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Cover picture: Aranda cruise "Sea-ice 2010", Gulf of Finland. Photograph by Ioanna Merkouriadi

THE INFLUENCE OF SEASONAL SEA ICE ON THE PHYSICS OF THE COASTAL WATERS – GULF OF FINLAND

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THE INFLUENCE OF SEASONAL SEA ICE ON THE PHYSICS OF THE COASTAL WATERS – GULF OF FINLAND

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ACADEMIC DISSERTATION IN GEOPHYSICS

To be presented, with the permission of the Faculty of Science of the University of Helsinki for public criticism in Auditorium A129 of Chemicum, A.I. Virtasen aukio 1, on November 14th, 2014, at 12 o'clock noon.

Contents

Nomenclature

A	=	area
c_p	=	specific heat of air
C_E	=	latent heat exchange coefficient in neutral conditions
C_H	=	sensible heat exchange coefficient in neutral conditions
e	=	atmospheric water vapor pressure
E	=	evaporation
FMI	=	Finnish Meteorological Institute
GoF	=	Gulf of Finland
h	=	ice thickness
H	=	water depth
L_E	=	latent heat of evaporation
L_f	=	latent heat of freezing
N	=	cloudiness
PSU	=	practical salinity unit
P	=	precipitation
Q_e	=	turbulent flux of latent heat
Q_H	=	turbulent flux of sensible heat
Q_L	=	net longwave radiative flux
Q_n	=	net heat flux
Q_P	=	heat flux from precipitation
Q_{sc}	=	net shortwave radiative flux
q_0	=	specific humidity of the surface
q_a	=	specific humidity of the atmosphere
r	=	actual Earth-Sun distance
r_0	=	average Earth-Sun distance
S	=	salinity
SST	=	sea surface temperature
SSIZ	=	seasonal sea ice zone
T_a	=	atmospheric temperature
T_P	=	precipitation temperature
T_{tr}	=	atmospheric clear-sky transmissivity
T_0	=	surface temperature
U_a	=	wind speed
V_i	=	ocean water inflow volume
V_o	=	ocean water outflow volume
V_r	=	river runoff volume
Z	=	solar zenith angle
ε	=	sea surface emissivity
ε_a	=	effective atmospheric emissivity
ξ	=	water surface level
ρ_a	=	air density
ρ_i	=	ice density
σ	=	Stefan-Boltzmann constant

This thesis is based on the following five articles, which are referred to in the text by their Roman numerals:

Paper I: Merkouriadi I., M. Leppäranta and K. Shirasawa. 2013. Seasonal and annual heat budgets offshore the Hanko Peninsula, Gulf of Finland. *Boreal Environmental Research*, **18**, 89–108.

Paper II: Merkouriadi I. and M. Leppäranta. 2013. Influence of landfast ice on the hydrography and circulation of the Baltic Sea coastal zone. *Oceanologia*, **55**(1), 147–166. doi:10.5697/oc.55-1.147.

Paper III: Merkouriadi I. and M. Leppäranta. 2014. Long-term analysis of hydrography and sea-ice data in Tvärminne, Gulf of Finland, Baltic Sea. *Climatic Change*, **124**, 849–859. doi: 10.1007/s10584-014-1130-3.

Paper IV: Merkouriadi I. and M. Leppäranta. 2014. Influence of sea ice on the seasonal variability of hydrography and heat content in Tvärminne, Gulf of Finland. *Annals of Glaciology*, accepted with minor revisions.

Paper V: Merkouriadi I. and M. Leppäranta. 2014. Physical, Chemical and Optical Properties of Estuaries in the Gulf of Finland, River Kymijoki. 22nd IAHR International Symposium on Ice, Singapore 2014, Proceedings.

Abstract

The Gulf of Finland is located in the seasonal sea ice zone (SSIZ), were sea ice forms in the wintertime and melts in late spring. This seasonality entitles this sea as a key area regarding the impact of climatic changes. When the basin of interest is located at the climatological edge of the SSIZ, there is also high inter-annual variability in the ice conditions.

The aim of this study was to examine the influence of the sea ice on the physics of the coastal waters in the Gulf of Finland. Three sites were chosen, two located at each side of Hanko Peninsula, northwest entrance of the Gulf, and one at the estuaries of River Kymijoki, northeast side of the Gulf. Long-term hydrographic and sea ice data were examined in order to study the inter-annual variability and trends of the hydrographic characteristics, heat content, freezing and break-up days and ice thickness during the last century in the coastal zone of the Gulf of Finland. The influence of the seasonal sea ice on the physics of the water body – hydrography, circulation, atmosphere-ocean interaction – was evaluated.

The results showed significant decrease of the ice season length by almost 30 days in the last century. The maximum annual sea ice thickness decreased by 8 cm in the last 40 years. In the last 85 years, surface water temperature increased by 1 ˚C and surface salinity increased by 0.5 PSU. The water body stratification in the coastal zone was strongly affected by the limited wind mixing in the wintertime. The circulation under ice became weaker by almost 1 cm s^{-1}. The ice cover was a good control measure of the net surface heat exchange. Solar radiation had a strong seasonal cycle with monthly maximum at 160 W m^{-2} and minimum below 10 W m^{-2}. Terrestrial radiation was mostly between –40 and –60 W m^{-2}. Latent heat exchange was much more important than sensible heat exchange, similar to the net terrestrial radiation values in summer and autumn.

Acknowledgements

After these amazing moments I truly feel the need to thank a list of people. First I need to point out how grateful and lucky I am to have Matti Leppäranta as a supervisor. Not only have I appreciated him as a scientist but also as a mentor. He gave me opportunities to travel all around the world and showed patience and understanding in every step. It is an honor to collaborate with people like Matti. His guidance, as well as his spirit I sincerely appreciate.

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I definitely want to thank my family, who was next to me each and every moment, regardless the time and the distance. They are and will always be deeply precious to me. "Like branches on a tree we all grow in different directions, yet our roots remain as one".

I am also very lucky and grateful to cross paths and become like family with some special people outside work. I owe great thanks to Kirsti and her whole family, and Suvi, who truly gave light to my life.

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Finally, the last and greatest "thank you" goes to my beloved sister Asimenia. This work is dedicated to her, the most beautiful person I have ever known. I hope this message would reach the skies my dearest "Lilika".

1. Introduction

About 10% of the world's ocean surface is covered by sea ice (Leppäranta, 2005). Physical processes such as solar, atmospheric, oceanic and tidal forcing control the growth, the decay and the drift of sea ice. Sea ice is mainly prominent at latitudes above 60˚; however it can occur seasonally in lower latitudes. The seas, on which ice forms in the wintertime and melts later in spring, belong to the Seasonal Sea Ice Zone (SSIZ). The Bo Hai Sea in China, the Sea of Okhotsk between Russia and Japan and the Baltic Sea are representative areas of the SSIZ.

In the SSIZ, the wintertime is of major importance in the physics and the ecology of the basins. In general, sea ice has a remarkable influence on the physics of the freezing seas by (a) forming an insulating surface film, (b) providing high albedo, (c) modifying the salt budget of the upper layer, and (d) preventing the transfer of the wind momentum to the water body. The sea freezes, and the evolution of the sea ice and the water body progress in an interactive manner. Freezing starts from the shallow coastal areas and develops further out during the winter, while melting starts from both the land and the open ocean boundary. The last pieces of ice to disappear are remnants of large pressure ridges. When the basin of interest is located at the climatological edge of the SSIZ, there is also high inter-annual variability in the ice conditions.

Sea ice has also a great influence on the ecological conditions of the water bodies. Precipitation accumulates on the ice surface together with atmospheric pollutants, which are released into the water body when the ice is melting. Moreover, when sea ice is growing it can capture suspended matter and sediments from the sea water, and in case of drifting ice can they can be transported far from the source area (Leppäranta et al. 1998). Sea ice offers a habitat to sea algae (Horner 1985, Norrman and Andersson 1994) and living environment for seals (Meier et al. 2004b). By influencing the water stratification, it can modify the water chemistry, such as the dissolved oxygen and the pH profiles, which in turn affect the biota of the marine ecosystems. Understanding the sea ice influence on the physics is vital in order to assess its impact in the marine environment.

The purpose of this work is to evaluate the influence of the coastal sea ice in physical and ecological properties of the water body. The study is mainly based on observations from particular coastal areas of the Gulf of Finland (hereafter denoted as the GoF). Heat exchange between the ocean and the atmosphere, profiles of hydrography and currents, pH and dissolved oxygen levels were analyzed both in ice-covered and open water seasons. In addition, the long-term trends and the seasonal variability of the hydrography, heat content, freshwater budget and sea ice were examined in the coastal zone of the GoF (Fig. 1).

