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Short-term variations of thermohaline structure in the Gulf of Finland

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Abstract

We present and analyze high-frequency observational data of thermohaline structure and currents acquired in the Gulf of Finland (Baltic Sea) using an autonomous buoy profiler and a bottom mounted acoustic Doppler current profiler in July–August 2009.

Vertical profiles of temperature and salinity were measured in the upper 50-m layer with a time resolution of 3 h and vertical profiles of current velocity and direction were recorded with a time resolution of 10 min. Although high temporal variations of the vertical temperature and salinity distributions were revealed, it was possible to define several periods with quasi-stationary vertical thermohaline structure. These quasi-stationary stratification patterns lasted from 4 to 15 days and were dominated by certain hydrophysical processes – upwelling, relaxation of the upwelling, wind induced reversal of the estuarine circulation, estuarine circulation, and downwelling. Vertical profiles of current velocities supported the concept of synoptic-scale quasi-stationary periods of hydrophysical fields. The periods with distinct layered flow structures and current oscillations with the prevailing period of 26 h were revealed. A simple model, where the heat flux through the sea surface, wind mixing, wind induced transport (parallel to the horizontal salinity gradient) in the upper layer and estuarine circulation were taken into account, simulated the observed changes in the vertical stratification reasonably well. The largest discrepancies between the observations and model results were found when water movement across the Gulf and associated vertical displacement of isopycnals (upwelling or downwelling) were dominant processes.

1 Introduction

The vertical stratification of the water column in the oceans and seas is a key factor shaping the distribution and transport of substances. The Gulf of Finland, a 400-km long and 48–135-km wide sub-basin of the Baltic Sea, is dominated by the fresh water discharge at the eastern end and free water exchange with the Baltic Proper through

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circulation, characterized by an inflow in the deeper layers and an outflow in the surface layer, is depending on the prevailing winds as well (Elken et al., 2003; Liblik and Lips, 2011). Thus, the wind induced changes in the vertical thermohaline structure are visible throughout the entire water column.

5 Simpson et al. (1990) have introduced a model to describe the vertical stratification in a tidal estuary by adapting the energy considerations used in the surface heating problem to describe the competition between the stabilizing effect of fresh water and the vertical mixing by tidal and wind stirring. A simulation of the monthly cycle based on this model including straining, stirring, and the estuarine circulation was in qualitative
10 agreement with the main features of the observations in the Liverpool Bay. Although the tidal stirring is not an issue in the Gulf of Finland, predicting the development of stratification is even more difficult problem since the stratification at a certain point is depending very much also on the across Gulf movements of water masses. The latter leads often to pronounced upwelling or downwelling events along the coasts (Lips et al.,
15 2009) while in some cases in up to 38 % of the surface area of the Gulf of Finland the surface waters are replaced by the upwelled waters (Uiboupin and Laanemets, 2009).

The simulations of the vertical stratification using 3-D numerical models are not so reliable yet (Myrberg et al., 2010). However, a number of studies have reported the importance of the vertical thermohaline structure to the ecosystem components of the
20 Gulf of Finland, such as phytoplankton species composition (Rantajärvi et al., 1998) and sub-surface maxima of phytoplankton biomass (Lips et al., 2010), cyanobacteria blooms (Lips and Lips, 2008), distribution of pelagic fish (Stepputtis et al., 2011), macrozoobenthos abundance (Laine et al., 2007) or oxygen concentrations in the near bottom layer (Maximov, 2006). Thermohaline structure and related processes in the
25 Gulf of Finland have been mainly studied using classical observations aboard research vessels. The remote sensing methods and Ferrybox systems do not reveal the vertical structure of water column. Because of the narrow width and high marine traffic intensity widespread technologies for water column profiling (like ARGO floats) have not been applied here. An autonomous profiling buoy station was first used in the Gulf of Finland

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were collected by acoustic Doppler current profiler (ADCP, Teledyne RD Instruments). The ADCP was mounted close to the buoy profiler and was set to separate 36 vertical bins by 2 m step. The shallowest bin was at the depth range of 9–11 m and the deepest bin at the depth range of 79–81.

5 Wind data from June to August were obtained from the Kalbådgrund meteorological station (Finnish Meteorological Institute) located in the central part of the Gulf and other hydrometeorological data (cloudiness, partial pressure of water vapor, relative humidity, air temperature, solar irradiation) at Harku meteorological station in Estonia (Estonian Meteorological and Hydrological Institute).

10 Information on the data sets used in the present paper is summarized in Table 1.

2.2 Definitions

In order to characterize the vertical thermohaline structure measured by the buoy profiler in the upper 50-m layer, the following parameters were defined and estimated: upper mixed layer depth (UML depth), the base of the thermocline (BT), the thickness of the thermocline and the depth of the strongest density gradient. The UML depth was defined as the minimum depth, where the criterion $\rho_z \geq \rho_4 + 0.25 \text{ kg m}^{-3}$ was satisfied (ρ_z is the density at the depth z and ρ_4 is the density at the 4 m depth). The base of the thermocline was defined as the maximum depth, where the temperature was $\geq 5^\circ\text{C}$.

20 The thermocline thickness was defined as the difference between the BT and UML depth and the depth of the strongest density gradient was defined as the depth where the greatest density increase between the consecutive horizons, calculated over the 0.5 m depth step, was observed.

