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Variability of pycnoclines in a three-layer, large estuary: the Gulf of Finland

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Thirty-five surveys were conducted across the Gulf of Finland from 2006 to 2013 to study the characteristics and variability of the two pycnoclines in this stratified estuary. Easterly winds caused a shallower position of the upper pycnocline near the southern coast and the deeper pycnocline along the northern coast. Westerly winds had an opposite effect. Surfacing of the upper pycnocline (upwelling) was observed several times while the upper mixed layer was deeper than 40 m in the case of downwelling. The deeper pycnocline weakened and deepened significantly during the southwesterly wind bursts while it was observed at shallower depths than 50 m several times during the periods of easterly winds. The upper pycnocline was on average 3 m shallower near the southern coast while the deeper pycnocline was leveled. The inclination of the upper pycnocline corresponding to the average local wind forcing agrees well with the general cyclonic circulation of the upper layer in the Gulf of Finland and the water exchange estimates between the gulf and the Baltic Proper. An average seasonal inclination of the pycnoclines showed high inter-annual variability depending on the prevailing wind forcing. Easterly winds caused stronger vertical stratification and horizontal gradients across the gulf while in the case of westerly winds, horizontal and vertical gradients were weaker.

Introduction

Estuaries are semi-enclosed coastal water bodies where oceanic water is diluted by freshwater from land. Horizontal density and sea level gradients result in an outflow in the upper layer and inflow in the deep layer (Geyer and MacCready 2014). In contrast to many seas in the world, tides do not play an important role in the Baltic Sea dynamics (Leppäranta and Myrberg 2009).

The Gulf of Finland is about 400 km long and 48–125 km wide a sub-basin of the Baltic Sea. There is no sill at the entrance into the gulf and water can freely exchange with the open Baltic Sea. Depths decrease from > 100 m in the western part of the gulf to < 10 m in the easternmost part in Neva Bay. Bottom slope perpendicular to the axis of the gulf is generally steeper in the southern part of the gulf. This topographic feature brings about the different characteristics of mesoscale processes along the northern and southern coast (Laanemets *et al*. 2009).

Freshwater input with its main source river Neva is at the eastern end of the gulf, while saltier water originates from the open Baltic Sea in the west, resulting in a typical estuarine regime in the gulf. The average river discharge to the gulf is around 3500 $m^3 s^{-1}$ (Bergström and

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Carlson 1994) with maximum flow in spring and autumn. Thus, surface salinity increases from about 1 g kg^{-1} in the easternmost part to 6 g kg^{-1} at the entrance to the gulf and the salinity difference between the bottom and the surface layer can reach > 6 g kg^{-1} (Lips *et al*. 2009). The water column in the gulf has one-, two- or three-layer thermohaline structure. In the deeper (> 70 m) part of the gulf, there is mostly a three-layer structure in summer and a two-layer structure in winter. The two pycnoclines separating these layers are the seasonal thermocline around 10–30 m depth, usually appearing together with halocline in the same depth range, and the deeper, quasi-permanent halocline at 50–80 m depth (e.g. Alenius *et al*. 1998, Liblik and Lips 2011).

Stratification pattern of the Gulf of Finland, including strength and position of both pycnoclines, is sensitive to the wind forcing as it was observed by continuous vertical profiling (Liblik and Lips 2012). Wind regime of the gulf consists of southwesterly wind dominating in the whole Baltic Sea and local wind blowing along the gulf axis (Soomere and Keevallik 2003).

The upper pycnocline (UP) separates the upper mixed layer from the cold intermediate layer in summer and it erodes in autumn due to thermal convection and wind mixing. The UP can temporarily re-form during calm wind conditions in winter (Liblik *et al*. 2013), but it completely establishes in April–May (e.g. Alenius *et al*. 1998), when the upper part of the water column is stabilized by thermal and/or haline stratification. Thermohaline structure in the upper mixed layer and seasonal thermocline vary along the gulf (e.g. Alenius *et al*. 1998, Liblik and Lips 2011) and across the gulf (Lips *et al*. 2009). Therefore, temporal variations in a certain location can be quite large (Liblik and Lips, 2012). Mesoscale processes such as eddies (e.g. Zhurbas *et al*. 2008), up/downwelling (e.g. Lips *et al*. 2009) and relocation of fronts (e.g. Pavelson *et al*. 1997), are mainly responsible for this variability. The spatial scale of those processes is 3–5 times greater than the Rossby radius of baroclinic deformation (typically 2–4 km, Alenius *et al*. 2003). Variations in the stratification pattern are most prominent when the inclination of the thermocline across the gulf is evoked by wind forcing (Liblik and Lips 2012). Frequently, the inclination is steep enough for shoaling of isopycnals, i.e. for an upwelling event (e.g. Haapala 1994, Lips *et al*. 2009, Lehmann *et al*. 2012). Upwelling events along one coast occur simultaneously with coupled downwelling events along the opposite coast of the gulf (e.g. Laanemets *et al*. 2005, Lips *et al*. 2009).

The deeper pycnocline (DP) separates saltier bottom water from the rest of the water column. This pycnocline is most of the time present in the deeper (> 70 m) areas (3000 km^2) of the gulf, but it can be remarkably weakened in a long-term due to the low inflow from the North Sea (Liblik and Lips 2011), and at the synoptic scale due to the blockage of estuarine circulation caused by the southwesterly wind forcing (Elken *et al*. 2003). Estuarine circulation could even be reversed and in extreme cases, this could lead to the complete vanishing of stratification in the gulf (Liblik *et al*. 2013, Elken *et al*. 2014) and formation of a barotropic flow system (Liblik *et al*. 2013). Cross-gulf inclination of the DP, as well as its reaction to wind forcing, have not yet been rigorously studied due to lack of necessary data. The results from summer 2006 (Lips *et al*. 2009) indicated that the inclination of the two pycnoclines might be opposite in some cases, i.e. if the UP is shallower near the southern coast then the DP could be shallower near the northern coast. However, the inclination was not estimated and the pycnocline shapes were described only by Lips *et al*. (2009). In this study, we tested the hypothesis that the inclinations of the two pycnoclines behave differently under the changing wind forcing.