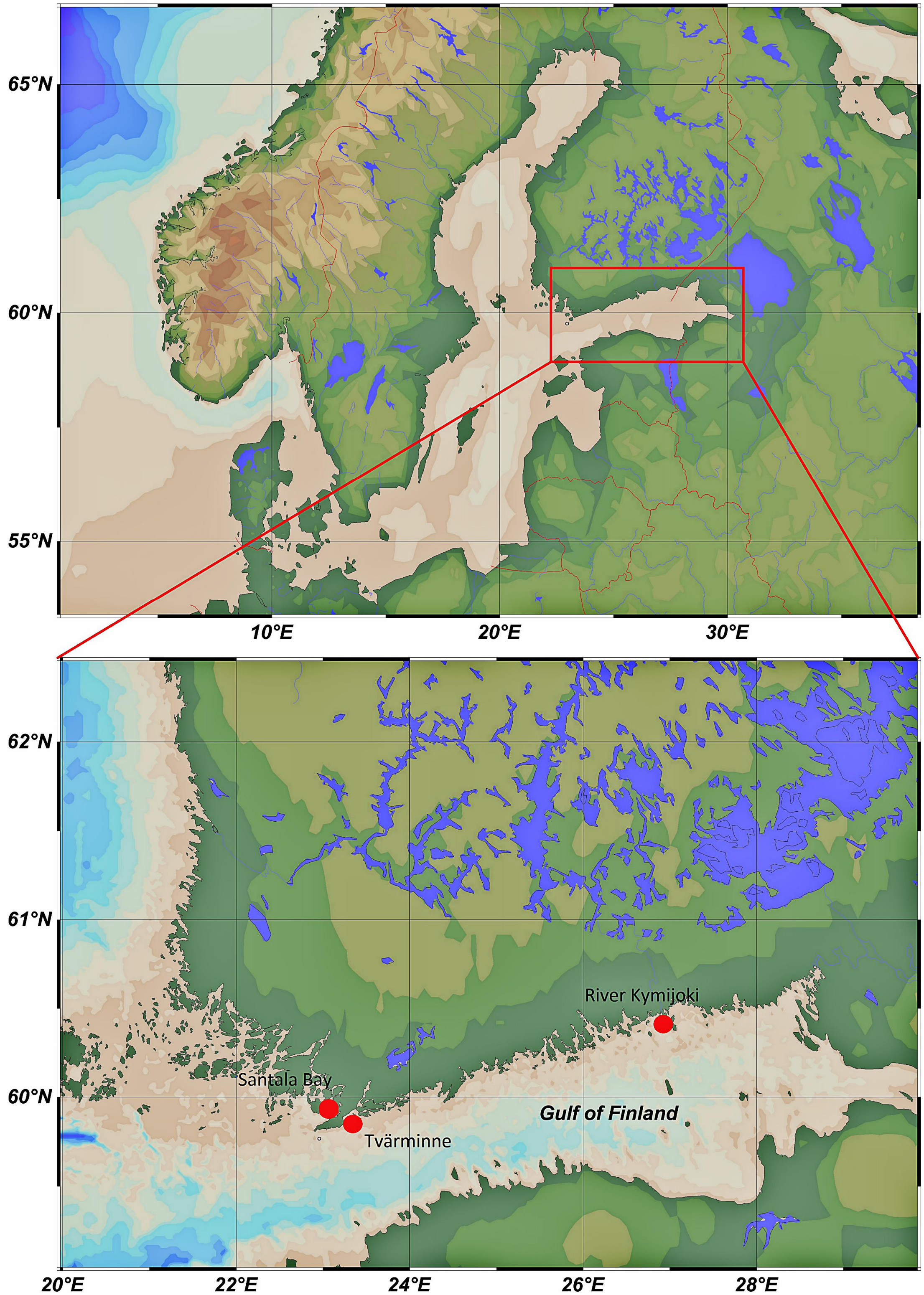


Figure 1. Map of the Baltic Sea (up) and the Gulf of Finland (down). Red dots represent the studied locations (Santala Bay, Tvärminne and River Kymijoki estuaries). Source: Ocean Data View.

This work is an attempt to investigate the SSIZ functions and processes, to build up our knowledge, and to contribute in understanding how future changes might influence the marine environment of the SSIZ. Extensive knowledge has been gained during the BALTEX and related programs concerning the Baltic Sea physics, as it was successfully reported by Omstedt et al. (2004). Regional research on meteorology and hydrography considerably improved the oceanographic knowledge and the ability to model the Baltic Sea system. However, there was need for additional information related to the sea ice role in the water and heat cycles, being reported as one of the main future challenges (Omstedt et al. 2004).

1.1 Author's Contribution

The author's personal contribution is hereafter presented for each publication.

Paper I, II, III, and IV: Ioanna Merkouriadi was responsible for the data analysis and the figures. The articles were written together with Matti Leppäranta. The total contribution of Ioanna Merkouriadi is 75%.

Paper V: Ioanna Merkouriadi was responsible for the data collection, the data analysis, the figures and the writing of the article. Total contribution of Ioanna Merkouriadi is 90%.

2. Baltic Sea and the Gulf of Finland

Being one of the largest brackish basins worldwide, the Baltic Sea is a landlocked intra-continental sea located in the Northern Europe. The only oceanic connection is in the southwest to the North Sea via the three narrow Danish Straits (Little Belt, Great Belt and Sound) and the Kattegat. The limited water exchange between the Baltic and the North Sea, together with the largely humid climate of the area, has resulted in the brackish nature of the Baltic Sea, the long residence time of its water masses, and its sensitivity in pollution of different kinds (Feistel et al. 2008).

The salinity of the Baltic Sea is on average lower than 10 PSU, and it varies significantly both vertically and horizontally. As a consequence of the basin's estuarine nature, there is a permanent halocline in the Baltic Sea, resulting in a continuously stratified water body. This limits the vertical mixing and consequently the oxygenation of the deep water layers. In addition, there is a strong horizontal salinity gradient from the North Sea saline boundary, up to the freshwater river mouths of the Baltic Sea interior.

In terms of climate, the Baltic Sea lies between maritime temperate and continental sub-Arctic zones. Therefore, there is large annual variation of the surface water temperature. Every winter, the Baltic Sea is partially ice covered (on average 45% of the total area) and during the most severe winters it freezes completely. In coastal and archipelago areas the ice starts to form as *landfast* ice, which is a solid and even ice sheet attached to the land. Elsewhere it appears as *drift ice* with mobile properties generated by wind and current forces (Leppäranta and Myrberg 2009). The offshore boundary of the fast ice zone is on average located at the 10 m isobath (Leppäranta 1981). Sea ice can be found in the Baltic Sea for up to seven months in a year, playing a very significant role in the physics and the ecology of the basin.

The Baltic Sea drainage basin contains 14 countries which are characterized by rapid political, industrial and socio-economic changes in the recent history, and there are 85 million people inhabiting the area (Omstedt et al. 2004). The increased human activities of the developed Baltic Sea countries, and the resulting loading of nutrients and pollutants, have turned the Baltic Sea into one of the most vulnerable marine environments. This triggered multilateral agreements, such as the Helsinki Convention (HELCOM, 1974 and HELCOM, 1992), according to which all countries would be responsible for monitoring, using common databases and enhancing the protection of “Our Sea” (the term used by the countries bordering the Baltic Sea). For more than a century, Baltic Sea has been one of the most investigated seas in the globe.

The GoF is the easternmost basin of the Baltic Sea (Fig. 1). It is connected to the Central Basin of the Baltic Sea at the west side and it is surrounded by three countries, Finland (to the north), Estonia (to the south) and Russia (to the east). Three major cities Helsinki, Tallinn and St. Petersburg are located on the coastal zone of the GoF. Being a shallow brackish basin, the GoF has been well-known of its inadequate ecological state and its sensitivity to contamination. This work is focusing in the GoF, so more information concerning the basic features of the basin is following hereafter.

2.1 Topography

The GoF is an elongated, estuarine sea, lying between 59° 11’ N, 22° 50’ E and 60° 46’ N, 30° 20’ E. It has a length of 400 km and width from 48 to 135 km. The mean depth is 37 m and the maximum is 123 m. The volume of 1,103 km^3 is about 5% of the total Baltic Sea volume, while the drainage area of 420,990 km^2 is 20% of the total Baltic Sea drainage area (Falkenmark and Mikulski 1975, Astok and Mälkki 1988). The north coast of the GoF is extremely complex, with numerous islands and skerries (Feistel et al. 2008). The southern coastline is rather steep and has more regular bathymetry (Leppäranta and Myrberg 2009). Peninsulas, such as Hanko and Porkkala, the island of Naissaar and the ridge between it and the Estonian coast, play the main role in steering the currents along the GoF. The deepest points of the GoF are located at the west side whereas in the easternmost part, the so-called Neva Bight, the mean depth is only 5 m. The GoF is generally rich in topographic features which play an important role in the modification of the circulation (Alenius et al. 1998).