The periods characterizing dominance of a few distinct processes were selected qualitatively on the basis of the observed variations in the vertical temperature and salinity distributions (Fig. 2) and TS-diagrams (Fig. 3). The mean values of parameters for a certain period were estimated as arithmetic averages over all profiles within the period while the wind characteristics presented in Sect. 3.1 were calculated with advanced time lag of 15 h (Elken et al., 2003). A number of criteria and parameters, such

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as the UML depth, BT depth and depth of a certain isohaline were tested to define the limits of the periods with specific quasi-stationary stratification patterns described in Sect. 3.1. Finally, the similarity of TS-curves was chosen as a qualitative criterion for separating the periods. Although, depending on the chosen criterion, the periods and estimated mean parameters in each period varied slightly, it does not affect the basic idea of the study – to show that it is possible to detect a number of quasi-stationary stratification patterns in the Gulf of Finland. However, some time slots between the detected periods were not assigned to any of them to keep the similarity of TS-curves within each period. A shift between the periods is discussed separately in Sect. 3.1.3.

Vertical stratification was described by the potential energy anomaly P (Simpson and Bowers, 1981; Simpson et al., 1990) calculated as:

$$P = \frac{1}{h} \int_{-h}^0 (\rho_A - \rho) g z dz, \quad \rho_A = \frac{1}{h} \int_{-h}^0 \rho dz; \quad (1)$$

where $\rho(z)$ is the density profile over the water column of depth h . The stratification parameter P (J m^{-3}) is the work required to bring about complete mixing of the water column under consideration. The stratification parameter in the estuaries has been estimated usually over the entire water column. In the present study, the integration was conducted until the depth of 40 m. This choice was defined by the aim to study the changes in the stratification pattern at the depths of the seasonal thermocline. The water column, characterized by the three-layer structure in the Gulf of Finland in summer (see e.g., Alenius et al., 1998), was divided into two. The calculations were restricted to the upper 40 m, that is close to the long-term mean depth of the cold intermediate layer (coldest point at the vertical temperature profile) of 42 m (Liblik and Lips, 2011).

2.3 Model setup

The time development of P was modeled in the present study as the sum of the following four terms:

$$\frac{dP}{dt} = S_b + S_m + S_a + S_e, \quad (2)$$

5 where the first term on the right S_b is the increase or decrease of stratification due to the upper layer heating or cooling, respectively. The second term S_m is the decrease of stratification due to wind mixing and the third term S_a is the parameter, which describes the decrease or increase of stratification due to the wind induced transport in the surface layer. The last term on the right S_e is the parameter describing the mean
10 estuarine flow that always increases the stratification.

The first two terms on the right S_b and S_m were calculated as suggested by Simpson et al. (1990):

$$S_b = \frac{\alpha g Q_{TOT}}{2c_p} \quad (3)$$

$$15 S_m = -\delta k_s \rho_a \frac{W^3}{h} \quad (4)$$

These terms are dependent on the surface heating/cooling rate Q_{TOT} (see below) and wind speed W , respectively. In the calculations, the depth $h = 40$ m was considered and the following constants were used: thermal expansion coefficient $\alpha = 1.5 \times 10^{-4}$, specific heat of seawater $c_p = 4000 \text{ J (kg C)}^{-1}$, air density $\rho_a = 1.3 \text{ kg m}^{-3}$, effective
20 drag coefficient $k_s = 10^{-3}$ and efficiency of mixing $\delta = 10^{-3}$.

The third term S_a was calculated using the equation given by Oey et al. (1987) and applied earlier by Pavelson et al. (1997) in the Gulf of Finland:

$$S_a = \frac{g \rho_y \tau^x h}{2f \rho_0}, \quad (5)$$

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where ρ_0 is the reference density of seawater – 1003 kg m^{-3} and f is the Coriolis parameter. S_a depends on wind stress τ_x , which can increase the seaward flow in the surface layer and, thus, stratification or vice-versa. The following assumptions and choices of parameters were made: the most appropriate wind direction for seaward flow intensification was 25° (see Elken et al., 2003; Lips et al., 2008), the along-gulf horizontal density gradient was $\rho_y = 5 \times 10^{-6} \text{ kg m}^{-4}$ (Alenius et al., 1998) and the upper mixed layer depth h was 15 m (Liblik and Lips, 2011).

The fourth term S_e was considered as a constant over the study period – $5.5 \times 10^{-5} \text{ J m}^{-3}$. It corresponds to a permanent outflow at the rate of 2 cm s^{-1} in the upper 15-m layer.

Without taking into account the advective heat fluxes, we can represent the total heat flux as it follows:

$$Q_{\text{TOT}} = Q_{\text{SW}} + Q_{\text{LW}} + Q_{\text{S}} + Q_{\text{L}}, \quad (6)$$

where Q_{SW} is the short wave radiation, Q_{LW} is the net long-wave radiation, Q_{S} is the sensible heat flux and Q_{L} is the latent heat flux.

Short-wave radiation was roughly considered as 90 % (constant sea surface *Albedo* of 10 % was assumed) of measured solar irradiation at Harku meteorostation.

The outgoing long-wave radiation is calculated by Stefan Boltzmann law and incoming long-wave radiation as Omstedt (1990) whereby following input data were used: air temperature, sea surface temperature, cloudiness and partial pressure of water vapor.

Sensible heat flux was calculated by bulk formula:

$$Q_{\text{S}} = \rho_a c_{\text{pa}} c_{\text{aw}}^{\text{S}} W (T_a - T_w), \quad (7)$$

c_{pa} is the specific heat of air ($\text{J kg}^{-1} \text{ K}^{-1}$), c_{aw}^{S} is the Stanton number, T_a is the air temperature and T_w is the sea surface temperature. Stanton numbers for stable ($T_a > T_w$) and unstable ($T_a < T_w$) atmospheric boundary layer are 0.66 and 1.13, respectively (Large and Pond, 1982).

estimates with the average monthly values of the UML depth in 1987–2008, 12.1 m in July and 14.9 m in August, the UML was shallower in July and deeper in August than the long-term mean. Similar tendencies were revealed in the mean BT depths: it was slightly shallower in July (25.1 m) and deeper in August (34.9 m) than the mean values in 1987–2008 (respectively 26.5 and 31.6 m). Nevertheless, the thicknesses of thermo-

cline in both months (14.8 and 17.5 m) were similar to the long-term mean values (14.4 and 16.7 m). The strongest density gradient was situated on average at 15 m depth in July and at 26 m depth in August, as the mean of the strongest gradient at profiles was in July 0.38 kg m^{-4} and in August 0.39 kg m^{-4} .