The two pycnoclines are physical barriers for heat, salt, inorganic and organic substances exchange between the three water masses. Thus, characteristics, such as inclination or strength of the pycnoclines have impacts on marine ecosystems of the gulf. For instance nutrients beneath the UP might become available for primary production if the UP is uplifted (e.g. Lips *et al*. 2011) while weakening of the DP allows to oxygenate of the hypoxic deep layers of the gulf (Liblik *et al*. 2013).

The aims of the present study were (1) to characterize the dynamics of the two pycnoclines, (2) to relate the transverse structure of pycnoclines

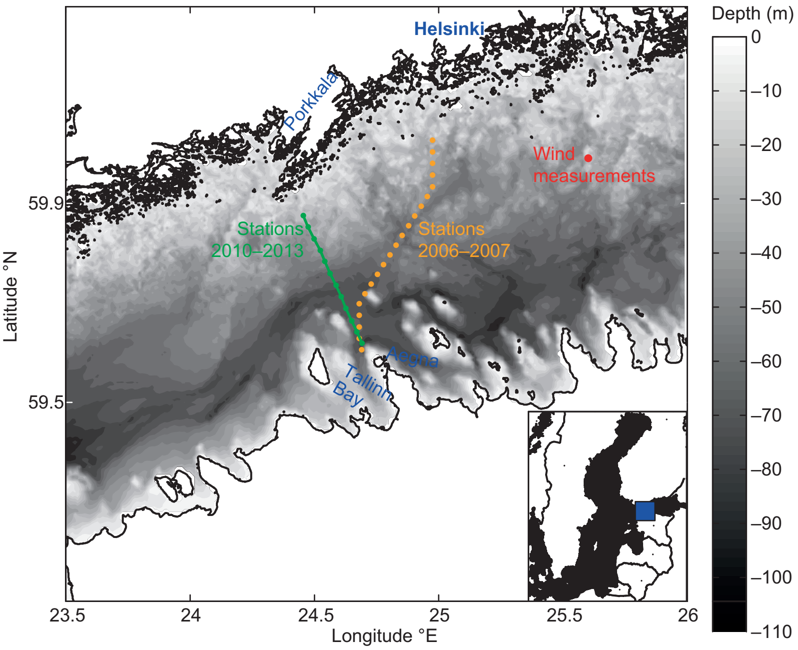

Fig. 1. Topographic map of the study area in the Gulf of Finland. The green line and dots indicate the AP transect and stations in 2010–2013, and the orange dots show the sampling stations in 2006–2007. The location of wind measurements at Kalbådagrund meteorological station is marked with a red dot.

to the forcing and suggest governing dynamics behind it, and (3) to map the typical stratification patterns in this non-tidal stratified estuary with multiple layers. Our results are based on the data from measurement campaigns consisting of 35 oceanographic surveys conducted along transects across the Gulf of Finland.

Data and methods

Oceanographic data

The data were collected in 2006–2007 and 2010–2013 from the central part of the Gulf of Finland. The surveys were carried out onboard r/v *Salme* (since 2007), which belongs to the Marine Systems Institute at the Tallinn University of Technology; and onboard the tug *Kake* (in 2006). Altogether 35 surveys along a transect perpendicular to the gulf axis were conducted. Most surveys (30) were carried out from May to August; three surveys were conducted in April, and one in September and November.

The measurements in 2006–2007 were carried out at 21 sampling stations established along a transect following the Tallinn–Helsinki ferry route (orange dots in Fig. 1). The original number of sampling stations was 27 but the data from 6 stations inside Tallinn Bay were not considered to make the transect comparable with the later survey and are not shown in Fig. 1. Since 2010, the measurements were carried out at 12 stations established along a transect between the Aegna Island and Porkkala Peninsula (hereafter AP station or transect, respectively) (green line and dots in Fig. 1). The data from the 13th station which was the shallowest on this transect and closest to the Aegna Island were not considered to make the transect comparable with the earlier survey and it is not shown in Fig. 1.

Vertical profiles of temperature and salinity were obtained using the SBE 19Plus (Seabird, 2006–2007) and OS 320plus (Idronaut s.r.l, 2010–2013) CTD (conductivity, temperature, depth) probes. The probes were regularly sent to the manufacturer for maintenance and calibration. In addition, the quality of the salinity data was checked against the water sample tested with high-precision salinometers, AUTOSAL and 8410A Portasal (Guidline). Water samples were collected with a Rosette sampler. Both CTD probes have accuracy better than 0.01 °C and 0.01 mS cm^{-1} for temperature and conductivity, respectively. Considering the variability range of temperature and salinity in the study area

