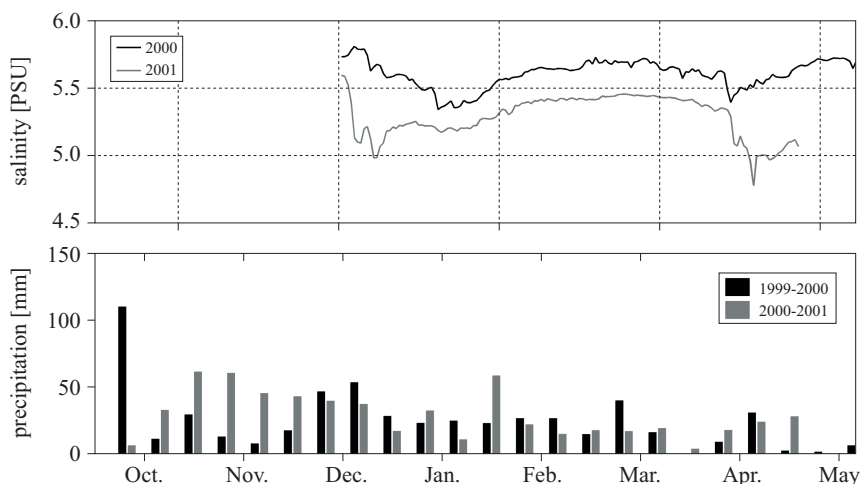
Figure 5. Salinity records in 1999–2000 (2.5 m depth) and 2000–2001 (2.0 m depth) averaged over 24-hour periods, Santala Bay. Precipitation data summed over 10-day periods, Tvärminne

the ice sheet and heat advection from the Gulf of Finland. The temperature increase was more rapid in 2000.

The salinity of the water was within 4.8–5.8 PSU, significantly lower in 2001 (the difference was approximately 0.1–0.5). At the beginning of the data collection in December, the level was 5.6–5.7 PSU in both years. Then a major drop occurred due to runoff. The decrease was much faster in December 2001, reaching values lower than 5 PSU, most likely due to the remarkable autumnal precipitation, which was approximately 30% heavier in November–December 2000 than in the year before. This resulted in an intensified salinity decrease to below 5 PSU in December–January 2000–2001. Precipitation was on average heavier in 2001 by almost 10% within the plotting period (Figure 5). After mid-January, the salinity started to increase in both years due to ice formation and the consequent brine rejection. Without water exchange, we have

$$S_1/S_2 = (H - h)/H, \tag{2}$$

where S_1 and S_2 are the salinities before and after ice formation, and h is the thickness of congelation ice. It is seen that congelation ice growth by 25 cm should increase the salinity by a factor of about 0.05 or by 0.25 PSU units, which is in fact quite close to what actually happened.

In the melting season there was another drop in the salinity due to freshwater runoff and sea ice melting. Again, the melting of a 25 cm ice layer should reduce the salinity by the amount shown by equation (2), but

the melting process also accounts for snow and snow-ice. In 2000 the salinity dropped approximately 0.4 before mid-April, just after the ice breakup, and in 2001 the salinity drop was 0.8. The main reason for the stronger salinity decrease in 2001 was the melting of the thicker snow-ice sheet resulting from the heavier precipitation. However, in both years the drop was more than that predicted by equation (2), and the difference is most likely due to the runoff of snow meltwater from land. After the ice season the salinity started to increase slowly as a result of vertical mixing of the water mass.

From February to the beginning of May 2001, both the Santala Bay and Längden CT sensors were recording. The results are plotted together for comparison (Figure 6). In midwinter the water temperature was similar at both sites. In spring the water temperature started to increase – at the beginning of March in Santala Bay and half a month later off Längden. After the ice had melted the rate of warming was fast in Santala Bay, 3–4°C per week. The temperature increase was slower off Längden, resulting in 3°C colder water at the beginning of May. In summer the Längden data showed synoptic scale variations of 2–4°C, which were not present in Santala Bay. At Längden there were short warm periods in summer and one remarkable cold advection event in the middle of June.

The water in the open sea was on average more saline than in Santala Bay. Salinity records showed a higher level and more variation off Längden, owing to the more dynamic conditions with mixing as well as advection from the east and west. In winter the level of salinity was 0.2 PSU higher off Längden. The salinity drop after the ice break-up was fairly smooth off Längden since the meltwater flux around the whole Gulf of Finland is well spread over time. In Santala Bay the drop was rapid and large, about 0.5 PSU in ten days, with the slow recovery starting at the beginning of May.