2.2 Hydrography

There is no sill in the entrance of the GoF, and the line from Hanko to the island of Osmussaar is considered as its western boundary (Leppäranta and Myrberg 2009). This is the reason why changes in the hydrographic conditions of the Baltic Proper are reflected in a continuous manner in the GoF. There is a saline water input from the west and an extensive freshwater input from the east due to the discharge of three major rivers (Neva, Kymijoki and Narva). River Neva alone, with mean discharge of 75.5 $km^3\ y^{-1}$, brings to the GoF 15% of the total freshwater input of the Baltic Sea (Mikulski 1970). The positive freshwater balance makes the GoF behaving as a typical estuarine system. This determines the basic hydrographic and ecological properties such as the estuarine circulation, the deepwater formation and ventilation, the stratification, and the balance of the nutrients (Feistel et al. 2008).

Being a transition zone, from freshwater in the east to the Baltic Proper saline waters in the west, the GoF is characterized by large horizontal and vertical variations in the hydrographic characteristics. The surface salinity varies from 5–6.5 PSU at the seaward end, down to 0–3 PSU at the landward end. At times, horizontal gradients of temperature and salinity can be extremely large due to local upwellings (Soomere et al. 2008). A permanent halocline is more prominent at the west (deeper) part of the GoF, separating warmer and fresher surface runoff water from colder and more saline water masses from the Baltic Proper. The halocline is located at 60–80 m depth in the west and the properties of the bottom water are largely dependent on irregular water intrusions, atmospheric and land runoff variations and changes in meteorological forcing (Elken 2006, Elken et al. 2006). At the eastern part of the GoF, salinity is increasing almost linearly with depth.

There is a considerable variation of the sea surface temperature (SST) in different seasons due to the great annual cycle of the solar radiation. The thermocline starts forming in May and SST reaches maximum values in July-August (15–20 ˚C). In shallow coastal areas, and especially close to river mouths, the stratification of the water column is strongest in spring. This is a result of increased surface temperature, maximum river discharge (decreased salinity), weak wave activity (Soomere 2005, Broman et al. 2006), and moderate transparency of the GoF waters (Fleming-Lehtinen et al. 2007).

2.3 Atmospheric forcing and circulation

The large-scale atmospheric circulation patterns over the Baltic Sea are governing the basic features of the winds in the GoF region (Soomere et al. 2008). Wind data records from the Finnish coast adequately represent the wind properties of the open sea. However, this is not the case in the Estonian coast (Keevallik 2003 a,b, Soomere and Keevallik 2003). On average SW winds are more frequent in the GoF. Moderate (6–10 m s^{-1}) and strong winds (> 10 m s^{-1}) originate mainly from S or SW on the northern coast, when on the southern coast they more often come from SW and W (Soomere and Keevallik 2003).

Studies on the basic properties of the GoF circulation initiated more than a century ago (Witting 1912, Palmen 1930). The mean circulation was grossly characterized cyclonic, with an average velocity of a few centimeters per second. However, this was a result of local and scarce observations. At short time scales, the main driving mechanism of the currents in the GoF is the wind stress. At longer time scales, density-driven currents become important due to the horizontal variations of temperature and salinity, which in turn cause pronounced horizontal buoyancy currents (Soomere et al. 2008). Another significant factor is the size of the GoF, which is large enough for Earth's rotation to affect the circulation (Witting 1912, Palmen 1930, Hela 1946). There is a high variability in speed and direction of the coastal currents, caused by the differences in the stability between the north and the south coast. In this context, stability, or persistency, of a current is the ratio between the vector and the scalar mean speed. By calculating the time difference between the annual minimum surface salinity in Utö and the annual maximum river runoff, the long-term mean flow across the GoF was estimated (Launiainen 1982). The result, 2.5 months, implied an average velocity of couple of centimeters per second (Mälkki and Tamsalu 1985).

2.4 Sea ice

Sea ice is present in the GoF each winter for 4–5 months. Freezing starts from the eastern side of the basin, at River Neva. The average day of freezing is 1 December and the last pieces of ice have disappeared by 1 May (SMHR & FIMR 1982). Maximum ice extent is reached in February or March. The probability of ice occurrence is higher in the east and the north part of the basin. This is due to the dominant S and SW winds in combination with the uneven Finnish coastline which supports a broad landfast ice zone.

The ice season in the GoF is more severe at the eastward end, where ice actually forms every winter, and progresses towards the west depending on the severity of the winter. Ice thickness varies between 30 and 80 cm in Vyborg and Neva Bays. Offshore the landfast ice zone, ice drifts under the influence of winds and currents with a non-linear rheological behavior. Depending on the wind direction, drift ice can either leave the GoF towards the

Gotland Sea or pack towards the landward ends, where it can form pressure ridges in case of compressive drift (Soomere et al. 2008).

Sea ice stratigraphy, i.e. the internal stratification and crystal structure of the ice sheet, indicates the origin and the mechanisms responsible for the ice growth. Although the GoF is a brackish basin, the ice has a fine-scale structure typical of sea ice (Palosuo 1961, Kawamura et al. 2001). This is indicated by the irregular crystal shapes and the significant brine entrapment. Freshwater ice type occurs only in estuaries were surface salinity is less than 1.5 PSU (Kawamura et al. 2002). The ice formation initiates in supercooled waters and in the landfast ice zone the ice normally grows down from the bottom as *congelation* ice (Kawamura et al. 2001). Together with the bottom growth, *superimposed ice* can be formed on the top of the ice surface due to water flooding through the ice sheet, melting of the snow or liquid precipitation. In the GoF, snow-ice can reach 10–50% of the ice sheet (Palosuo 1963, Granskog et al. 2004) and it scatters up to 30% more light than the clear congelation ice.

When ice starts forming, it initially contains 20–40% of the parent water salinity, a percentage which depends on the growth rate (Palosuo 1963, Granskog et al. 2004). In the molecular diffusion of salt and heat in a liquid, a cellular ice-water interface forms that can enclose liquid brine pockets between crystal platelets (Leppäranta and Myrberg 2009). The brine pockets provide habitat for sea algae and they also influence the optical properties of the ice by absorbing light. As sea ice grows, salinity is released due to gravity drainage. When the ice gets warmer the brine pockets form channels, resulting in brine rejection and almost zero ice salinity within the ice pack in spring.

Due to the large economic impact of sea ice in the marine transportation and foreign trade, observations in the GoF became essential (Askne et al. 1992, Seinä 1994, Alenius et al. 2003). The time series collection of freezing and ice break-up dates, initiated already in the 1800's in the GoF (Leppäranta and Seinä 1985, Jevrejeva et al. 2004). When winter traffic became more important, coastal monitoring increased (Palosuo 1953). Ice charts have been available since the beginning of 1960's (SMHI and FIMR 1982). The availability of these time-series has been exceptionally useful for oceanographic research in the GoF.

3. Materials and Methods

3.1 Study sites and data

The areas under consideration in this study were Santala Bay, Tvärminne and the estuaries of River Kymijoki, all located in the northern coast of the GoF along the Finnish coast.

Both Santala Bay and Tvärminne are located in the Hanko Peninsula, northwest side of the GoF. River Kymijoki's delta is located at the city of Kotka, east side of the Finnish coast of the GoF. The data from Santala Bay and River Kymijoki estuaries are available at the University of Helsinki. Regular weather observation and marine station data belong to the Finnish Meteorological Institute (FMI) and access to those should be discussed with the FMI.

3.1.1 Santala Bay

Santala Bay (59° 55'N, 23° 05'E) communicates with the GoF through a southwest passage and with the inner archipelago through a wider opening northeast. A joint Finnish-Japanese sea ice experiment took place in Santala Bay in four successive years (1999–2002). It included both seasonal monitoring and intensive field campaigns. The aims of this project was to collect ice, oceanographic and meteorological data in order to examine the structure and properties of the Baltic Sea brackish ice, heat budget and solar radiation transfer through the ice sheet. More information concerning the automatic station deployed in the bay can be found in Papers I and II. Data from two winters (1999–2000 and 2000–2001) were used here in order to estimate the seasonal and annual heat budgets and the influence of landfast ice on the hydrographic properties and the circulation of the water body. The maximum depth in Santala Bay is 10 m.

3.1.2 Tvärminne

Tvärminne Storfjärden (59° 51.250'N, 23° 15.815'E) is located at the east coast of the Hanko Peninsula. Tvärminne Zoological Station and the FMI provided long-term hydrographic and sea ice data from the site during the last century. The purpose of this analysis was to examine the natural variability and trends of the hydrographic properties, freezing and break-up dates, ice thickness, freshwater budget and heat content during the last century. In addition, the sea ice influence on the seasonal variability of the hydrography and the freshwater and heat exchanges were evaluated.

Hydrographic data were available in Tvärminne Storfjärden since mid-1926. Data were collected 3 times per month at 6 different depths (surface, 5 m, 10 m, 15 m, 20 m and 30 m). Measurements were interrupted during World War II, from March 1940 to May 1942, when the region was occupied by the Soviet Union. The maximum depth in Tvärminne Storfjärden is 35 m. More information on the data is included in Papers III and IV.