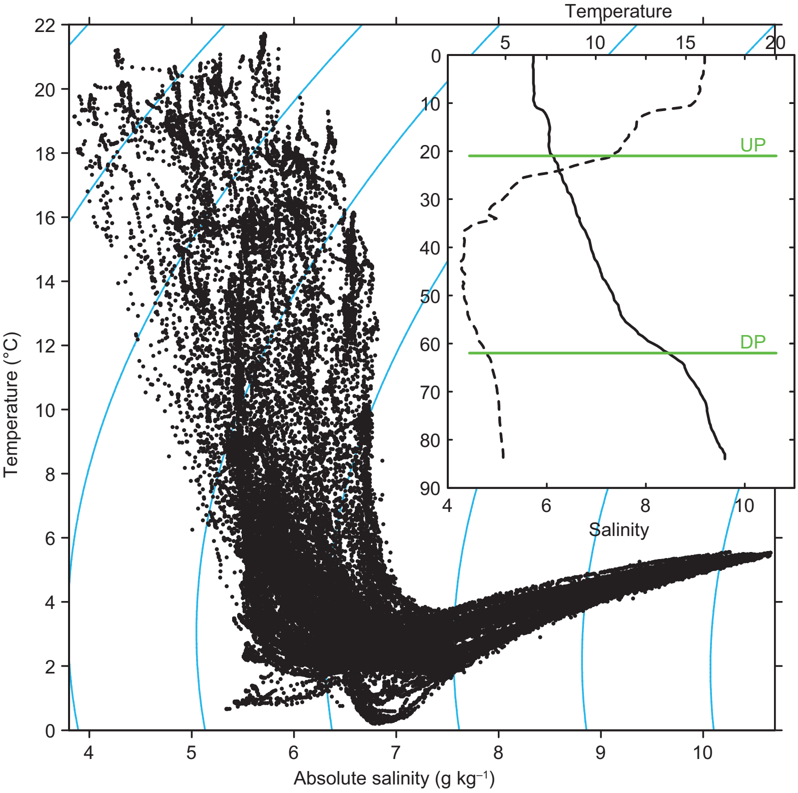

Fig. 2. Temperature–salinity diagram from all measurements taken in the Gulf of Finland along the transects TH in 2006–2007 and AP in 2010–2013 (*see* the location of transects and stations in Fig. 1). Blue lines are isopycnals (kg m^{-3}). Typical temperature (dashed line) and salinity (solid line) profiles and respective UP and DP depths are shown in the insert.

(Fig. 2), such measurement accuracy can be considered more than sufficient.

Meteorological data

Meteorological conditions were characterized by wind data from the Kalbådagrund weather station (Finnish Meteorological Institute). The station is located in the open sea at an off-shore lighthouse, approximately 40 km east from the transects (Fig. 1). It represents marine wind conditions very well (Keevallik and Soomere 2010), as are no obstructions nearby. In order to estimate variation in the UP in the past, the wind data from 1981 to 2013 were used in the analysis. The wind speed and direction measurements were carried out at an elevation of 32 m above the sea surface, and the data were available every third hour as 10-min averages. The wind speed was adjusted to the reference height of 10 m and wind stress was calculated following Large and Pond (1981) as:

$$\tau = \rho_{\text{air}} C_{\text{D}} |U| U_{10}, \qquad (1)$$

where C_{D} is the drag coefficient and U_{10} is the wind speed at the reference height of 10 m.

Calculation procedures

Here we present salinity in absolute values (g kg^{-1}). Conversion from the practical salinity to absolute salinity was done according to Feistel *et al*. (2010) using the Gibbs SeaWater Oceanographic Toolbox (McDougall and Barker 2011). Density is presented as potential density anomaly σ_0.

The raw data that were stored with vertical resolution of 0.5 m were extrapolated from the shallowest measurement bin (approx. 1–2 m depth) to the surface of each station. To create time series covering the entire period 2006–2013, the 2006–2007 stations were virtually translocated parallel to the gulf’s SW-NE axis to the 2010–2013 AP transect and then the values measured at those stations were assigned to the respective and closest AP stations. Finally, the temperature and salinity distributions on a regular grid of 12 horizontal locations (distance between stations — 2.9 km) and 0.5 m vertical bins were created for each survey to be the basis for the graphs presented in this paper. Altogether 420 CTD profiles (12 profiles in each of 35 surveys) were used in the analysis.

To define the depth of the UP, the minimum density (ρ_{min}) and the density corresponding to the minimum temperature (ρ_{cold}) were found for each survey. The UP density (ρ_{UP}) was defined as $(\rho_{\mathrm{cold}} + \rho_{\mathrm{min}})/2$ and the depth of the UP at each station was defined as the shallowest depth at which the density was $\geq \rho_{\mathrm{UP}}$. Although ρ_{UP} varied from survey to survey, one ρ_{UP} value was valid for the whole transect. The UP depth was detected only if ρ_{UP} isopycnal existed at a certain station. Thus in case of strong upwelling/downwelling events, ρ_{UP} and depth of the UP was not detected at all stations. The purpose of using such methodology was to show the dynamics of the UP along the transect. When $\rho_{\mathrm{cold}} - \rho_{\mathrm{min}} \leq 0.5$ kg m^{-3}, the UP and its depth were not defined for the whole transect. The UP was not determined for one spring survey (4 April 2012), when the inversed thermal stratification was observed in the upper layer.

The depth of the center of the deep pycnocline (DP) was defined as the shallowest depth where salinity was ≥ 8.4 g kg^{-1}. The critical value (8.4 g kg^{-1}) was chosen on the basis of mean profiles (Liblik and Lips 2011) as the strongest salinity gradient was found around this salinity value. The UP and DP were calculated with 0.5 m vertical resolution.

The strength of the UP was defined as $\rho_{\mathrm{cold}} - \rho_{\mathrm{min}}$ and the strength of the DP as $\rho_{\mathrm{max}} - \rho_{\mathrm{cold}}$, where ρ_{max} is the maximum density measured during a survey.

The general across-gulf slope of pycnoclines for each survey was estimated by calculating linear regression between the values of pycnocline depth and respective distance from the first station. The slope was calculated only if the depths of pycnocline centers from at least six stations were available for the transect. Due to this limitation one survey (4 April 2012) was omitted from the UP-, and three surveys (8 November 2011, 20 July 2012 and 13 August 2012) were omitted from the DP-slope calculations. Positive slope values indicate that the pycnocline was deeper near the northern coast while the negative ones that it was deeper near the southern coast.

Results

Vertical profiles

Water properties varied in a wide range during the surveys (Fig. 2): temperature varied from 0.2 °C in the intermediate layer to 21.7 °C (Fig. 3) in the surface layer, and salinity from 3.9 g kg^{-1} in the surface layer to 10.7 g kg^{-1} in the bottom layer (Fig. 4). The total range for density was 1.2–8.4 kg m^{-3} (Fig. 5).