The monthly progress of temperature and salinity was plotted in ΘS diagrams for both years (Figure 7). In 2000, the earlier sea ice formation is shown in the ΘS plots. The water density decreased after mid-December because of the lower salinity caused by the heavy autumnal precipitation. When the ice started to form, the density increased owing to brine rejection, reaching maximum values in mid-winter in both years. In April, during the melting season, there was a clear salinity drop, which resulted in a density decrease. This was due to the ice breakup and freshwater mixing, combined with increased water temperatures. In May, the salinity became more stable and the density decreased, mostly due to the increasing water temperature. The main difference between the two years was the variability in water
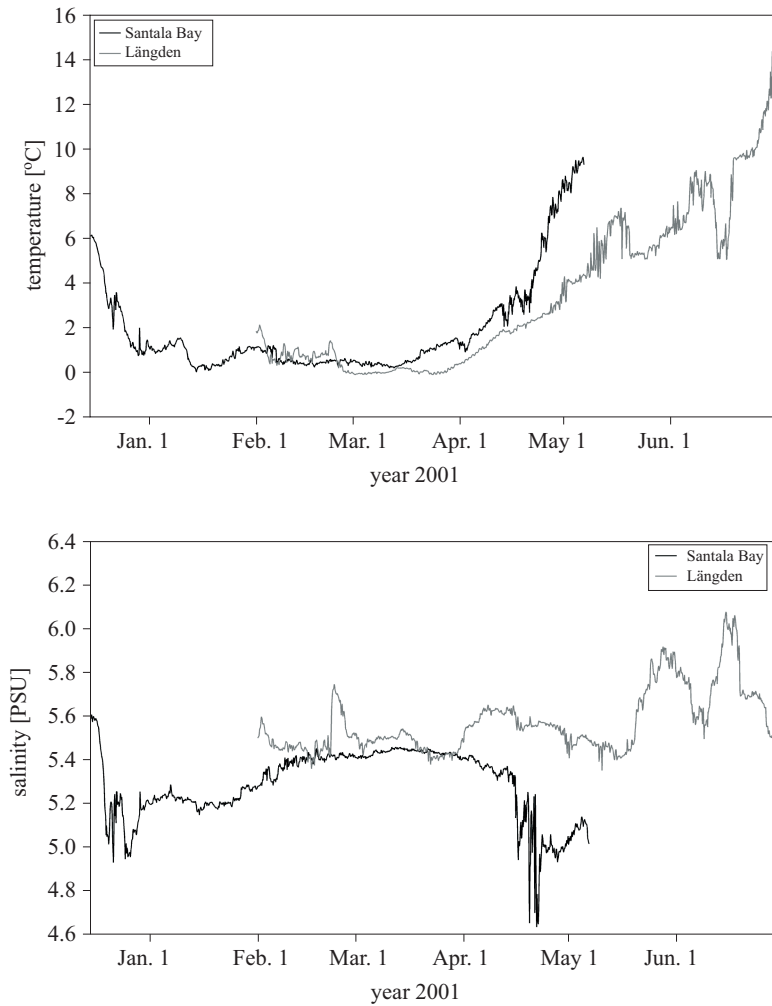
Figure 6. Water temperature (upper) and salinity (lower) in Santala Bay and off Längden, 2001

density, which was greater in 2000, with higher density anomalies $3.70 < \sigma_t < 4.70$ (σ_t is defined as the density excess from 1000 kg m^{-3}; the unit is kg m^{-3}). However, the density anomaly in 2001 was within $3.70 < \sigma_t < 4.45$.