The average flow pattern of the study period was characterized with the movement to the north-east and east in the upper 60 m and to the north-west below that depth. The average current speed varied in a range of $7.3\text{--}12.6 \text{ cm s}^{-1}$, whereas it was $> 10 \text{ cm s}^{-1}$ in the upper layer, above 20 m and in the deep layer, below 62 m depth.

The observed variations in the vertical distribution of temperature, salinity and current velocity can be interpreted as a result of influence of different hydrophysical processes. A qualitative description of the processes in response to the atmospheric forcing was presented by Lips et al. (2011) and can be summarized as the following. South-easterly winds, which are favourable for upwelling near the southern coast, caused an upwelling event near the southern coast on 7–13 July, and the upwelling waters reached the buoy station on 10 July resulting in a temporal temperature decrease and salinity increase measured by the profiler on 10–12 July (Fig. 2). Mainly westerly-south-westerly winds prevailed in the area from 15 July until the end of July and caused the deepening of the thermocline and south-eastward flow in the 20 m upper layer and north-westward flow below the thermocline. The appearance of more saline water in the UML on 26 July was related to this flow structure.

A period of weak winds was observed during the first 10 days of August. The flow structure was characterized by a northward (north-westward) flow in the surface layer, and an eastward flow below the thermocline. The temperature increase in the surface

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layer and the strengthening of stratification occurred in response to the calm weather. Strong wind pulses, observed from 10 August until the end of the measurement period, caused, first, strong current oscillations in the whole water mass and later, when westerly and north-westerly winds prevailed, an intense downwelling event, which was detected at our measurement site as the sharp deepening of the UML from 17 to 19 August.

Considering this qualitative description of the dynamics of the thermohaline structure, the five periods were selected within the whole study period (see Fig. 2 and Table 2), which could be related to the following dominant processes: 1 – upwelling, 2 – relaxation of the upwelling, 3 – wind induced reversal of the estuarine circulation, 4 – estuarine circulation, and 5 – downwelling.

3.1.2 Characterization of the selected periods

Upwelling. In the first period, the thermohaline structure was affected by upwelling, resulting in a thin, cold and saltier UML and shallow base of the thermocline (BT; see Table 2). The mean UML and BT depths, and the thickness of the thermocline were 8.4 m, 14.3 m and 5.9 m, respectively. In the temperature and salinity scatter plots for the first selected period (Fig. 3a), three groups with characteristic TS-distribution were visible (TS-dots were grouped into three clouds). These groups can be regarded as the three phases in the development of the upwelling event or movement of upwelling waters into the study area. The TS-curves indicate a slightly larger salinity increase (at a fixed temperature) at the thermocline depths than that in the upper layer. Due to the upwelling event, the sea surface temperature dropped during the period (Fig. 4), although the period's average heat flux into the sea was positive (131 W m^{-2}). The mean temperature in the surface layer was the lowest and consequently the temperature gradient through the water column (difference at 3 and 40 m) was the smallest (9.9°C) out of the five periods, but the density difference was still 3.0 kg m^{-3} . The latter was due to the high salinity at 40 m depth, which resulted in a very strong salinity gradient through

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the thermocline. The strongest density gradients of the each profile were situated at relatively shallow depths, the mean was only 10.7 m in the first period.

Upwelling relaxation. In the second period, the meteorological conditions were characterized by a clearly positive heat flux (109 W m^{-2}) and relatively strong winds from south-west, though occasional strong wind pulses from south-east occurred as well. The south-westerly winds caused relaxation of the upwelling and thereafter BT depth shortly began to decline while UML depth even became slightly thinner through the period. The UML depth varied in a range of 6.5–16 m and BT in a range of 22.5–35 m while the mean values were estimated at 11.0 m and 29.4 m, respectively, and the mean thickness of the thermocline was 18.4 m.

The sea surface temperature, varying in the ranges $14.7\text{--}16.8^\circ\text{C}$, was clearly higher than that in the first period and salinity, varying in the ranges 4.6–4.8, was close to those values in the first period. Since the temperature gradient through the water column (12.5°C ; difference at 3 and 40 m) was stronger and the salinity gradient (2.2) weaker than in the first period, the density gradient (3.0 kg m^{-3}) was similar to the upwelling period. The second period's TS-diagrams (Fig. 3a and b) show, that ordinary summer stratification was re-established in the area. TS-curves were mostly straight lines in this period, which could indicate that the relaxation of the upwelling contributes well to the vertical mixing of the Gulf of Finland waters (Lips et al., 2009).

Reversed circulation. Moderate and strong winds mostly from south and west prevailed in the third period. The mean E-W wind component was 5.6 m s^{-1} , N-S component 1.9 m s^{-1} and the mean speed 6.7 m s^{-1} . The latter is in accordance with the observed flow pattern (Fig. 2): eastward flow occurred in the upper layer and a strong outflow from the Gulf in the deep layer (Fig. 2). The mean heat flux into the sea was 91 W m^{-2} that led to the corresponding surface layer temperature increase during the period. The surface layer temperature and salinity varied from 16.7 to 17.7 and from 4.9 to 5.2, respectively. The mean salinity gradient through the water column had dropped to 1.6, a slightly stronger temperature gradient (12.8°C) was detected and the mean density gradient (2.6 kg m^{-3}) had decreased. The UML and BT depth varied in ranges

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15–19.5 and 34–39.5 m and were on average 18.4 and 36 m, respectively. As the BT situated deeper than typically, the mean thickness of the thermocline was as high as 17.6 m.