3.1.3 River Kymijoki

Finally, one year of successive measurements (2011) took place in the estuaries of River Kymijoki, Gulf of Finland. Physical, chemical and optical data were collected during four successive measurement campaigns along two cross-sections at River Kymijoki estuaries. In addition, open access data records from OIVA data base [Environmental and Location-based Expert Services] were analyzed for seasonal variations (Fig. 2). Purpose of this work was to examine the physical, chemical and optical properties of the estuaries in the GoF and the influence of sea-ice. Additional information on the instrumentation and the data sources can be found in Paper V.

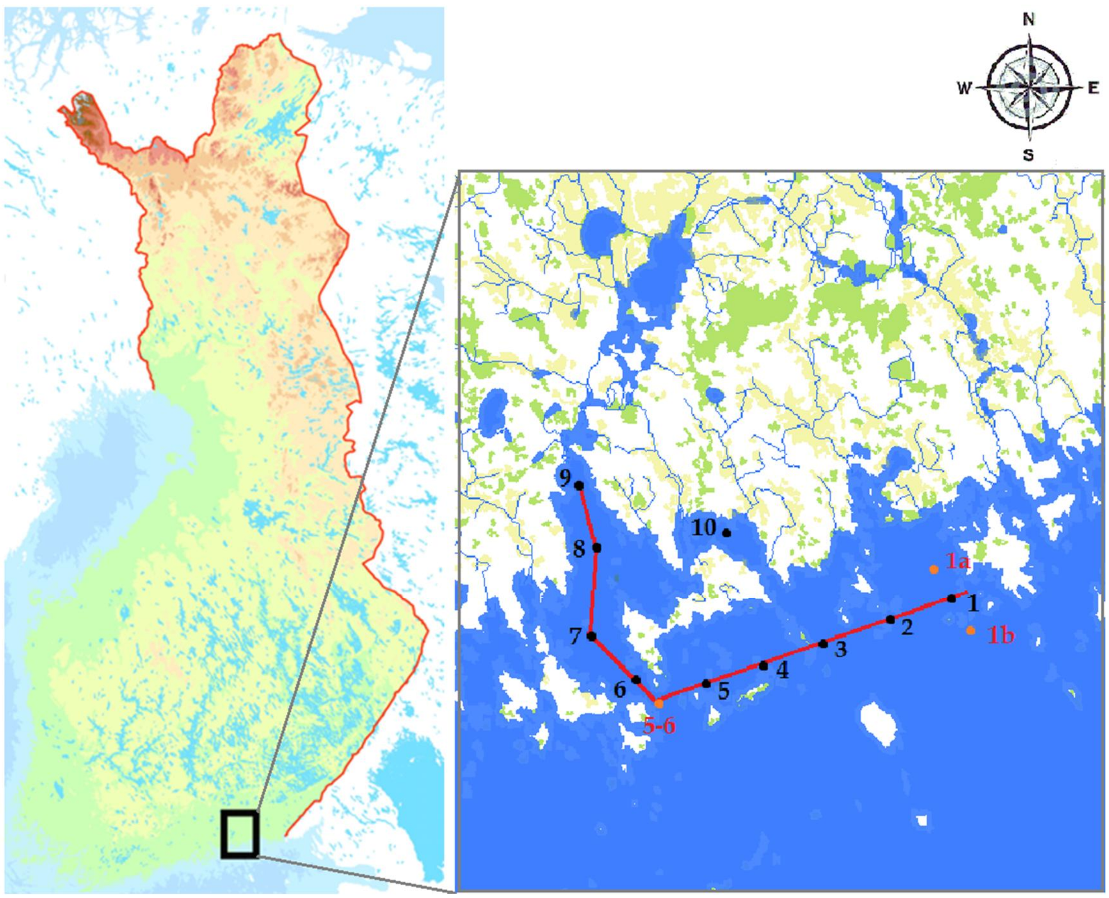


Figure 2. Map of River Kymijoki estuaries and the cross-sections. Black points are the ones measured by the University of Helsinki and orange points are from OIVA online database.

3.2 Methods

3.2.1 Heat budget

The heat exchange between the sea surface and the atmosphere was estimated in Santala Bay for two years, 2000 and 2001. The net surface heat exchange between the ocean and the atmosphere consists of solar radiation (Q_{sc}), terrestrial radiation (Q_L), turbulent heat fluxes (Q_H and Q_e), and heat flux from precipitation (Q_P) (Leppäranta and Myrberg 2009).

The heat balance terms are positive when the heat direction is from the atmosphere to the water:

$$Q_n = Q_{sc} + Q_L + Q_H + Q_e + Q_P \tag{1}$$

Net solar radiation

The net solar radiation is the difference between the incoming and the outgoing solar radiation flux. The incoming radiation (Q_s) can be either measured directly or estimated by an atmospheric-astrophysical formula (Iqbal 1983). Throughout the experiment, incoming solar radiation was measured by pyranometer and PAR sensors. However, the formula below was used to fill in the data gaps when the automatic station was not operating:

$$Q_s = \cos Z T_{tr}(Z,e) F(N,Z)(r_0 / r)^2 Q_{sc} \tag{2}$$

where Z is the solar zenith angle, T_{tr} is the atmospheric clear-sky transmissivity, e is the atmospheric water-vapor pressure, F is the fraction that indicates the effect of cloudiness N ($0 \le N \le 1$), r and r_0 are the actual and the average Earth-Sun distances and Q_{sc} = 1.376 kW m^{-2} is the solar constant. The transmissivity and cloudiness corrections were taken from Zillman (1972) and Lumb (1964), respectively.

Net terrestrial radiation

The net terrestrial radiation is the difference between the thermal radiation emitted by the atmosphere and the thermal radiation emitted by the sea surface. The thermal radiation emitted by the sea surface is given by the gray-body law:

$$Q_{L_0} = \varepsilon \sigma T_0^4 \tag{3}$$

where ε is the surface emissivity, equal to 0.99 for water and 0.97 for ice/snow (Saloranta 2000), σ = 5.67 10^{-8} W m^{-2} K^{-4} is the Stefan-Boltzmann constant, and T_0 is the absolute surface temperature in Kelvin.

The thermal radiation emitted by the atmosphere is a more complicated term since it is not generated by a plane, homogeneous surface. Instead, it is a combinative result of atmospheric water droplets, aerosol and molecules in different heights and temperatures. The formulae used in the calculations were:

$$Q_{L_a} = \varepsilon_a \sigma T_a^4 \tag{4a}$$

$$\varepsilon_a = \varepsilon_a(N, e) = (a + be^{1/2})(1 + cN^2) \quad (4b)$$

where ε_a is the effective atmospheric emissivity and a, b and c are emission law constants, often taken as 0.68, 0.036 mbar$^{-1/2}$ and 0.18 respectively for the Baltic Sea (Omstedt 1990).

Turbulent heat fluxes

For the estimation of momentum, heat and moisture exchange between the sea and the atmosphere, turbulent boundary layer theory was used with the so called bulk formulae:

$$Q_H = \rho_a c_P C_H (T_a - T_0) U_a \quad (5)$$

$$Q_e = \rho_a L_E C_E (q_a - q_0) U_a \quad (6)$$

where ρ_a and c_P are the density and specific heat of air, L_E = 2.5 MJ kg^{-1} is the enthalpy of evaporation, q_0 and q_a are the specific humidity of the surface and the atmosphere, respectively, and U_a is the wind speed. C_H and C_E are the Stanton and Dalton number, or the bulk transfer coefficients. They can be taken as constants in neutral atmospheric conditions, normally varying between 1.0×10^{-3} and 1.5×10^{-3} (Andreas 1987). However, the atmospheric stratification above the sea-ice surface is not always neutral (Launiainen et. al 2001). Therefore, the turbulent transfer coefficients were calculated based on the Monin-Obukhov similarity law (Garratt 1992).

Precipitation

Precipitation is another heat exchange mechanism, which can be negligible except when phase changes take place:

$$Q_P = \rho[c(T_P - T_0) + L_f \chi_P]P \quad (7)$$

where ρ and c are the density and the heat capacity of the precipitating medium (water or ice), χ_P = –1, 0 or 1 for solid to liquid phase change, no phase change, or liquid to solid phase change, L_f = 335 kJ kg^{-1} is the latent heat of freezing, T_P and T_0 are the precipitation and sea surface temperatures, and P is the precipitation.

3.2.2 Oceanic Heat Flux

During the wintertime in the SSIZ, heat exchange at the atmospheric boundary layer results in ice formation. The latent heat, which is released / absorbed during the ice formation / melting, can be calculated when the ice thickness is known:

$$Q_i = -\rho_i L \frac{dh}{dt} \qquad (8)$$

where ρ_i is the ice density, L is the latent heat of freezing, and h is the ice thickness. An indirect way to estimate the oceanic heat flux is to take the residual between Q_n and Q_i. In general, oceanic heat flux is not a well-known quantity and it is here anticipated to be of the order of 10 W m^{-2} (Shirasawa et al. 2006).