Finally, we examined the freshwater budget of Santala Bay using the local model (equations 1a, b). In this model the runoff was neglected since there are no major inflows within the bay. In order to close the freshwater budget, the Finnish Meteorological Institute (FMI) provided hourly sea level data records from a mareograph located in Hanko. Sea level changes are caused by atmospheric forcing and water mass exchange
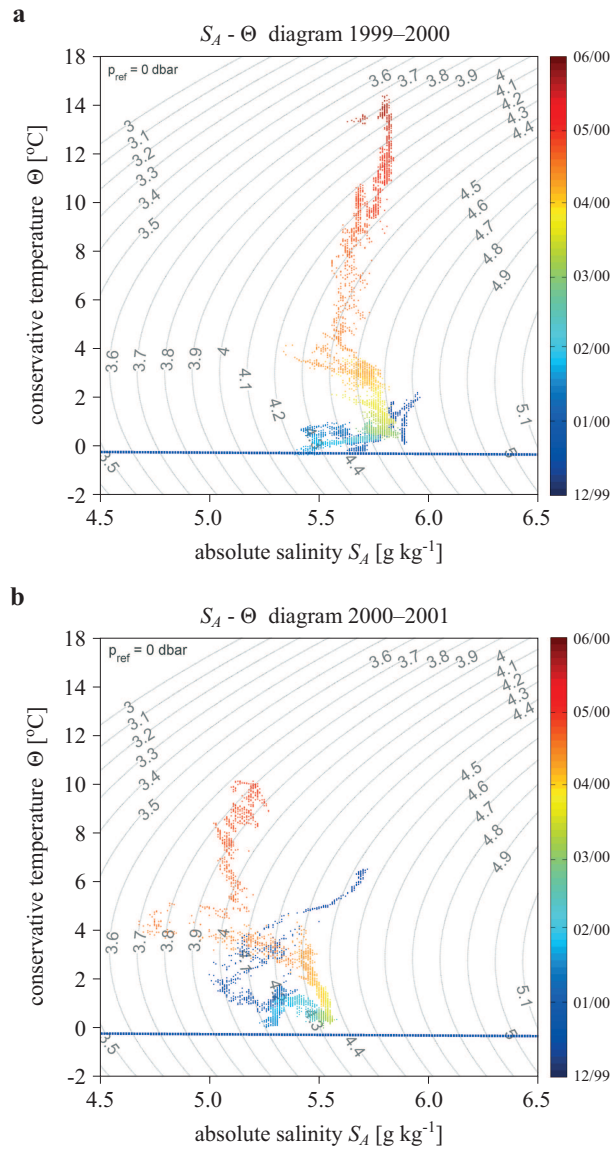
Figure 7. ΘS plots displaying the monthly progress of hydrographic characteristics in Santala Bay in 1999–2000 (a) and 2000–2001 (b). The colour scale indicates the time in months and the grey curves are the isopycnals (in σ_t units kg m^{-3})

with the Gulf of Finland. Thus, by excluding the atmospheric freshwater flux from the volume changes within the bay, we can estimate the horizontal water mass exchanges (Figures 8, 9). In addition, we modelled the salinity in the absence of horizontal exchange and compared it with the salinity

observations (Figures 8, 9). In this way we can identify the origin of the inflows, since the salinity of the Gulf of Finland is always higher than that in Santala Bay.
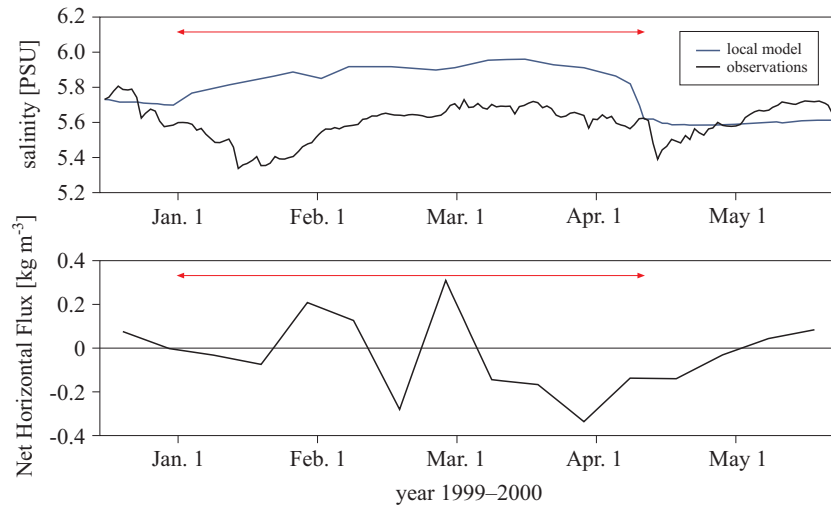