It is seen in the TS-diagrams and mean vertical profiles (Fig. 3b and c) that the upper layer salinity has increased remarkably while the salinity at the thermocline depths has decreased if comparing to the earlier period. These changes are in accordance with the eastward flow in the upper layer and westward flow in the thermocline and below it (Fig. 2). This flow pattern, known as the reversal of the estuarine circulation (Elken et al., 2003; Lips et al., 2008), caused also most probably the observed deepening of the base of the thermocline (Figs. 2 and 3b).

Estuarine circulation. The fourth period was characterized by weak winds from north and north-east. On average, the E-W wind component was 1.5 m s^{-1} , N-S wind component was 0.6 m s^{-1} and the mean wind speed (4.8 m s^{-1}) was lowest of the five periods. The mean heat flux was 48 W m^{-2} and the highest daily heat fluxes up to 128 W m^{-2} were found in this period. The currents were directed most of the time out from the Gulf in the upper layer and into the Gulf in the deeper layer (Fig. 2).

Relatively calm wind conditions and positive heat flux resulted in a thin upper mixed layer. Though the salinity varied around the study periods overall mean (4.5–5.0), the sea surface temperature was clearly the highest of five periods varying from 17.4 to 19.9. The UML depth was as low as 7.5–10 m during the most of the period. The BT depth was close to 40 m during the first days of the period, but gradually moved to the shallower position up to 25 m depth. As a result, the thermocline, which was thicker than 20 m in the beginning, became thinner than 10 m at some point during the period. Since the temperature gradient (14.7°C) through the water column was clearly the largest of five periods due to the warm surface layer, the density gradient (3.2 kg m^{-3}) was the strongest as well.

The changes seen in the TS-diagram (Fig. 3c and d) can be explained by the influence of estuarine circulation – westward flow in the upper layer and eastward flow below the thermocline, and surface warming. The characteristic TS-curve was close to

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the straight line due the increase of salinity at the thermocline depths and formation of a fresher and warmer near surface layer due to the calm conditions.

Downwelling. Wind regime in the final period was characterized by strong wind pulses blowing mainly from the west and with the mean wind speed of 6.5 m s^{-1} . The daily mean heat fluxes varied around the zero, but on average the heat flux was slightly negative (-19 W m^{-2}). The strong winds from the west caused downwelling near the Estonian coast and as a result, the mean UML and BT were deepest of five periods: 25.8 and 38.7 m, respectively. The depth of the maximum density gradient was located on average at 30.1 m depth. Due to changes in wind forcing, strong oscillations with amplitude $> 30 \text{ cm s}^{-1}$ occurred in the entire water column. The study period's maximum current speed of 48 cm s^{-1} was measured in the beginning of this period.

Since the isopycnals were forced deeper by downwelling, the mean salinity gradient through the water column and, therefore, density gradient as well, were lowest of five periods – 1.0 and 2.2 kg m^{-3} , respectively. The fifth period characteristic TS-curve (Fig. 3d) is strongly influenced by the occurred downwelling event. Due to the eastward transport in the upper layer and vertical mixing (TS-curve is nearly a straight line from surface to 40 m), the upper layer salinity is relatively high and salinity gradient through the thermocline is relatively weak.

3.1.3 Shift from reversed to estuarine circulation

The stratification pattern during the third period was influenced by the dominating flow in the upper layer to the east and in the thermocline to the west resulting in a characteristic TS- curve (Fig. 3b) with slightly fresher waters in the thermocline beneath the saltier water mass in the upper layer. The water column in the fourth period had a clearly different characteristic TS-curve, which was almost a straight line in the TS-plot. The shift from the third to fourth period could be defined differently based on TS-characteristics and flow structure. As seen in the TS-plot (Fig. 3c), a saltier water masses appeared in the upper part of the thermocline (depth range 20–25 m; marked as “transition period” in Fig. 3c) and a slightly fresher water mass in the deeper part

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(30–35 m) of the thermocline. These changes were well in accordance with the vertical distribution of current vectors: an eastward flow dominated in the upper part and a westward flow in the lower part of the thermocline. The strongest eastward current was observed exactly between the same depth range (20–25 m), where the mentioned saltier water mass appeared.

The flow structure (Fig. 5) during the transition period was very variable in the upper 60-m layer, but the strong current was almost permanently directed to the north-west in the deep layer (below 60 m depth), similarly to that during the third period of reversed circulation. The flow in the upper layer was affected by anticyclonic oscillations, which caused variations of the current speed from 0 to 15 cm s^{-1} . The flow in the thermocline depths was stronger and more stable in the upper part of the thermocline (upper 25 m), but weak and variable in the deeper part of the thermocline (25–40 m). The period of observed oscillations coincided well with the most pronounced spectral peak in the whole study period – 26 h. A fast transition of the flow structure occurred on 31 July–1 August – the layered flow was replaced with an eastward current, synchronously oscillating in the entire upper 60 m layer and the westward flow ceased in the deep layer. Further on, a typical estuarine circulation scheme was established gradually with a westward flow in the upper layer and eastward in the deeper layers (see Fig. 2). As a result, the TS-curve was straightened (Fig. 3c), although a saltier water mass was appearing occasionally in the thermocline until 2 August.

3.2 Comparison between observed and modeled upper layer dynamics

In the present subchapter, we present a comparison between the measured and modeled changes in the stratification and upper layer temperature. Calculation techniques were described in the methods Sect. 2.2–2.3. For the temperature estimates, the upper layer was assumed to be 18 m thick. This choice was based on the best agreement between the observed and modeled temperature changes, and the chosen value was close to the observed mean UML depth in August (17.4 m).