In the temperature field, the most pronounced feature was the seasonal thermocline and a warm upper mixed layer in summer. The thermocline strength, position and inclination varied considerably. For instance, the upper mixed layer temperature in July was > 20 °C (e.g. 22.VII.2010 in Fig. 3) or only 13–14 °C (4.VII.2012 in Fig. 3). In spring, when thermal stratification was very weak (26.IV.2007 in Fig. 3), vertical gradient of salinity typically stabilized (26.IV.2007 in Figs. 4 and 5) the water column. Considerable haline stratification (4.IV.2012 in Fig. 4) was present even if in the upper layer the temperature was close to the temperature of maximum density (4.IV.2012 in Fig. 3). Surface water warming (e.g., 4.IV.2012 in *see* Fig. 3) when the upper layer temperature was below the temperature of maximum density resulted in convective mixing. However, if the buoyancy flux due to advection of low salinity water in the surface layer had been higher than the buoyancy loss due to surface warming, the water column might have still be stratified (4.IV.2012 in Fig. 5).

Often strongly inclined thermocline was observed, indicating that upwelling events occurred near the southern (e.g., 15.VIII.2006 in Fig. 3) or northern coast (e.g. 28.VI.2011 in Fig. 3), being coupled with the downwelling events along the opposite coast. Upwellings or downwellings were usually visible also in the salinity distribution as the seasonal thermocline was accompanied with a relatively strong salinity gradient in summer. Upwelled sub-surface

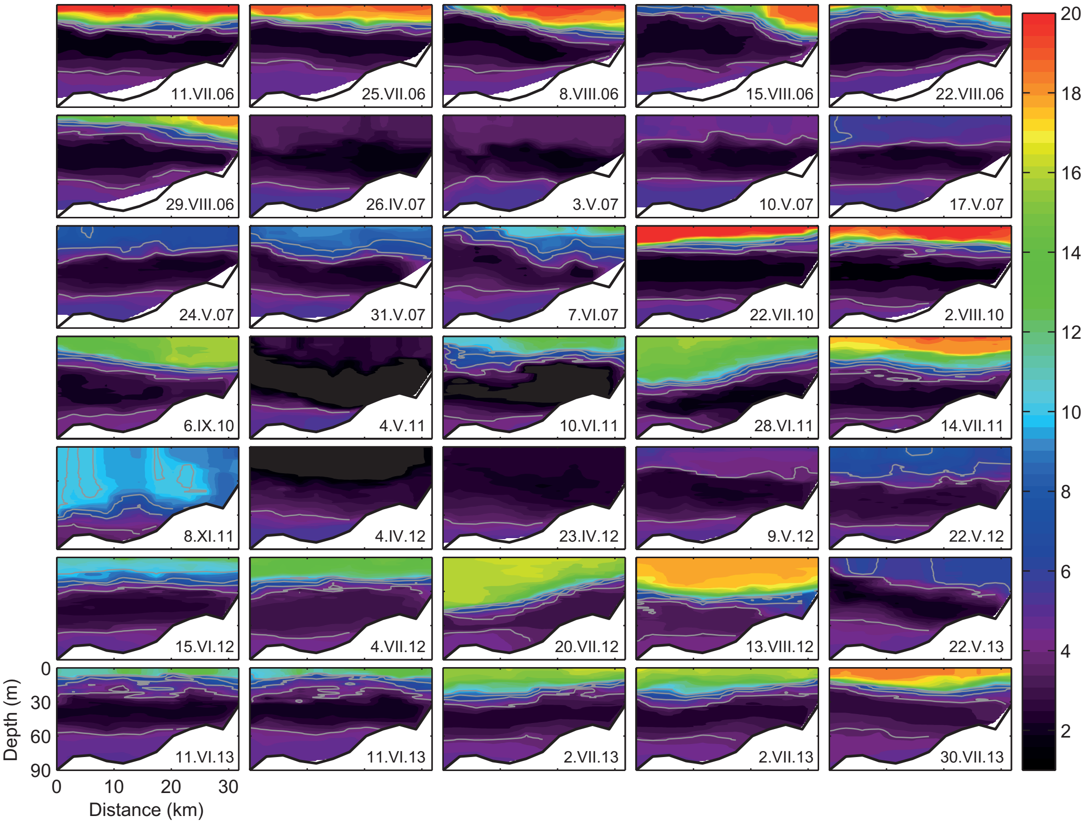

Fig. 3. Vertical profiles of temperature (°C) along the AP transect. Distance is calculated from the southernmost station (Fig. 1, green).

water was usually colder and saltier than the surrounding ambient surface water while downwelling water was typically warmer and fresher than the ambient water in the same depth range (*see* e.g. 8.VIII.2006 in Figs. 3 and 4). However, it was not always the case. For instance, clearly shallower thermocline was observed near the northern coast on 28.VI.2011 (*see* Fig. 3), but such structure could not be found in the salinity distribution (Fig. 4). Furthermore, contrary to the previously described tendency, there was relatively fresher water above and within the thermocline depth range at the northern side of the gulf. The fresher water was probably transported earlier from the eastern part of the gulf before the cross-gulf movement caused inclination of the thermocline. Latter is a good example of how different processes — in this particular case the along-gulf advection and vertical movement of isopycnals in opposite directions at one and the other side of the gulf — simultaneously affect the thermohaline structure of the gulf waters.