3.2.3 Freshwater budget

In order to examine the circulation pattern in Santala Bay, a box model was created based on the salinity changes and the conservation of the water mass:

$$\frac{d\xi}{dt} + \frac{H}{\bar{\rho}}\frac{d\bar{\rho}}{dt} = P - E + \frac{V_r + V_i + V_o}{A} \qquad (9)$$

$$\frac{dS(H+\xi)}{dt} = \frac{S_i V_i - S_o V_o}{A} \qquad (10)$$

where ξ is the sea-level elevation, H is the mean depth, $\bar{\rho}$ is the mean density, P is the precipitation, E is the evaporation (and sublimation), V_r is the river runoff , V_i and V_o are the inflow and outflow volumes and A is the area. The purpose was to model the salinity changes in case of no horizontal water exchange and to compare the results to the salinity observations. The residual would then correspond to the horizontal water exchange.

3.2.4 Validation of the long-term trends

For the examination of the temperature, salinity and sea ice long-term trends in Tvärminne, linear regression was used based on the least squares estimation of the parameters. The significance of the correlation coefficients was estimated via hypothesis testing for validating the trends. The significance level was taken as 5%. The null hypothesis (no correlation) was rejected if the probability of the validity was < 0.05 and, in this case, the correlation was considered significant (Emery and Thomson 2001).

3.2.5 Spectral analysis

Spectral analysis was applied to the time series of physical properties in order to identify periodical signals. The power spectral density (PSD) function transfers the signal from the time to the frequency domain. When plotting the transformed signal it is possible to identify periodicities represented by sharp peaks in specific frequencies (Emery and

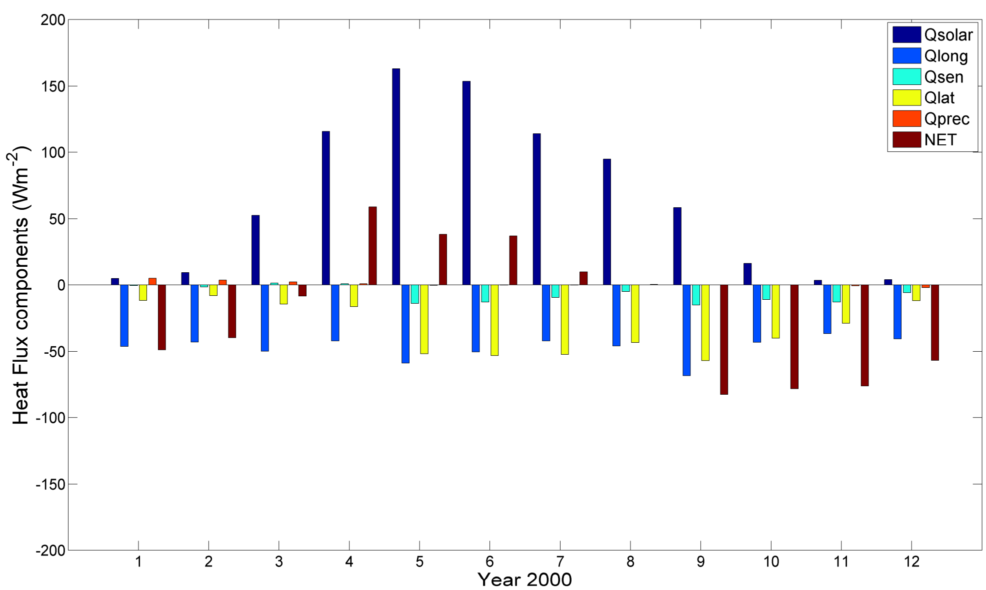
Thomson 2001). In addition to the peaks, oceanographic data also show a broad peak, or hill, at the low frequency range. The reason is that energies are fed to the ocean usually from atmospheric variations in such low frequencies. Then the energy decreases exponentially towards higher frequencies. The PSD was calculated by a two-sided periodogram based on the Discrete Fourrier Transform.

4. Results

4.1 Sea ice influence on the heat budgets

The heat exchange between the sea surface and the atmosphere was examined for two years in Santala Bay (Paper I). Solar radiation is the main heat source of the Earth system and it also provides the direct heating of the Baltic Sea. The net solar radiation flux is highly sensitive to cloudiness, so the corresponding months of maximum values can vary significantly in different years (Fig. 3). In spring and summer time, solar radiation was the dominant factor in the heat balance of Santala Bay.

The average level of the net terrestrial radiation was –50 W m^{-2}. Values were maximized under clear sky conditions, when the difference between atmospheric and surface temperature was high. The turbulent heat fluxes are strongly wind dependent, and so the seasonal variability is linked with the wind regime. The latent heat fluxes (on average –30 W m^{-2}) were more significant than the sensible heat fluxes (on average –10 W m^{-2}). During the ice season they both decreased significantly.



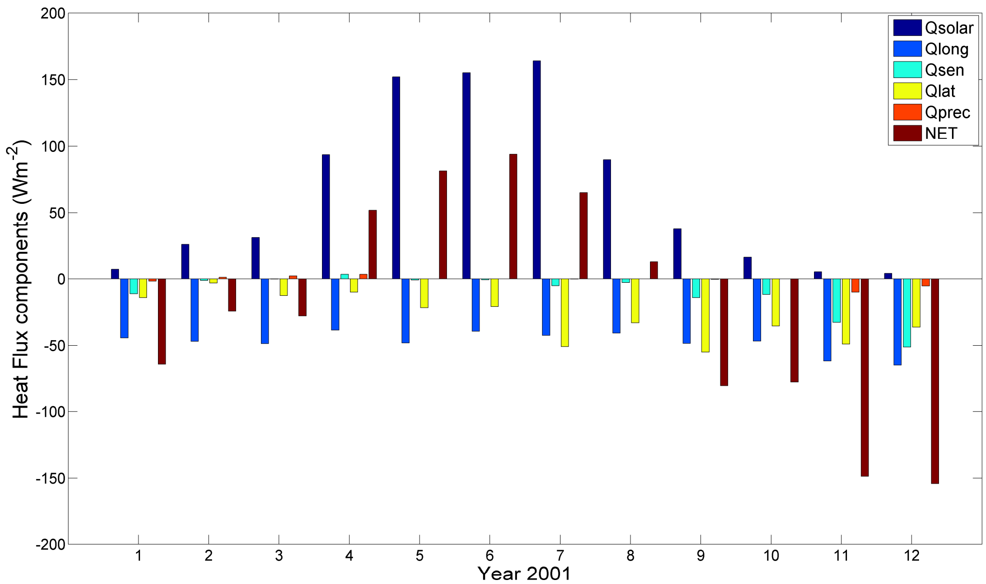


Figure 3. Monthly averages of the heat flux components for 2000 and 2001. Qsolar = net solar radiation, Qlong = net terrestrial radiation, Qsen = sensible heat flux, Qlat = latent heat flux, Qprec = precipitation heat flux, NET = net heat flux.

Finally, the heat flux from precipitation becomes important in case of phase changes. This is translated into liquid precipitation on ice surface or solid precipitation on open water, with resulting latent heat absorbed or released by the ice or the sea surface. Average monthly values reached down to –10 W m^{-2} in November 2001, meaning that there was considerable amount of snowfall on open water.

The net heat flux in Santala Bay was on average –20 W m^{-2} in both years. This heat loss must have been compensated by advection from the central GoF. More detailed results on the annual cycle of the heat flux components and the radiation balance in Santala Bay can be found in Paper I.

4.2 Sea ice influence to hydrography and circulation

The influence of sea ice in hydrography and circulation was also examined in Santala Bay for two years (Paper II). The temperature of the water body was close to 0 ˚C during the ice season and began to rise after March, before the ice break-up season. This was due to the solar radiation penetrating through the ice sheet and possible advection from the central GoF.

The salinity was related strongly to the freshwater input from the atmosphere and the land. During the ice season atmospheric precipitation accumulates on the ice surface and affects the water body only after the ice break-up. Salinity increase during the ice season is mainly caused by the sea ice growth and the consequent brine rejection and/or due to advection phenomena from the more saline waters of the GoF. In fact, congelation ice growth by 25 cm should increase the salinity by a factor of about 0.25 PSU in the study basin.

The freshwater budget was examined by a box model which was discussed in Chapter 3.2.3. By modeling the salinity in the absence of horizontal exchanges and comparing it to the observed values, the origin of the inflows could be identified. The major salinity inflows occurred mainly in February and in the beginning of March and were associated with advection events from the GoF.

The average wind velocity from both years was 3.6 m s^{-1} and it had no effect in the current system during the ice season. Current velocity values under ice decreased by almost 1 cm s^{-1}. The average current direction was more aligned along the north-west during the wintertime. Finally, the frequency spectra of the current field components showed that the main part of the velocity variance was in the synoptic scale and seiches.