Figure 8. Daily averages of the local salinity model plotted together with salinity observations (upper), and net horizontal water mass exchange averaged over 10-day periods (lower), 1999–2000. The red arrow indicates the ice season
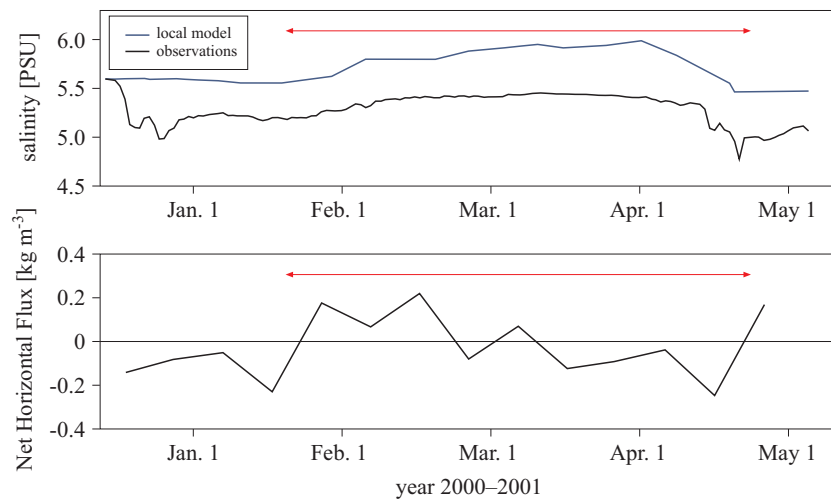

Figure 9. Daily averages of local salinity model plotted together with salinity observations (upper), and net horizontal water mass exchange averaged over 10-day periods (lower), 2000–2001. The red arrow indicates the ice season

The results in both years showed that salinity values were lower (up to 0.4 PSU) than those the local model had predicted. However, the patterns were similar. This was due mainly to the autumnal precipitation and further mixing, which caused a major salinity decrease, even after the sea ice had started to form (year 1999–2000). This mixing process can explain the lower salinity values, which were not captured by the local model. Judging by the net horizontal fluxes, the major inflows (positive values) occurred mainly in February and at the beginning of March. After mid-March the values turned negative until May, when horizontal inflows occurred once more. The major inflows were associated with a salinity increase (Figures 8, 9) due to advection from the Gulf of Finland.

Water flow

The daily averages of current velocity and direction were analysed and plotted together with wind velocity and direction for both years (Figures 10,
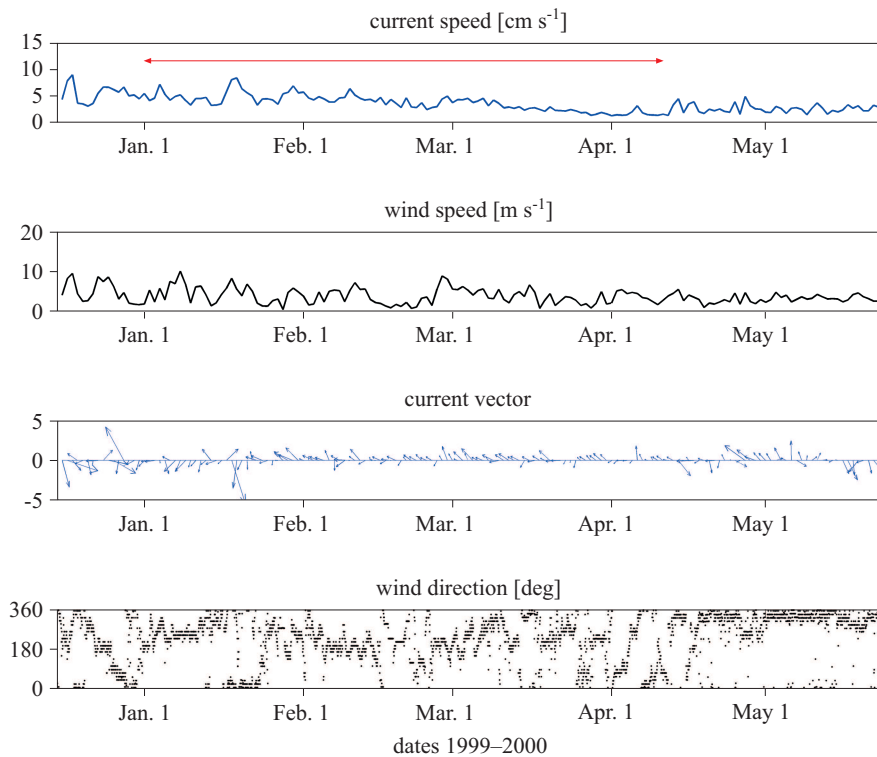