Wind-generated advection of fresher/saltier water from east/west and vertical mixing caused surface salinity to vary in the range of 4–6 g kg^{-1} or sometimes even beyond this limit. Similar wind-driven changes occurred in the deep layer, but the changes in salinity were opposite to those in the surface layer. In other words, an increase in salinity in the surface layer was accompanied by its simultaneous decrease in the bottom layer as a result of south-westerly wind forcing and *vice-versa* during north-easterly winds. That could lead to near disappearance of haline stratification (e.g. 8.XI.2011 in Fig. 4) or very strong (e.g. 22.VIII.2006 in Fig. 4) haline stratification, respectively. However, as winds also evoke previously described inclination of the pycnoclines and resulting upwelling/downwelling events, changes in the thermohaline fields are often difficult to interpret.

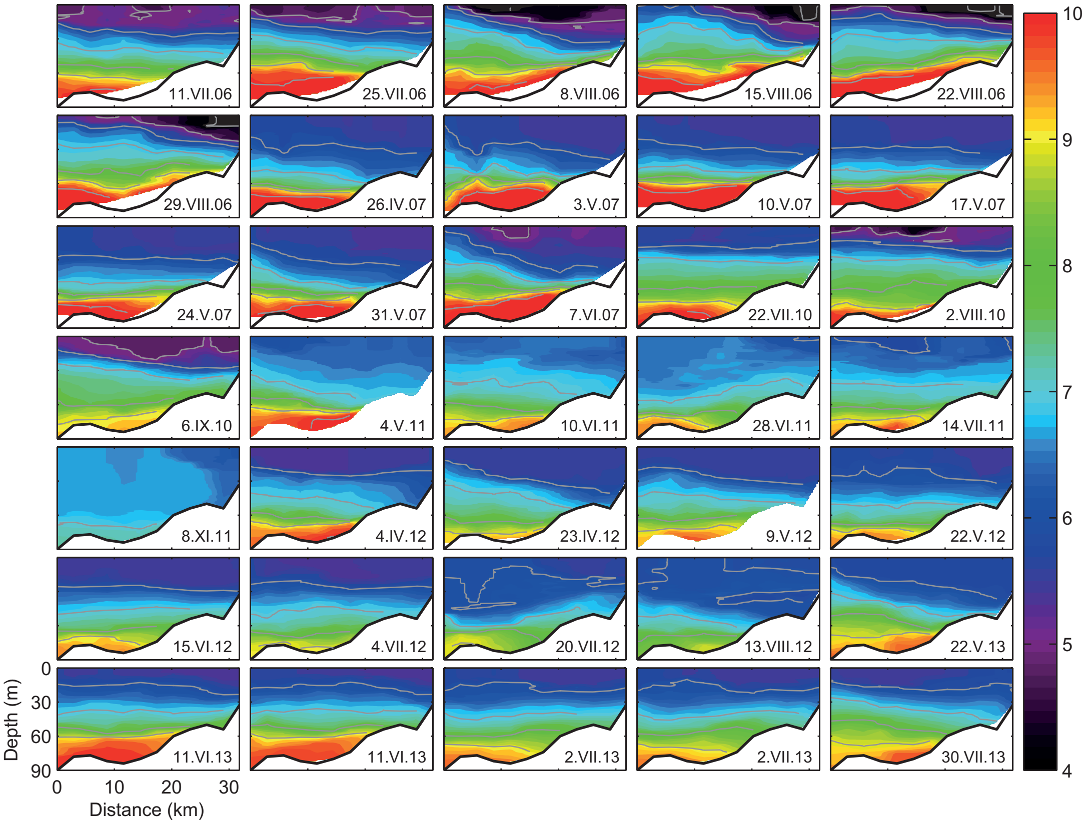

Fig. 4. As Fig. 3, but for salinity (g kg^{-1}).

Effects of wind forcing on pycnoclines

In the Baltic Sea, the most frequent winds are from SW. For the analysis, we first selected the wind component (direction), which best correlated with the UP/DP inclination. Later, we related and analyzed the UP/DP inclination in respect to the wind stress of the selected direction.

The center of the UP was detected at 382 out of 420 stations (35 surveys, 12 stations). Both, upwellings and downwellings caused disappearance of the UP. For instance, the UP shoaled several times near the southern coast (e.g. 15.VIII.2006 in Figs. 3–5) and downwelling strained the UP close to the bottom several times near the northern coast in spring, when thermal stratification was very weak (e.g. 22.V.2013 in Figs. 3–5). The center of the UP was not detected for the survey on 4.IV.2012, as the temperature minimum was found at the surface during this early spring cruise. The average depth of the center of the UP was 21 m whereas it was 20 m if only May–September surveys were taken into account. The range of variability of the UP depth was from several to 60 m (*see* Fig. 6a). The deepest UP was observed during the only cruise in November. Such a deep UP was a combined result of autumn convection and strong estuarine circulation reversal event as it can be expected from a strong southwesterly wind impulse (Table 1). In summer, the center of UP was usually not deeper than 30 m (Fig. 6a). However, there were two downwelling events along the southern coast during which the depth of the UP declined down to 41 m and 46 m on 28.VI.2011 and 20.VII.2012, respectively, while on the same dates at the northernmost station the centers of the UP were at 14 m and 17 m, respectively.

The strength of the UP was strongly related to the seasonality of the upper mixed layer temperature. The strength was below 0.8 kg m^{-3} during all three April surveys while the highest