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the measurements the secondary thermocline was established. But mostly, the stratification decrease caused by the downwelling was not reproduced by the model since the downward and upward movements of isopycnals (and pycnoclines) due to the near shore convergence/divergence were not included into the model.

4 Discussion and conclusions

High-resolution vertical profiling has revealed remarkable variations of the vertical distribution of temperature and salinity in the Gulf of Finland in July–August 2009. Based on the known synoptic scale variability in the atmospheric forcing, we assumed that the variations in the vertical thermohaline structure could also reveal the variability characterized with some quasi-stationary stratification patterns occurring for the time periods with the same length of several days. Five periods with characteristic vertical temperature and salinity distributions (and TS-curves) were selected and mean parameters of thermohaline structure in each period were estimated. While the mean temperature and salinity in the upper layer, UML and BT depths for the entire study period differed only slightly from the long-term mean values (estimated by Liblik and Lips (2011) on the basis of data from 1987–2008), the average parameters for a certain selected period could differ from each other and the long-term average considerably. It shows that the prevailing synoptic scale forcing and related processes alter the vertical stratification significantly, which in turn could lead to the certain vertical dynamics of phytoplankton community in this stratified estuary (Lips et al., 2011).

The selected quasi-stationary stratification patterns lasted from 4 to 15 days and were dominated by distinct hydrophysical processes – upwelling, relaxation of the upwelling, reversal of the estuarine circulation, ordinary estuarine circulation, and downwelling. Some of these mentioned processes occur in mesoscale while some are related to the estuarine (basin-scale) circulation pattern, which can be reversed depending on the prevailing wind forcing (Elken et al., 2003). In case of the reversed circulation scheme, the thickness of the thermocline was increasing and the stratification

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decreasing, and a clear change of the direction of current velocity was observed in the thermocline. Although the layered flow structure was superimposed by remarkable current oscillations, this observational result supports the suggestion that the winds, which generate along-gulf flow in the upper layer, cause in turn opposite flow beneath, and changes in stratification can be modeled as proposed by Simpson et al. (1990). We note that the sub-surface biomass maxima in the vertical distribution of phytoplankton were detected during this period at the same depths in the thermocline (Lips et al., 2011) as the change in current direction. Similar links between the vertical structure of hydrophysical fields and occurrence of sub-surface maxima of phytoplankton biomass have been observed also in other regions (e.g., Velo-Suarez et al., 2010).

Temporal changes of TS-curves give indications about the circulation pattern in the Gulf of Finland bearing in mind the existing horizontal gradients of salinity (Lips et al., 2009). If a section of the TS-curve was shifted to lower (higher) salinities in comparison with that recorded at the same location and density range earlier, a movement of waters from east to west (from west to east) should have been occurred. The observed changes of TS-curves have demonstrated the sensitivity of stratification (vertical thermohaline structure) to the prevailing wind events, especially when estuarine circulation or its reversal were dominant processes. This is another approval for using wind-dependent term in the stratification model in the form of Eq. (5), where the flow in the upper layer along the Gulf (parallel to the average salinity gradient) is taken into account.

Vertical profiles of current velocities supported the concept of synoptic-scale quasi-stationary periods of hydrophysical fields. Strong in- and outflow events, with speed up to 48 cm s^{-1} from/to the Gulf both in the upper and deeper layer alternated during periods of dominance of different quasi-stationary stratification patterns. The flow structure in shorter time-scales was often affected by oscillations with most pronounced spectral peak at 26 h that is close to 27 h, which is one of the dominating oscillation periods in the Gulf of Finland suggested by Jönsson et al. (2008), and revealed also during earlier field studies, e.g. by Lilover et al. (2011).

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A comparison of the observed and calculated changes of upper layer temperature and potential energy anomaly suggests that the upper layer dynamics and vertical stratification conditions in the Gulf of Finland can be simulated reasonably well when the surface transport along the Gulf prevails. The largest mismatches between the modeled and measurement-based changes of potential energy anomaly and upper layer temperature were found during the upwelling event, when the upwelling waters reached the study site (buoy station). However, according to the Ferrybox data (Lips et al., 2011), the upwelling front extended a couple of kilometers to the north from the buoy station. Thus, it could be expected that in the central part of the Gulf, the accordance between the model and measurements would be still relatively good. Nevertheless, during major upwelling events, such as has occurred in August 2006 (Lips et al., 2009), the model would still miss the significant decrease in stratification and upper layer temperature.

Thus, we suggest that in certain cases the vertical stratification depends strongly on the water movement across the Gulf and associated vertical displacement of isopycnals. To advance the simple model presented in the present paper, an additional term should be added to the existing model (Eq. 2). This term has to account for the wind induced drift of surface waters across the Gulf and resulting convergence or divergence of waters and vertical movement of isopycnals. If the wind impulse or cumulative along-gulf wind stress is strong enough for the surfacing of the thermocline (see e.g., Haapala, 1994; Uiboupin and Laanemets, 2009), the formation and behavior of the upwelling front has to be taken into account as well. Since these processes depend on the along-gulf wind stress, it is reasonable that the largest mismatches between the model and measurements were found in case of easterly winds (see Figs. 4 and 6). A series of high-resolution CTD sections across the Gulf, such as those presented by Lips et al. (2009), are needed for the parameterization of the influence of upwelling/downwelling to the stratification depending on the along-gulf wind stress and distance of the site from the shore.

Although the movements across the Gulf seem to be the main reason of inconsistency, other sources, such as spatial variability in atmospheric forcing, irregularity of

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advective heat and salt transport or parameterization errors could also contribute to the mismatches. For instance, the meteorological data for heat flux estimates were obtained from the on-shore station and the sea surface temperature was taken from a single site (buoy station). Furthermore, we mostly described the processes at the thermocline depths knowing that in the deeper parts of the Gulf the water column has three-layer structure and the dynamics should be more complicated. However, we showed that in certain conditions the simple stratification model is able to simulate the observed changes.