Figure 10. Daily averages of current and wind velocity and direction in Santala Bay (15.12.1999–23.05.2000). The red arrow indicates the ice season

current speed [cm s^{-1}]

wind speed [m s^{-1}]

current vector

wind direction [deg]
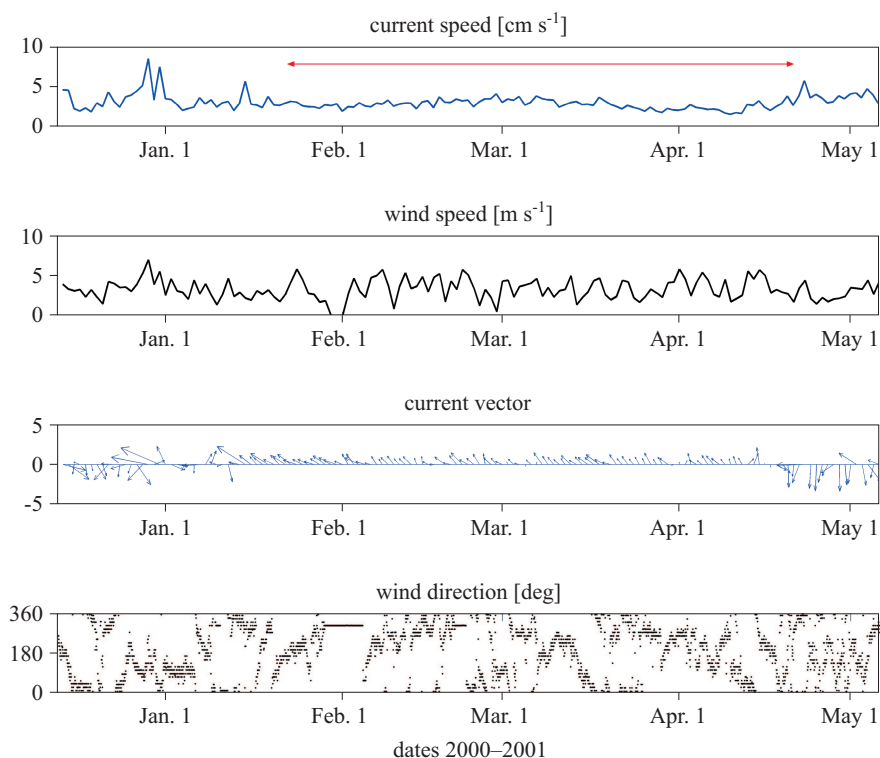
dates 2000–2001

Figure 11. Daily averages of current and wind velocity and direction in Santala Bay (15.12.2000–06.05.2001). The red arrow indicates the ice season

11). In 2000 the average current velocity decreased from 5.4 cm s^{-1} in open water conditions to 3.8 cm s^{-1} during the ice season. The variability of currents was lower during the ice season. The same was observed in 2001, when the mean current velocity decreased from 3.3 cm s^{-1} to 2.6 cm s^{-1}. In addition, there was a clear trend of current velocity decreasing towards the summer. However, this decrease was much smaller than that often observed in medium-size lakes. In Lake Pääjärvi (area 13.4 km^2, mean depth 15 m), southern Finland, for example, the current velocity is of the order of millimetres per second during the ice season (Huttula et al. 2010).

The average wind velocity was 3.9 m s^{-1} and 3.3 m s^{-1} in 2000 and 2001 respectively. The daily average current direction was mainly north-westerly during the ice season. The current velocities from before, during and after the ice season are shown in the compass plots in Figure 12. The circles inside the plots indicate the proportions and the colour scale displays the different velocities. It seems that in both years the currents in Santala Bay were moving mainly north-westwards and south-eastwards. During the
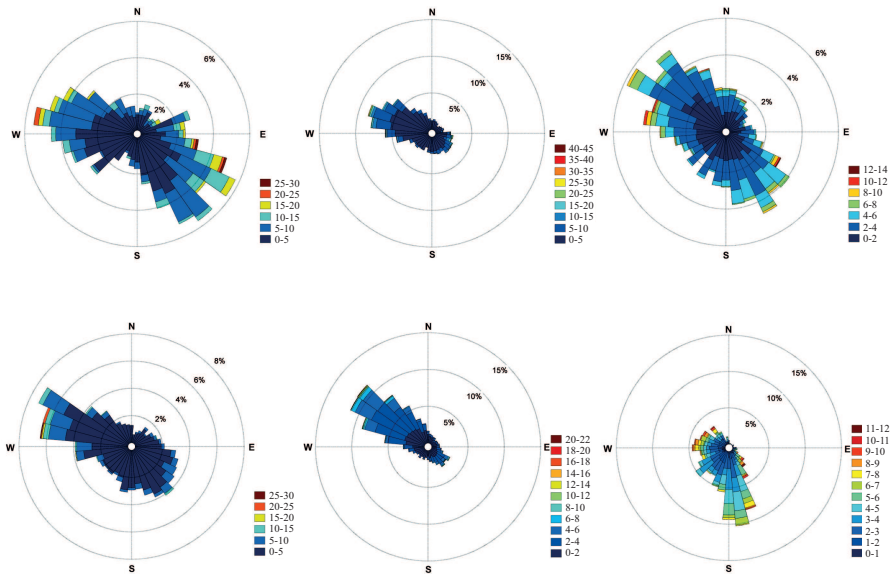
Figure 12. Compass plots of current velocity and direction in Santala Bay from before (left), during (middle) and after (right) the ice season for 1999–2000 (upper) and 2000–2001 (lower)