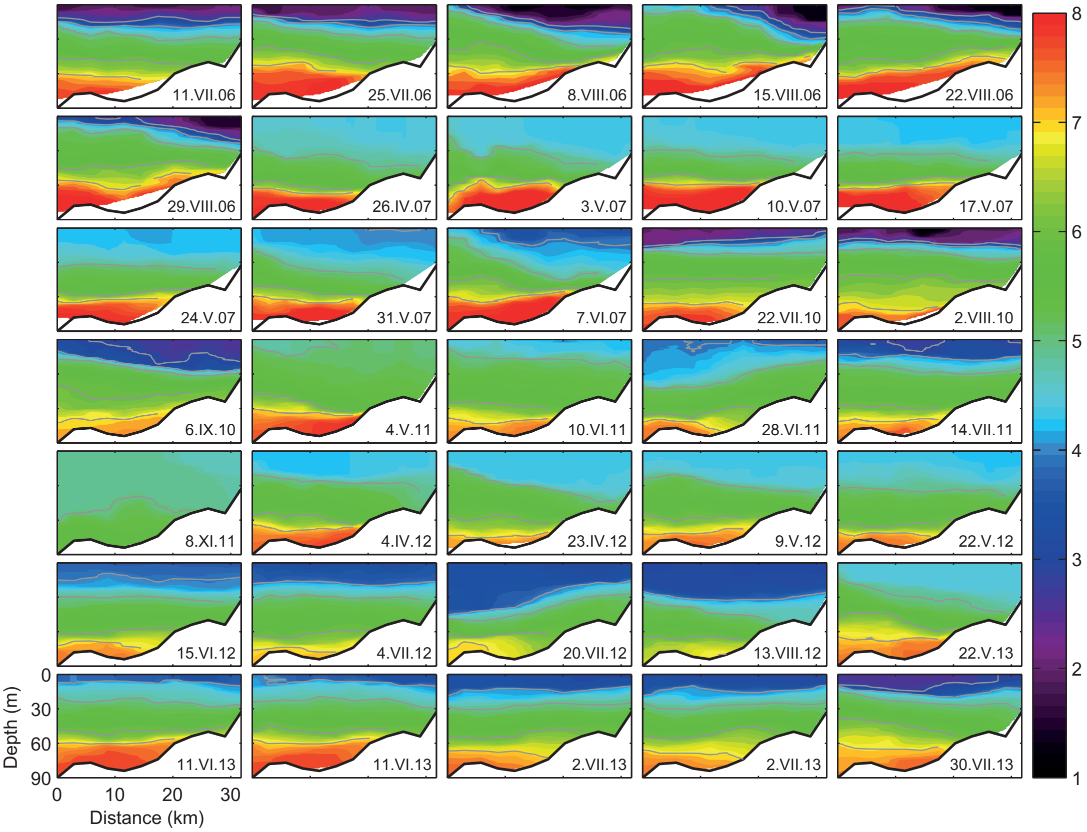

Fig. 5. As Fig. 3, but for density (σ_0, kg m^{-3}).

values (> 4.25 kg m^{-3}) were observed several times in August.

The depth of the DP center, defined as the depth of 8.4 g kg^{-1} isohaline, was located on average at 60 m, being typically in the range from 50 to 70 m (*see* Fig. 6b). The DP center depth < 50 m was observed only in few surveys in 2006. Typically, the DP was not found at the four northernmost stations as the sea bottom is shallower than 60 m there. The only survey, during which the isohaline 8.4 g kg^{-1} was not observed, and the DP was not detected at all, was conducted in November 2011, when a strong reversal event caused disappearance of the halocline. It was the same survey when the deepest center of the UP was observed.

The strength of the DP had a slight decreasing tendency from spring to autumn. On top of that, seasonal decrease in the DP strength and high variability of it were also observed (Table 1).

Shallower UPs and DPs were associated with the greater strength of pycnoclines (Fig. 6a and b, respectively). In case of the UP, the lower strength values were recorded when the UP was located deeper in the southern part of the gulf.

In order to estimate the general cross-gulf inclination of the pycnoclines, linear regressions between pycnocline strengths and their distances from the southernmost AP station (*see* Fig. 6a and b) were calculated. Positive slope values indicate that the a pycnocline was deeper near the northern coast while negative values show that it was deeper near the southern coast. On average, the UP and DP slopes were +0.24 m km^{-1} (p < 0.01) and +0.02 m km^{-1} (n.s.), respectively. If only those surveys when the seasonal thermocline was well-established (May–September) were taken into account, the average UP and DP slopes would be +0.21 m km^{-1} and 0 m km^{-1}, respectively. The UP was on average 7–8 m higher at the southernmost station than at