In conclusion, on the basis of the high-resolution profiling of the water column in July–August 2009, the quasi-stationary stratification patterns, which lasted from 4 to 15 days and were dominated by certain hydrophysical processes – upwelling, relaxation of the upwelling, wind induced reversal of the estuarine circulation, estuarine circulation, and downwelling, were distinguished. Vertical profiles of current velocities supported the concept of synoptic-scale quasi-stationary periods of hydrophysical fields. The periods with distinct layered flow structures and current oscillations with the prevailing period of 26 h were revealed. The layered flow structures as well as sub-mesoscale intrusions of waters with different temperature and salinity along the isopycnals were principal features in the period of reversed estuarine circulation and its transformation back to the ordinary scheme. A simple model, where the heat flux through the sea surface, wind mixing, wind induced transport (parallel to the horizontal salinity gradient) in the upper layer and estuarine circulation were taken into account, simulated the observed changes in the vertical stratification reasonably well. The largest discrepancies between the observations and model results were found when water movement across the Gulf and associated vertical displacement of isopycnals (upwelling or downwelling) were dominant processes.

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Kalbådagrund and the Estonian Meteorological and Hydrological Institute for meteorological data from the coastal stations.

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Table 1. Measurement information.

Data type	Data availability		Measuring interval
	From	To	
CTD profiler	30 Jun 2009	28 Aug 2009	1 or 3 h
Current profiler	23 Jul 2009	31 Aug 2009	10 min
Wind data	1 Jun 2009	31 Aug 2009	3 h
Cloudiness	1 Jun 2009	31 Aug 2009	3 h
Other meteorological data	1 Jun 2009	31 Aug 2009	1 h

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Table 2. Mean upper mixed layer depth and the base of thermocline depth in different periods.

Period number	Period	The state and/or development of thermohaline structure	Mean UML depth (m)	Mean BT depth (m)
1	5 Jul–12 Jul	Upwelling	8.4	14.3
2	20 Jul–25 Jul	Upwelling relaxation	11.0	29.4
3	25 Jul–28 Jul	Estuarine circulation reversal	18.4	36.0
4	31 Jul–15 Aug	Estuarine circulation	11.3	31.5
5	18 Aug–29 Aug	Downwelling	25.8	38.7

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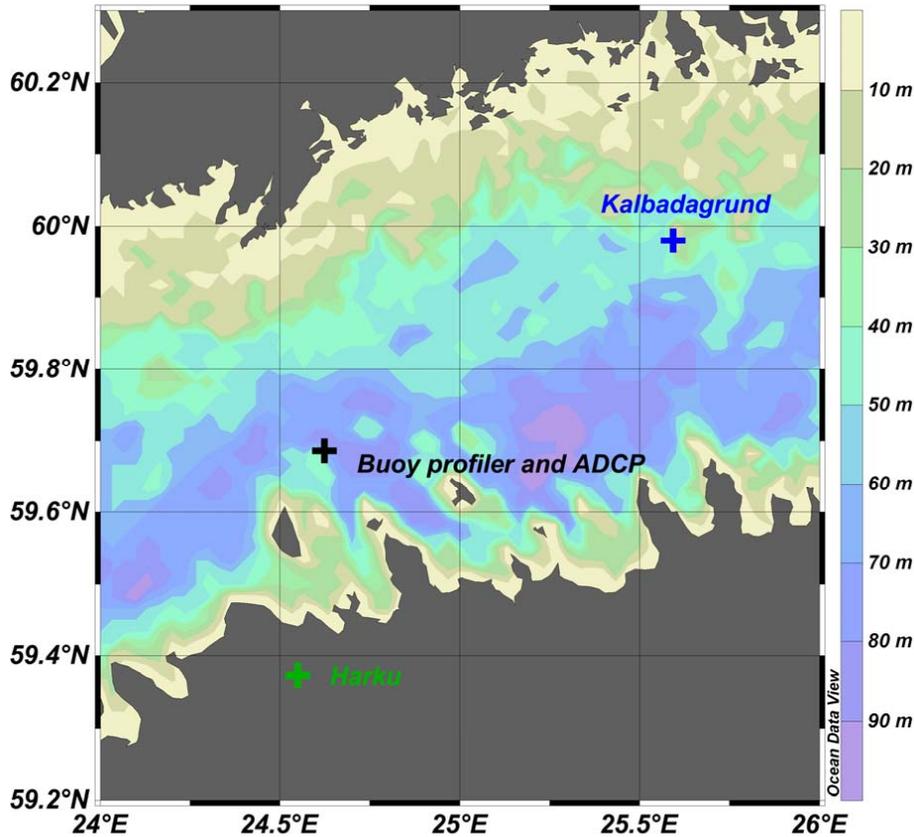


Fig. 1. Locations of the buoy profiler and ADCP mooring, Kalbådagrund and Harku meteorological stations.