ice season, apart from the velocity decrease, the distribution of the current directions was more aligned to the north-west and south-east (Figure 12 – middle plots).

The current observations showed limited water movement towards the opening to the Archipelago Sea (north-east direction). One possible explanation is that the south-west passage is too narrow and shallow, so the Gulf of Finland water enters Santala Bay through the north-east passage (Figure 1). In addition, the bottom topography and/or the effect of the small islands on the eastern side of the bay could have modified the current direction locally.

The cross-correlation function was estimated separately for the open water and the ice season. The results showed a better correlation between the current and the wind speed in the open water cases. The correlation peaks reached 0.4 at a zero lag, and there was a clear daily cycle (~ 24 hours). During the ice season, there was no correlation pattern. In 2000 the correlation was below 0.2 and in 2001 below 0.1. Even though the correlation was stronger in ice-free conditions, the correlation values were generally low. This means that the currents were not strongly affected by the local winds. In the open water case there was a 24-hour cycle, which may be due to the diurnal weather cycle, the Baltic main basin seiche or tides.
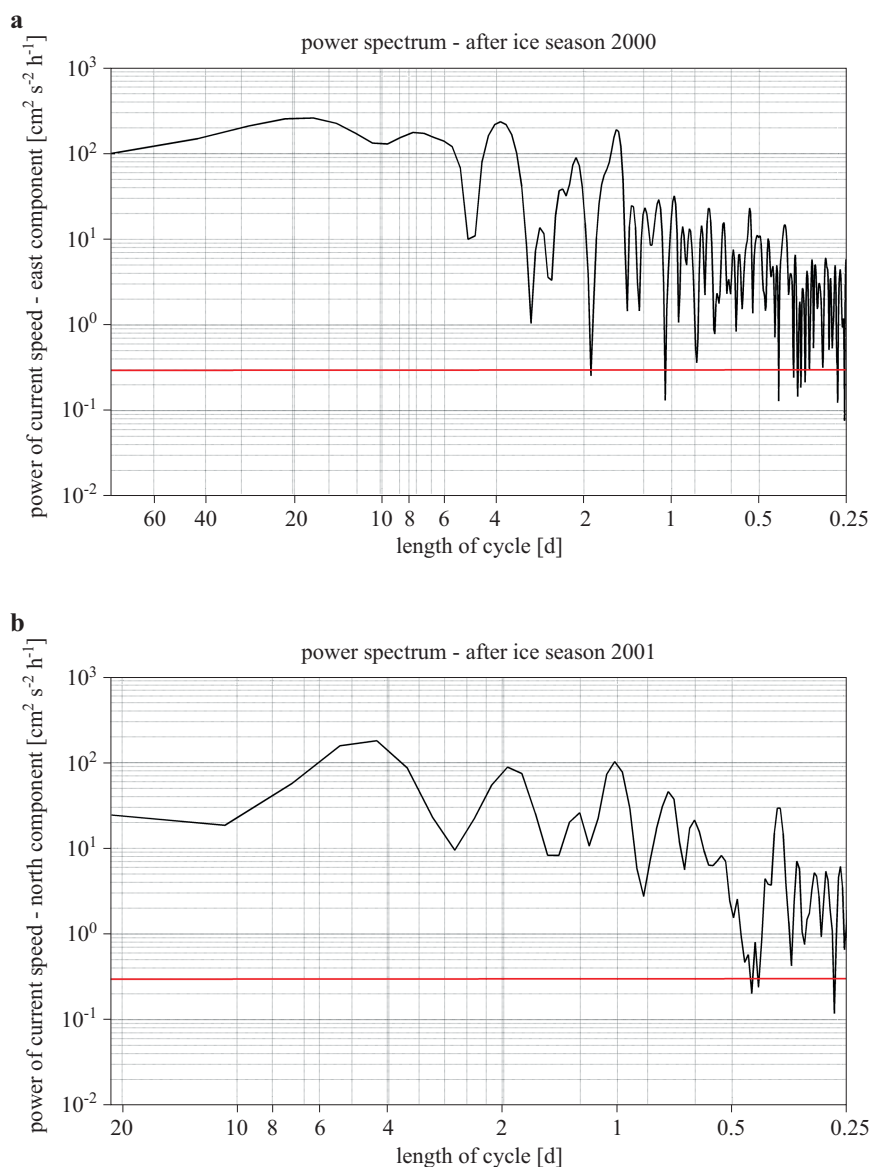
a