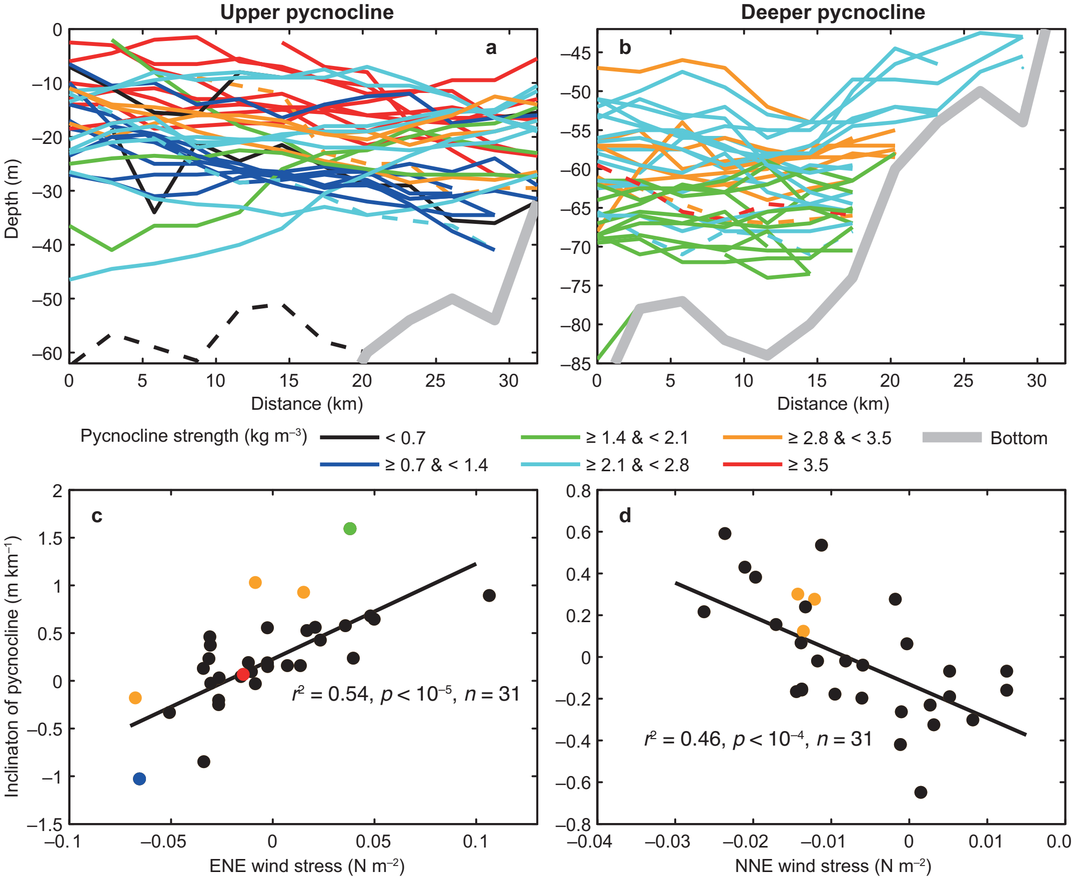

Fig. 6. Locations (distance from the southernmost station on the AP transect) of the (**a**) UP and (**b**) DP along the cross-section in the Gulf of Finland during 35 surveys. (**c**) Wind forcing (average wind component from ENE 2–6 days before the survey) *vs.* inclination of the UP 2–6 days before a survey, and (**d**) 2–6 week mean wind stress *vs.* inclination of the DP. Orange dots are the April and November surveys, which were not used in the regression analysis. Red, green and blue dots are the surveys on 30 July 2013, 15 August 2006 and 20 July 2012, respectively, described in more detail in the chapter "Selected UP patterns".

the northernmost station of the (32-km long) AP transect. Variability of both pycnocline slopes was very high. The UP slope varied in the range from –1.0 to +1.6 m km^{-1} (Fig. 6c) and its standard deviation was 0.50 m km^{-1}, while the DP slope varied from –0.7 to +0.6 m km^{-1} (Fig. 6d) with the standard deviation of 0.30 m km^{-1}. The UP (DP) slope value was in 59% (50%) of the cases smaller than –0.20 m km^{-1} or greater than +0.20 m km^{-1}. Hence, it shows that inclined pycnoclines regularly appeared in the gulf.

According to the mean values and variability range of the UP inclination and strength, the vertical gradient of the along-gulf current speed can be estimated assuming the geostrophic balance. The average inclination of 0.24 m km^{-1} and the thermocline strength of 2.25 kg m^{-3} suggest a difference between the current speed at the surface and in the intermediate layer being as great as 4.2 cm s^{-1}. The observed extreme values of the UP inclination and strength correspond to the current velocity range from –54 cm s^{-1} (outflow) to 19 cm s^{-1} (inflow) in the surface layer.

The effect of wind forcing on the inclination of the UP was evaluated using a linear regression analysis (data from 31 surveys in May–September). Three surveys in April and one in November were excluded in order to describe the situation when the seasonal thermocline was well established. Regressions for all combinations of different periods (up to two months) and directions were calculated. The best correlation

(Fig. 6c) between wind forcing and the UP slope was found with 2–6 days (before the survey) average wind component from ENE (60°–80°). Thus, shallower pycnocline near the southern coast was associated with ENE wind (Fig. 6c). This result was expected, since the western part of the Gulf of Finland is ENE–WSW oriented and therefore, the Ekman drift caused by the ENE winds should cause uplift of isopycnals in the southern part of the gulf. The regression line ($\alpha = 9.99\tau + 0.23$, where α is the inclination in m km^{-1} and τ is the wind stress in N m^{-2}) slope suggests that a 10^{-2} N m^{-2} change in wind stress results in a 0.1 m km^{-1} change in the inclination of the UP. To simplify, we can assume that there is a stationary ENE wind of 5 m s^{-1} during the first period and 5 m s^{-1} WSW wind during the second period. According to the regression equation, the inclination difference between the two periods would be 0.70 m km^{-1}. In the case of the first event, the UP would be at the southernmost station 18.5 m shallower than at the northernmost station. In the second event, the UP would be 4 m shallower at the northernmost station.

Table 1. Characteristics of wind forcing and pycnoclines. Two-to-six days before survey mean wind stress was calculated for the UP and 2–6 week mean wind stress for the DP.