4.3 Long-term analysis of hydrography and sea ice in Tvärminne

Long-term trends of temperature, salinity and sea ice were examined in Tvärminne Storfjärden based on time-series data from the last 85 years (Paper III). The surface temperature increased by 1 ˚C at the surface and 0.8 ˚C at the bottom of Storfjärden. Similar increase was also observed in the air temperature. The surface salinity increased by 0.5 PSU, whereas at the bottom no significant trend was observed. The surface and the bottom salinity can follow different patterns since their evolution is driven by different mechanisms, the surface water flux and the deeper water advection.

The SST anomalies in relation to the mean of the normal meteorological period 1931–1960 were calculated (Fig 4). The grey bars indicate the residuals, and the solid black line presents the 15 years running mean. There was a clear increasing trend, remarkable after the 1990’s.

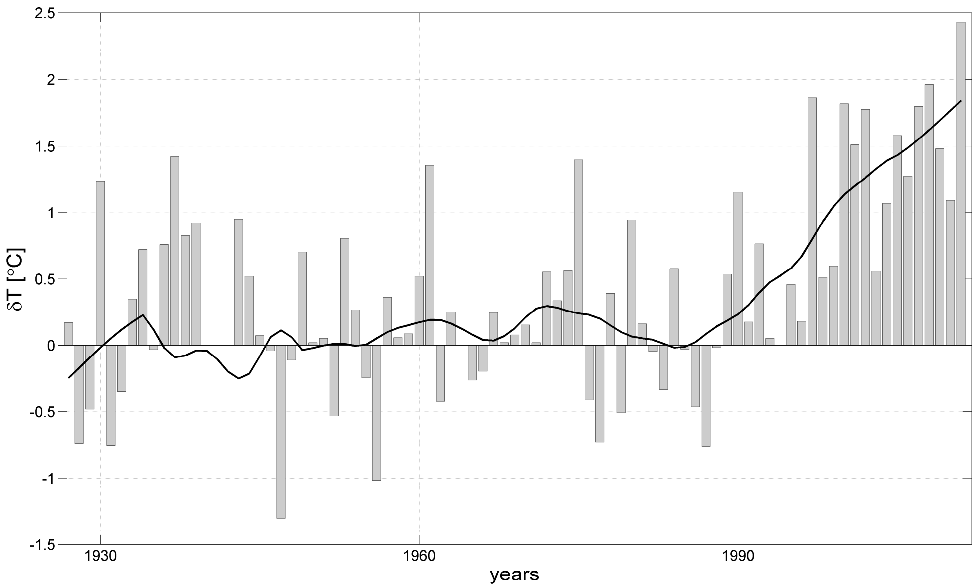


Figure 4. SST variations (anomalies relative to 1931–1960 mean) in Tvärminne. The black line is the time series filtered with a 15 years running mean.

The long-term heat content of the water body was examined in Storfjärden. From the spectral analysis two peaks were observed, a major one in the 12-month period and a lower one in the 6-month period (Fig 5). The 6-month peak was the 2nd harmonic correction to the annual cycle. The spectral density decreased weakly, proportional to frequency to the power of –0.5.

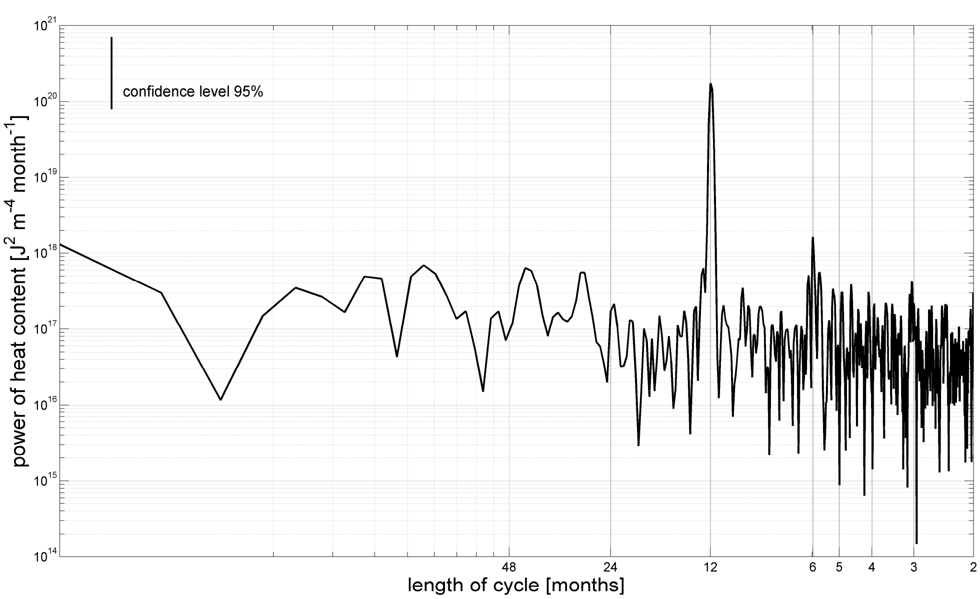


Figure 5. Power spectrum of the heat content in Tvärminne Storfjärden in the last 85 years.

Ice phenology data have been collected for more than a century in Hanko and Russarö. The probability of ice occurrence was 0.96 in Hanko and 0.91 in Russarö, which is further offshore. The length of the ice season decreased by 30 days during the last century. Ice and snow observation data from Jussarö during the last 40 years are shown below (Fig 6). The trend indicated that the annual maximum sea ice thickness decreased by 8 cm in the last 40 years. However, the trend was not statistically significant at the 5% level.

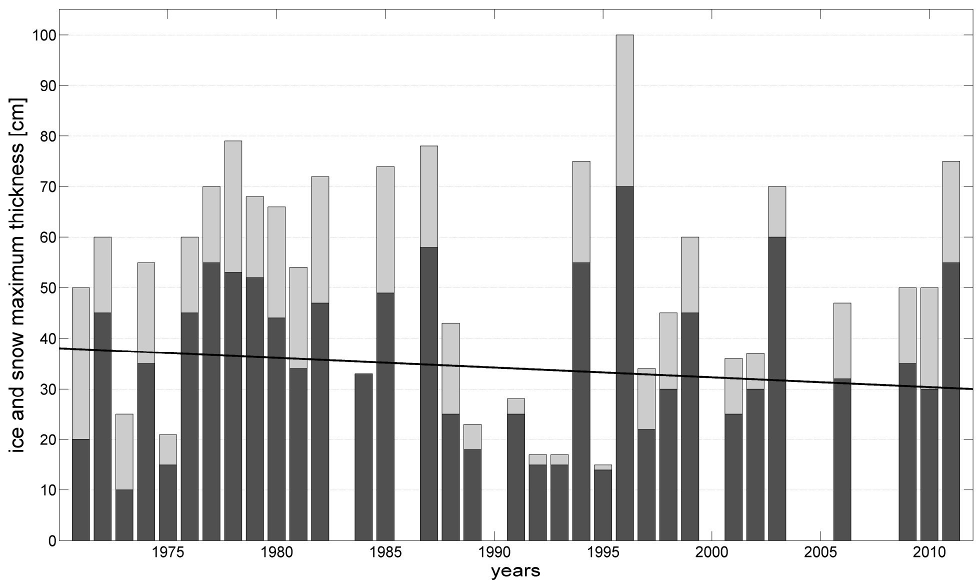


Figure 6. Annual maximum ice (dark grey) and snow (light grey) in Jussarö, 1971–2011. Black line is the linear regression of the ice thickness.

Finally, the sea ice impact on the annual cycle of the SST was examined by calculating the correlation coefficients between the SST and the number of *real ice days*, referring to the number days of actual sea ice occurrence. After the ice season, from April towards July, the correlation decreased (from –0.6 to –0.2). Opposite pattern occurred before each ice season where correlation increased from September towards December (from –0.1 to –0.4). In the dataset of 85 years, the correlation threshold for statistical significance was 0.2 in absolute value. The average ice season in the area is from mid-January to beginning of April. Therefore, the thermal memory of the water surface was 2–2.5 months.

4.4 Sea ice influence on the seasonality of hydrography, freshwater budget and heat content

The same long-term dataset was used to examine the seasonal variability of temperature, salinity and heat content in Storfjärden (Paper IV). The highest variations of the hydrographic properties occurred at the surface since they were primarily driven by the atmosphere. The monthly averaged surface temperature varied between 0.2 ˚C and 16.7 ˚C. The minimum was observed in February and maximum in August. The bottom temperature averages were from 0.6 ˚C to 8.8 ˚C, minimum in March and maximum in September, lagged by one month compared to surface due to the vertical diffusion of heat. The water column became mixed in October, just before the ice formation. After the ice break-up, the surface waters started to warm up and the water column became stratified. Greater vertical temperature gradients occurred in August.