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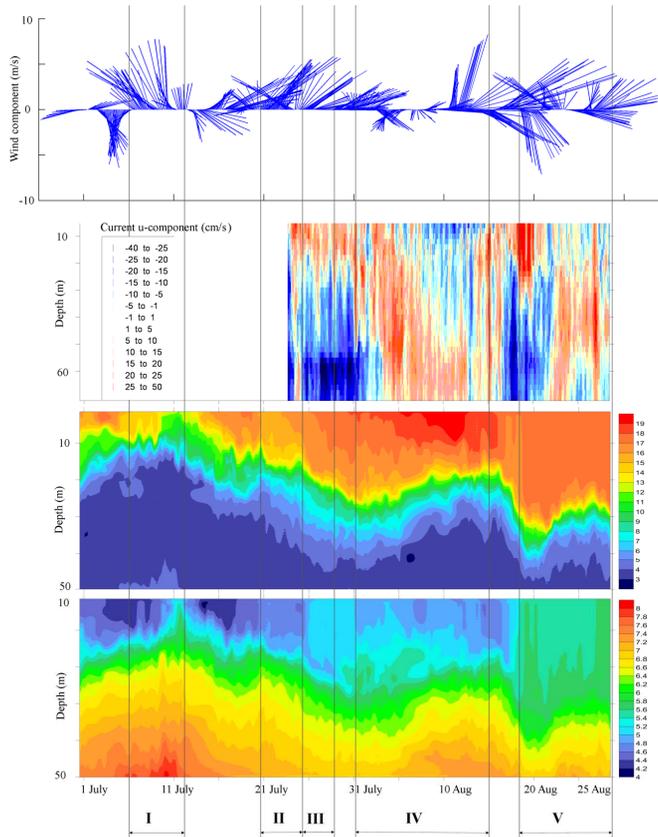


Fig. 2. Wind vectors in Kalbådagrund, E-W component of horizontal current velocity, temperature and salinity at the buoy station (see location in Fig. 1) in summer 2009.

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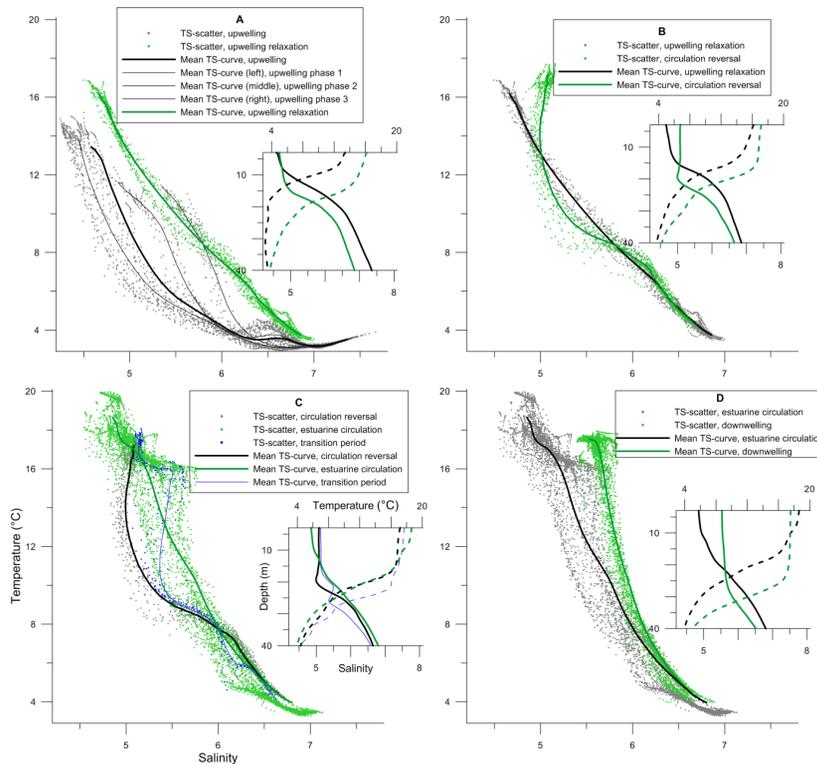


Fig. 3. TS-diagrams. Temperature and salinity scatter plots, mean TS curves and mean temperature and salinity profiles in five periods: first and second period **(A)**, second and third period **(B)**, third and fourth period **(C)** and fourth and fifth period **(D)**. In panel **(A)**, the three phases of the first period are indicated with black thin curves, in panel **(C)** transition period between third and fourth period is drawn out with blue dots and lines. Black curves and grey dots represent the earlier period and green curves and dots represent the later periods in each plot. In the panels of mean vertical profiles the solid curves represent salinity and dashed curves represent temperature.

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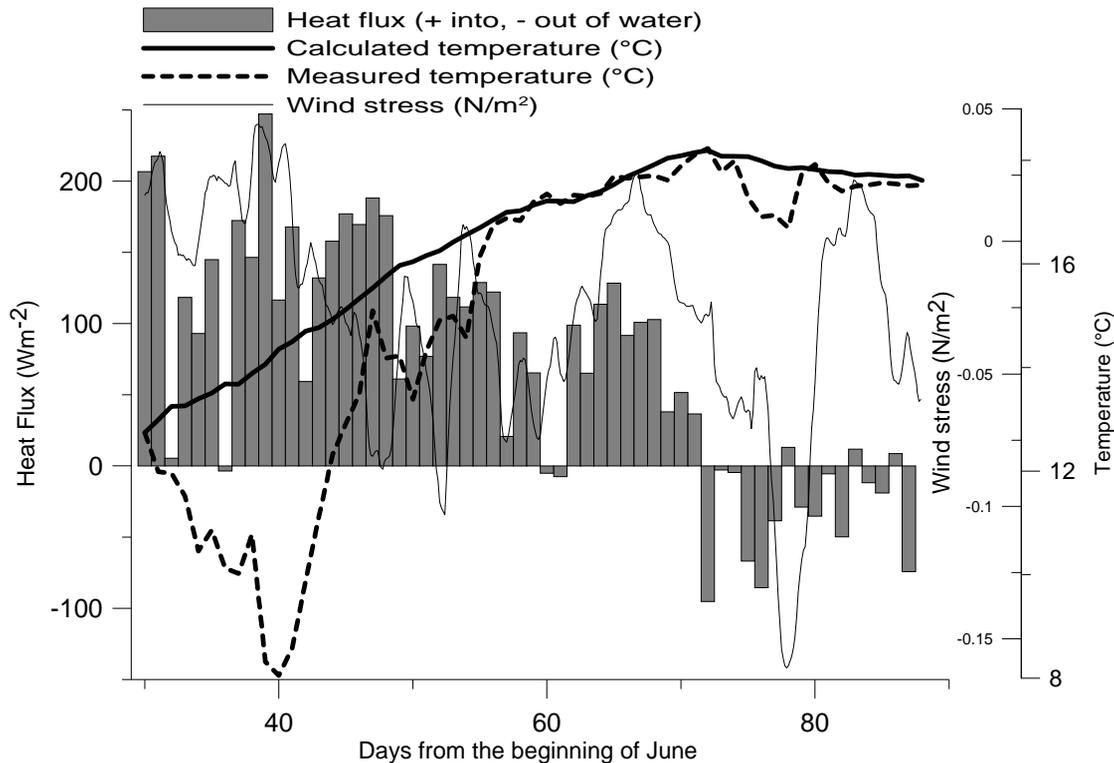