power spectrum - after ice season 2000

b

power spectrum - after ice season 2001

Figure 13. Power spectra of the easterly (2000) and northerly (2001) components of the current speed after the ice breakup in Santala Bay in 2000 (a) and 2001 (b). The red line indicates the measurement noise

Finally, we analysed the frequency spectra of the current field components (Emery & Thompson 2001). The measurement noise was calculated on the basis of the current meter's accuracy, ± 0.5 cm s^{-1} (Huttula et al. 2010). The main part of the velocity variance was found to be in the synoptic scale and seiches. After the ice breakup an additional energy peak was found in

a 4-day cycle (Figure 13). However, during the ice season, the spectra were fairly even without distinct energy peaks.

4. Discussion

This study of the hydrography and circulation of Santala Bay covered two years and was based on field observations. The temperature and salinity profiles of Santala Bay in 2000 and 2001 corresponded well to what we had anticipated from the weather conditions. Salinity acted as a good indicator of ice formation and breakup in Santala Bay, where the conditions are less dynamic. The ΘS plots gave information on the water density progress throughout both years. In 2000, the water density variability was larger with density anomalies higher by approximately 0.5 kg m^{-3}. A box model was introduced based on the water exchange rate and the salinity evolution. From the above comparison we concluded that advection from the Gulf of Finland takes place. This confirms the results of our previous heat budget analysis in Santala Bay (Merkouriadi et al. 2013).

On the whole, the weather conditions had a clear impact on the local hydrography. The Längden records served as a good reference for comparison between the inner archipelago and the Gulf of Finland. Salinity values were altogether higher off Längden. The salinity drop after the ice breakup was less obvious in the Gulf of Finland and salinity fluctuations were greater, indicating more dynamic conditions. In comparison to long-term data from Tvärminne (Granqvist 1938), monthly average water temperatures were higher by 2°C.

The current and wind speed cross-correlation analysis showed a correlation of up to 0.4 in open-water conditions and almost no correlation during the ice season. The prevailing winds in both years were north-westerlies and westerlies, and the main current directions were towards the north-west and south-east. A clear weakening of the current speed, of approximately 1 cm s^{-1}, was observed during the ice season. The north-west and south-east modes were even more sharply defined than during the open-water period. This was expected, since ice modifies the transfer of the wind momentum to the water body. It seems, therefore, that currents in Santala Bay are connected not with local winds but with the local bathymetry and regional wind events. The spectral analysis showed significant peaks only after the ice breakup, in the synoptic scale.

Spectral analysis of the current components has been performed in other coastal regions of the Baltic Sea (e.g. Mälkki 1975, Alenius & Mälkki 1978) in the open-water season, focusing mainly on short-term current variability. As in our study, Alenius & Mälkki (1978) noticed that the current energy was more evenly distributed over different frequency ranges in the shallow

coastal zone. However, the maxima of spectral densities also corresponded to tidal and seiche movements.

Acknowledgements

References

Alenius P., Mälkki P., 1978, *Some results from the current measurement projects of Pori-Rauma region*, Fin. Mar. Res., 224, 52–63.

Alestalo J., Häikiö J., 1976, *Ice features and ice-thrust shore forms at Luodonselkä, Gulf of Bothnia, in winter 1972/73*, Fennia, 144, 1–24.

Emery W. J., Thomson R. E., 2001, *Data analysis methods in physical oceanography*, 2nd edn., Elsevier, Amsterdam, 371–461.

Feistel R., Nausch G., Wasmund N. (eds.), 2008, *State and evolution of the Baltic Sea, 1952–2005: a detailed 50-year survey of meteorology and climate, physics, chemistry, biology, and marine environment*, John Wiley & Sons Inc., Hoboken, NJ, 703 pp., http://dx.doi.org/10.1002/9780470283134.