The seasonal variability of the surface salinity had an interesting behavior. A large drop of the surface salinity occurred from December (6.1 PSU) towards March (3.6 PSU). This was probably associated with the reduced winter mixing mechanisms, which confined a freshwater layer originating from land runoff just below the ice sheet (Granskog et al. 2005). Salinity was increased after March at a constant rate of 1 PSU / month. In general, long-term averages of the salinity values varied between 3.6 PSU and 6.2 PSU. The minimum was observed in March and maximum in October due to vertical convection and mixing in the water column. In order to assess the sea ice influence on the large salinity drop from December to May, years of extreme ice coverage (real ice days > 120) and ice free years were examined more closely. The drop was largely connected to the ice occurrence and it was almost undetected during ice free years.

The seasonal variability of the water body temperature and salinity, the minimum air temperature, the average precipitation, and the monthly maximum ice thickness were examined (Fig 7). The water temperature was almost one month lagged compared to the atmosphere in the late ice season. The increasing trend of precipitation towards the summer coincided with increase in the surface salinity. Therefore this increase was connected to the wind impact and advection from the GoF. The sea ice thickness reached maximum values in March and ice was disappeared completely by May.

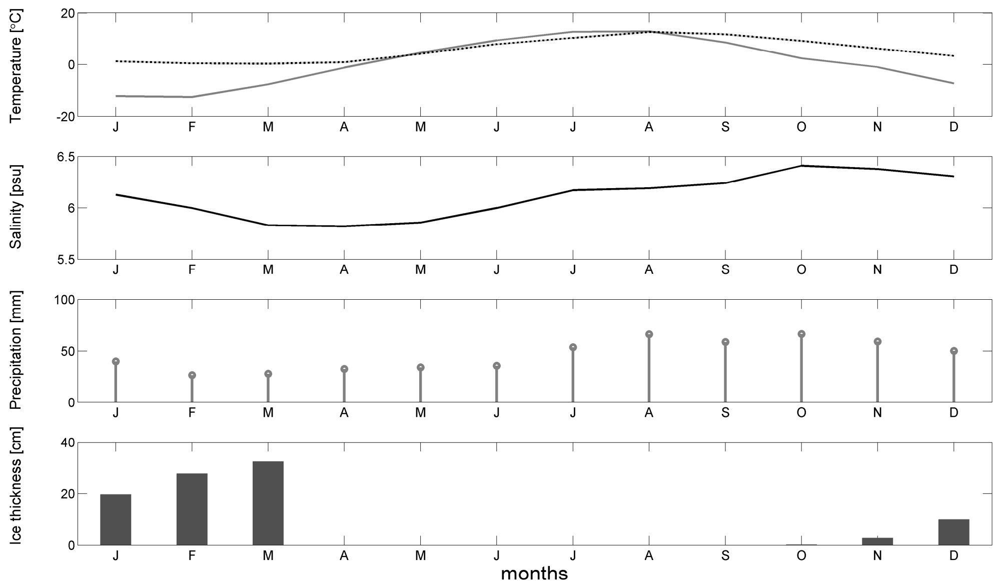


Figure 7. Seasonal variation of the vertically averaged water temperature (dashed line), air temperature minimum (grey line), surface salinity, precipitation, and maximum ice thickness in Tvärminne (1926–2011). Water temperature and salinity data are from Tvärminne Storfjärden. Air temperature is from Tvärminne weather station. Precipitation data is from Hanko and Tvärminne weather stations. Ice thickness is modeled with thermodynamic growth model.

In addition, the annual course of the heat content was examined based on temperature differences of the water body. Sea ice formation and break-up were taken into account (Fig 8). From September until February the water was losing heat mainly to the atmosphere. From March onwards, the heat budget turned positive to balance the winter loss. The heat fluxes caused by the ice formation and break up did not affect the annual level of heat content since they vanished in annual averages. However, the contribution of the ice break-up to the heat budgets (~ 40 W m^{-2}) was important in the spring months, because it occurred in a short period of time.

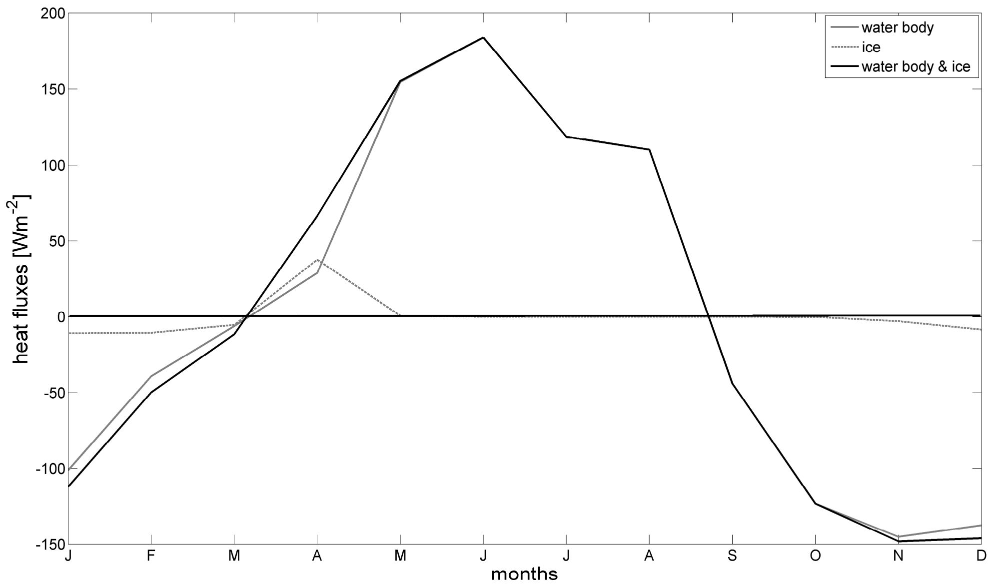


Figure 8. Monthly averaged heat fluxes from water temperature changes and sea ice formation and break-up in Tvärminne Storfjärden (1926–2012).

Finally, the annual cycle of the freshwater budget was examined based on the monthly salinity changes of the water body (Fig. 9). The freshwater budget was positive during the ice season and it turned negative after the ice break-up. The following hypothesis was used in order to explain this behavior. In the wintertime, when the surface was ice covered, the wind did not mix the water body. Land runoff entered Storfjärden via the Pojo Bay, where it formed a significant freshwater layer which was kept under the ice throughout the wintertime. In addition, there was weak circulation under the ice and consequently limited water exchange between the coast and the central GoF. After the ice break-up conditions became more dynamic and mechanisms such as vertical mixing and horizontal advection increased the salinity of the water body. This hypothesis requires further research, i.e. current system and river runoff, in order to be additionally supported.

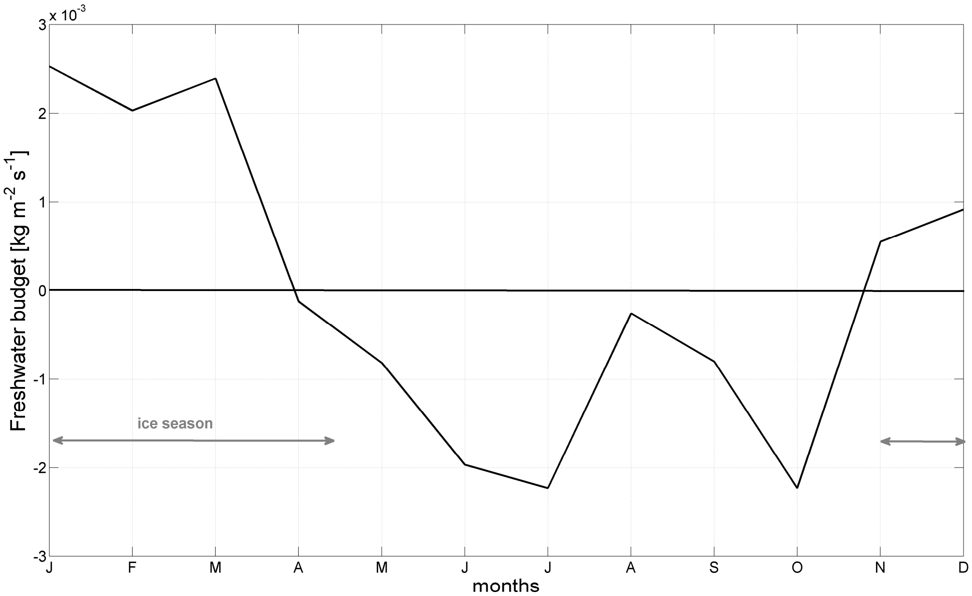


Figure 9. Monthly averaged freshwater budget in Tvärminne Storfjärden (1926–2012). Grey line indicates the maximum seasonal ice length.

4.5 Sea ice influence on estuarine water properties

The seasonal variations of physical, chemical and optical properties were examined along two cross-sections at River Kymijoki estuaries in four years 2010–2013 (Paper V). In all the observed winters, Kymijoki estuaries were ice-covered. Water temperature varied from 0 ˚C under ice, up to 25 ˚C at the surface in August. The water column became thermally stratified after the ice break-up in April, and the strongest thermocline occurred in August at 10 m depth. Water salinity decreased closer to the river mouth, where it reached the lowest values, almost zero. In the wintertime, salinity was lower by 1–1.5 PSU on average, especially just below the ice sheet. The halocline was much stronger in the winter, located at 5 m depth.