Fig. 4. Development of calculated and measured temperature, along-gulf (70°) wind stress and total heat flux. Total heat flux and temperature are presented as 1-day mean values and wind stress as 3-day running mean.

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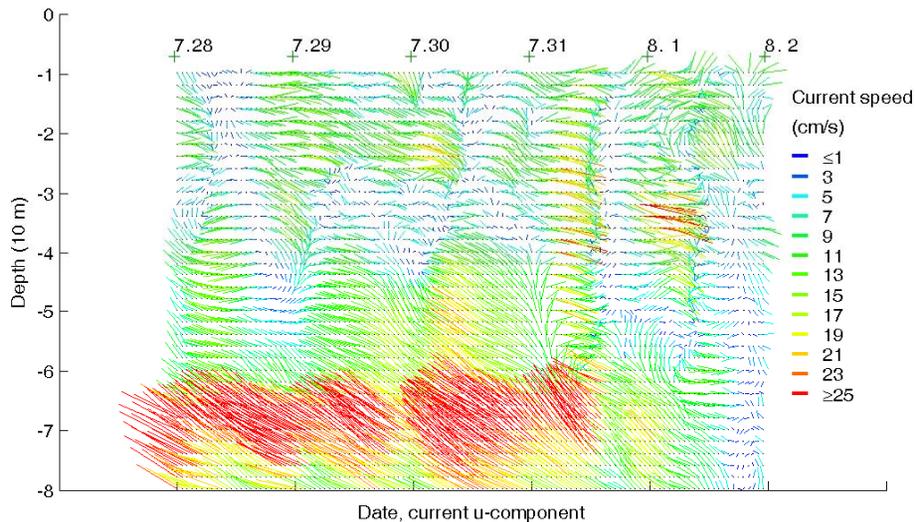


Fig. 5. Vertical distribution of vectors of horizontal current from 28 July to 2 August. Current vectors are averaged with the time step of 1 h.

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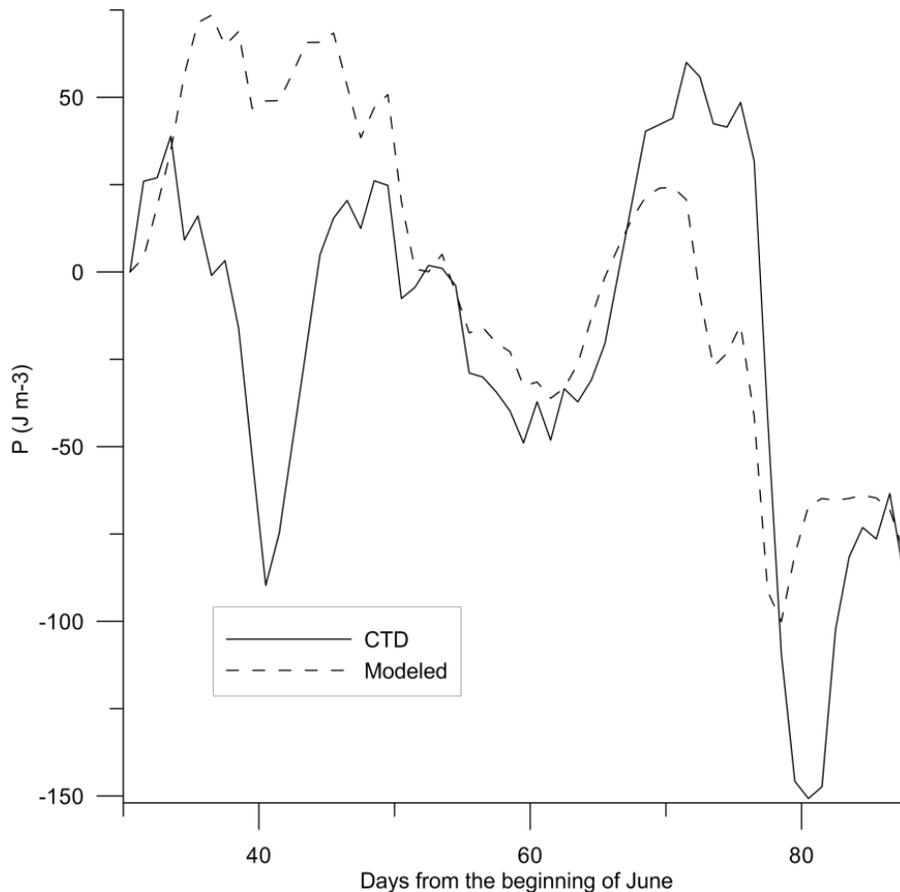


Fig. 6. Development of potential energy anomaly (P). Potential energy anomalies, modeled (Eq. 2) and calculated from CTD data (Eq. 1), are presented as 1-day mean values. Modeling started from zero and the first value was subtracted from the whole CTD-based dataset to synchronize both time-series.

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