Fonselius S., Valderrama J., 2003, *One hundred years of hydrographic measurements in the Baltic Sea*, J. Sea Res., 49 (4), 229–241, http://dx.doi.org/10.1016/S1385-1101(03)00035-2.

Girjatowicz J. P., 2004, *Ice thrusts and piles on the shores of the Southern Baltic Sea coast (Poland) lagoons*, Baltic Coast. Zone, 8, 5–22.

Granqvist G., 1938, *Zur Kenntnis der Temperatur und des Saltzgehaltes der Baltischen Meeres an den Küsten Finnlands*, Merentutkimuslaitoksen Julkaisu, 122, 166 pp.

Granskog M. A., Leppäranta M., Kawamura T., Ehn J., Shirasawa K., 2004, *Seasonal development of the properties and the composition of landfast sea ice in the Gulf of Finland, the Baltic Sea*, J. Geophys. Res. – Oceans, 109 (C2), http://dx.doi.org/10.1029/2003JC001874.

Huttula T., Pulkkanen M., Arkhipov B., Leppäranta M., Solbakov V., Shirasawa K., Salonen K., 2010, *Modelling circulation in an ice covered lake*, Est. J. Earth Sci., 59 (4), 298–309, http://dx.doi.org/10.3176/earth.2010.4.06.

Jevrejeva S., Drabkin V. V., Kostjukov J., Lebedev A. A., Leppäranta M., Mironov Ye. U., Schmelzer N., Sztobryn M., 2004, *Baltic Sea ice seasons in the twentieth century*, Clim. Res., 25, 217–227, http://dx.doi.org/10.3354/cr025217.

Kawamura T., Shirasawa K., Ishikawa N., Lindfors A., Rasmus K., Ehn J., Leppäranta M., Martma T., Vaikmäe R., 2001, *Time-series observations of the structure and properties of brackish ice in the Gulf of Finland*, Ann. Glaciol., 33 (1), 1–4, http://dx.doi.org/10.3189/172756401781818950.

Leppäranta M., 2012, *Ice season in the Baltic Sea and its climatic variability*, [in:] *From the Earth's core to outer space*, I. Haapala (ed.), Lect. Notes Earth Syst. Sci. 137, Springer-Verlag, Berlin-Heidelberg, 139–149.

Leppäranta M., 2013, *Land-ice interaction in the Baltic Sea*, Est. J. Earth Sci., 62, (in press).

Leppäranta M., Myrberg K., 2009, *Physical oceanography of the Baltic Sea*, Springer-Praxis, Heidelberg, Germany, 219–225, http://dx.doi.org/10.1007/978-3-540-79703-6.

Leppäranta M., Tikkanen M., Shemeikka P., 1998, *Observations of ice and its sediments on the Baltic Sea coast*, Nord. Hydrol., 29 (3), 199–220.

Lisitzin E., 1957, *On the reducing influence of sea ice on the piling-up of water due to wind stress*, Comment. Phys.-Math./Soc. Scient. Fennica, 20 (7), 1–12.

Lisitzin E., 1959, *Uninodal seiches in the oscillation system Baltic proper – Gulf of Finland*, Tellus A, 11 (4), 459–466, http://dx.doi.org/10.1111/j.2153-3490.1959.tb00056.x.

Mälkki P., 1975, *On the variability of currents in a coastal region of the Baltic Sea*, Merentutkimuslaitoksen Julkaisu, 240, 3–56.

Merkouriadi I., Leppäranta M., Shirasawa K., 2013, *Seasonal and annual heat budgets offshore Hanko Peninsula, Gulf of Finland*, Boreal Environ. Res., 18, in press.

Ojaveer H., Jaanus A., Mackenzie B. R., Martin G., Olenin S., Radziejewska T., Telesh I., Zettler M. L., Zaiko A., 2010, *Status of biodiversity in the Baltic Sea*, PLoS ONE, 5 (9): e12467, http://dx.doi.org/10.1371/journal.pone.0012467.

Palmen E., 1930, *Untersuchungen über die Strömungen in den Finnland umgebenden Meeren*, Soc. Sci. Fennica, 12, 1–94.

SMHI & FIMR, 1982, *Climatological Ice Atlas for the Baltic Sea, Kattegat, Skagerrak and Lake Vänern (1963–1979)*, Sjöfartsverket, Nörrkoping, 220 pp.

Soomere T., Myrberg K., Leppäranta M., Nekrasov A., 2008, *Progress in physical oceanography of the Gulf of Finland, Baltic Sea*, Oceanologia, 50 (3), 287–362.