The pH values were between 7 and 8 and minimum occurred in the winter just below the ice sheet. The dissolved oxygen values varied between 6 mg l^{-1} and 11.5 mg l^{-1}. In the summertime oxygen records were lower compared to the ones under the ice. The lowest oxygen value (2.1 mg l^{-1}) was recorded in the bottom of a small bay where one of River Kymijoki branches falls. This was probably due to limited water exchange in combination with strong stratification of the water column. Finally, the photosynthetically active radiation (PAR) decreased exponentially down to 2m and got almost zero values below 10 m depth.

Under-ice plume formation due to the high buoyancy of the freshwater and the limited wind mixing was observed also here (Granskog et al. 2005, Paper IV). This is a very important feature of the GoF coastal waters with implications in both the physics and the ecology of the water column in the wintertime. Under-ice plumes can also have a positive feedback in the ice season length, due to the higher freezing point of the fresher water. In addition, melting process may slow down due to the limited oceanic heat flux (Granskog et al. 2005).

There has been very limited research on the coastal hydrography of estuarine systems which belong to the seasonal sea ice zone (Alasaarela and Myllymaa 1978, Ingram 1981, Ingram and Larouche 1987). This work is ongoing and the future plans include: (i) additional winter data from River Kymijoki estuaries and (ii) comparison to more coastal regions of the Baltic Sea. In this direction, a joint project in collaboration with the University of Stockholm at Himmerfjärden, Swedish coast of the Western Gotland Basin, started in winter 2014.

5. Summary and conclusions

We live in an era where climate is undergoing natural and anthropogenic changes. Global warming is not anymore just a hypothesis but a scientific fact. Therefore, it becomes crucial to investigate the environmental response under ongoing climatic changes. In the last decades, attention on climatic change scenarios has been increasing (Carter et al. 2004, Jylhä et al. 2004). The SSIZs are key areas regarding the impacts of climate change, since the annual ice extent is strongly sensitive to small changes in the winter atmospheric temperatures (Haapala and Leppäranta 1996, Meier et al. 2004a, Stigerbrandt and Gustaffson 2003, Omstedt and Chen 2001). Studies based on mathematical modeling have shown that the Baltic Sea would become completely ice covered or ice free at mean winter air temperatures of –6 and 2 ˚C respectively (Omstedt and Hansson 2006).

There has been extensive research on the sea ice physics and the driving forces that cause the sea ice formation and break-up (Haapala and Alenius 1994, Haapala and Leppäranta 1996, Jaagus and Kull 2011). However, it is important to investigate what is the impact of the sea ice on the physics of the water body. This helps to evaluate the consequences of different climate change scenarios. Physical and chemical water properties have been examined in different locations and seasons in the GoF. The purpose was to study the inter-annual and seasonal variation of the GoF properties and to evaluate the role of the seasonal sea ice in the annual course of the GoF. Three areas from the Finnish coast were chosen, two located in the archipelago, at the western end of the GoF, and one at the River

Kymijoki estuaries, eastern side of the GoF, to embody the estuarine conditions. This work is based on calculations, which were standing mainly on observations.

At first, heat exchanges between the water surface and the atmosphere were examined. Sea ice acts as an insulator between the ocean and the atmosphere and it controls the thermodynamics. The thermodynamic processes, which were analyzed for Santala Bay, are the main driving force of the water temperature and the sea ice in the Baltic Sea. The seasonal growth and melting of the sea ice is mainly controlled by the terrestrial radiation. It is important to know the net annual heat flux because it gives information on the horizontal advective processes. The negative net annual heat budget, being also the case of Santala Bay, tells that heat was compensated by advection from the central GoF. The annual averages of the heat components were within the limits of past model and observation studies in the Baltic Sea (Omstedt and Rutgersson 2000, Meier and Döscher 2002, Niros et al. 2002, Döscher and Meier 2004). For the first time in this study the latent heat fluxes from ice growth and melting were compared to the net surface heat flux. The patterns were similar and the differences could be attributed to the oceanic heat flux and to the solar penetration through the ice sheet, especially towards the end of the ice season. This comparison can also act as a measure of method inaccuracies.

Next step was to examine the hydrographic features and the circulation under the ice. In coastal bays, such as Santala Bay, where the conditions are less dynamic, salinity acted as a good indicator of ice formation and break up. When the ice was growing salinity increased just below the ice sheet due to brine rejection. Later in the melting season, surface salinity dropped due to the sea ice meting and the land runoff. The box model based on the freshwater exchange and the salinity evolution showed the horizontal inflows and outflows from the GoF and confirmed advection phenomena which were already observed in the heat budget analysis. In addition to this, a clear weakening of the current speed, by approximately 1 cm s^{-1}, was observed under the ice. Spectral analysis was performed in the current components. This has been done before only in open water conditions and focusing mostly in short-term current variability (Mälkki 1975, Alenius and Mälkki 1978). Our results agreed that the current energy was evenly distributed over different frequency ranges in the coastal zone. The spectral peaks corresponded to tides and seiches.

Long-term analysis of physical properties in Tvärminne helped to understand the trends and examine the annual cycles. The long-term variation of water temperature is a proper indicator of climatic variability (Haapala and Alenius 1994), whereas the long-term salinity variation gives information on the water exchange mechanisms (Falkenmark and Mikulski 1975). Surface water temperature was increased by 1 ˚C in the last 85 years in Storfjärden. This result agreed with related studies in the Baltic Sea which showed increased trends in both air temperature and SST (Fonselius and Valderrama 2003, Rönkkönen et al. 2004, Siegel et al. 2006). An increase of the SST by 0.5–0.8 ˚C was estimated in the last 15–40 years in the Baltic Sea (Soomere et al. 2008). Also by analyzing the correlation between the SST and the real ice days, the thermal memory of the surface was estimated to be 2–2.5 months.

The surface water salinity increased by 0.5 PSU in the same period and the trend was considered statistically significant. The impact of climatic changes in the salinity and the consequent stratification of Baltic Sea has been a critical question. Related studies have shown high inter-annual salinity variations, up to 1 PSU, but no significant trend (e.g. Winsor et al. 2001). Other authors have observed that water temperature and salinity are positively correlated in the Baltic Sea with an increase of 1–2 PSU in the Gotland Sea during the 20th century (Matthäus and Lass 1995). Sea ice influences the surface salinity in a seasonal basis but the impact vanishes in annual averages. The observed positive trends in Tvärminne can only be associated with decreased freshwater supply or increased inflow events of warm and saline water from the Danish Straits. Our results were similar to the Gotland Sea and the Sea of Bothnia long-term analysis of Fonselius and Valderrama (2003).

An interesting pattern was observed in the annual cycle of the salinity in Tvärminne Storfjärden. The monthly averaged vertical distribution showed that mainly the surface layer was affected, changing up to 2.6 PSU during one year. However, an unusually big drop of the surface salinity occurred during the ice season. This decrease was prominent only in ice covered years and almost undetected in ice-free years. This pattern could be associated with the limited wind mixing under the ice, which resulted in a trapped freshwater layer originating from the land runoff. In the spring, river runoff gets maximum values in the GoF (Mikulski 1970). However, the water body salinity increased after the ice break-up. This was probably due to the increased wind mixing, vertical convection and advection of more saline waters from the central GoF.

Sea ice observations initiated more than a century ago in the Baltic Sea. The main reason was that sea ice has always had large economic consequences due to its major impact on the marine transportation and the foreign trade (Askne et al. 1992, Seinä 1994, Alenius et al. 2003, Leppäranta and Myrberg 2009). Ice phenology and thickness data from both observations and modeling were used here to examine the trends. During the last century, the ice season length has massively decreased, by 30 days, in the Finnish archipelago. This was in agreement with the results of related studies (Alenius et al. 2003, Leppäranta and Seinä 1985, Jevrejeva and Leppäranta 2002, Jevrejeva et al. 2004). Ice thickness data from Jussarö in the last 40 years showed average decrease of about 8 cm. This result was also supported by related studies (Soomere et al. 2008).

Finally, the seasonal variability of chemical properties, such as dissolved oxygen and pH, was examined in River Kymijoki. In normal winters the estuaries are completely ice-covered and the water temperature is close to zero centigrade. Also, under the landfast ice the water body is not affected by precipitation or wind. Thermal stratification started after the ice break-up in April. In the summer when the water body was stratified, oxygen values decreased by almost 6 mg l^{-1} compared to the winter averages. This decrease was partly associated with the water temperature. In the summer, when temperature is warmer, the concentration of saturation is much lower. pH got minimum values in the winter just below the ice cover, most likely due to the low salinity values. The PAR values decreased rapidly down to 2 m depth.

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