Cruise no.	Date	Wind stress from ENE (10^{-2} N m^{-2}) for the UP	Wind stress from NNE (10^{-2} N m^{-2}) for the DP	UP strength (kg m^{-3})	DP strength (kg m^{-3})	Inclination of the UP (m km^{-1})	Inclination of the DP (m km^{-1})
1	11.VII.2006	–3.04	–1.71	3.65	2.74	–0.03	0.16
2	25.VII.2006	–1.20	–2.36	3.72	2.80	0.19	0.59
3	8.VIII.2006	4.80	–1.38	4.42	2.61	0.68	–0.16
4	15.VIII.2006	3.80	–0.61	4.42	2.65	1.59	-0.20
5	22.VIII.2006	–3.10	0.15	4.46	2.56	0.46	–0.65
6	29.VIII.2006	5.00	0.32	4.25	2.50	0.65	–0.33
7	26.IV.2007	–0.85	–1.22	0.67	3.27	1.03	0.28
8	3.V.2007	2.35	–0.11	0.56	3.45	0.42	–0.42
9	10.V.2007	–3.07	–0.03	0.73	3.32	0.37	0.06
10	17.V.2007	–1.05	0.82	0.75	3.31	0.10	–0.30
11	24.V.2007	–3.14	0.27	0.82	3.17	0.23	–0.23
12	31.V.2007	2.10	–0.18	1.08	3.18	0.56	0.28
13	7.VI.2007	3.57	–0.60	1.55	3.38	0.58	–0.04
14	22.VII.2010	–5.07	–1.45	3.92	2.18	–0.33	–0.17
15	2.VIII.2010	0.72	–1.33	4.78	1.97	0.16	0.24
16	6.IX.2010	1.67	–0.10	3.38	1.57	0.53	–0.26
17	4.V.2011	1.36	–2.10	0.59	2.60	0.16	0.43
18	10.VI.2011	3.97	–1.97	1.30	2.26	0.24	0.38
19	28.VI.2011	–3.38	–2.63	1.92	1.89	–0.85	0.22
20	14.VII.2011	–1.57	–0.82	2.98	2.01	0.05	–0.02
21	8.XI.2011	–6.75	–4.25	1.20	–	–0.18	–
22	4.IV.2012	1.77	–1.43	–	3.70	–	0.30
23	23.IV.2012	1.53	–1.36	0.76	2.34	0.93	0.12
24	9.V.2012	–0.27	–0.95	1.26	2.13	0.56	–0.18
25	22.V.2012	–0.25	–1.39	1.28	2.01	0.15	0.07
26	15.VI.2012	–3.41	–1.38	1.83	2.07	0.13	–0.15
27	4.VII.2012	–0.86	–1.18	2.19	1.77	–0.03	–0.02
28	20.VII.2012	–6.55	–1.51	2.44	1.58	–1.03	–
29	13.VIII.2012	–2.64	–2.70	2.30	1.72	0.03	–
30	22.V.2013	10.65	–4.62	0.89	2.36	0.89	0.57
31	11.VI.2013	–0.26	0.52	2.17	2.30	0.19	–0.19
32	12.VI.2013	–0.26	0.52	2.12	2.34	0.17	–0.07
33	2.VII.2013	–2.66	1.25	2.58	2.04	–0.25	–0.16
34	3.VII.2013	–2.66	1.25	2.46	2.04	–0.20	–0.07
35	30.VII.2013	–1.45	–1.12	3.05	2.11	0.07	0.54

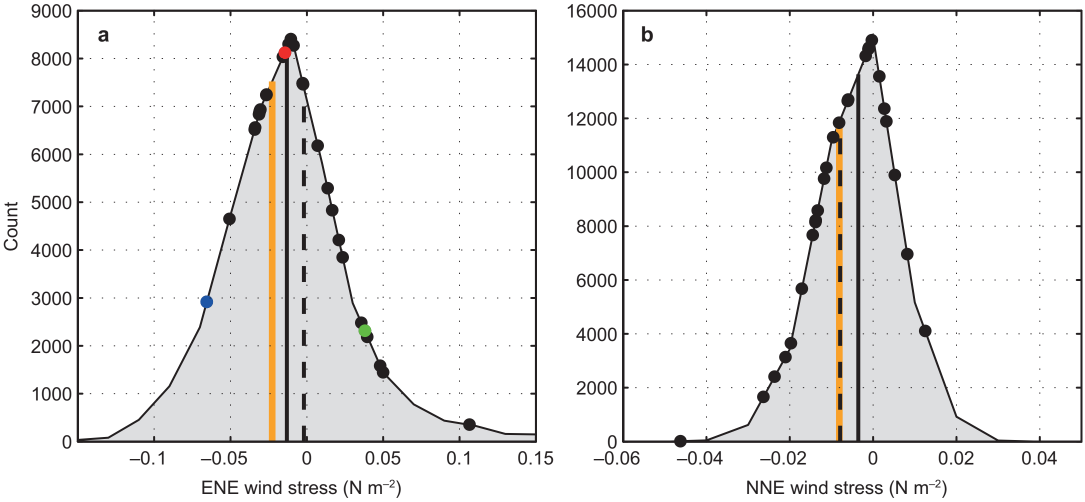

Fig. 7. Histograms of wind stress from (**a**) ENE for the UP and (**b**) NNE for the DP in May–September 1981–2013. Time window of the calculations of ENE wind stress was 2–6 days before the surveys. For instance for 1 May at 12:00 the wind from 25 April at 12:00 to 29 April at 12:00 was used. The time window of the calculations of NNE wind stress was 2–6 weeks before the surveys. The histogram was calculated in 0.02 N m^{-2} steps for ENE wind stress and in 0.01 N m^{-2} steps for NNE wind stress. Solid vertical lines show average wind stress in May–September 1981–2013, dashed lines show average wind stress for the 31 (UP) and 29 surveys (DP), and the orange vertical lines show wind stress, which corresponds to the leveled pycnoclines according to the calculated regressions (Fig. 6c and d, respectively). Red, green and blue dots are surveys on 30 July 2013, 15 August 2006 and 20 July 2012, respectively, described in more detail in the chapter "Selected UP patterns".

It can be expected that in the case of a thinner upper mixed layer, the same wind forcing can induce stronger inclination than it would be in the case of a deeper upper mixed layer. It means that the most remarkable outliers below/above the regression line in Fig. 6c, are surveys when the shallower UP was recorded. The two most prominent cases (green and blue dots in Fig. 6c) and one typical case (red dot in Fig. 6c) of the UP inclination are discussed in more detail in the chapter "Selected UP patterns". It is evident from the histogram of the long-term wind stress data (Fig. 7a) that even stronger wind impulses can occur than those two selected prominent cases.

As already mentioned above, the average slope of the UP in the data set covering 31 surveys (May–September) was +0.21 m km^{-1}. Mean 2–6 days pre-survey ENE wind stress calculated for 31 surveys was close to zero (–0.002 N m^{-2}; *see* dashed vertical line in Fig. 7a), whereas the mean calculated for May–September 1981–2013 was –0.013 N m^{-2} (solid vertical black line in Fig. 7a). Combining the latter with the corresponding regression line (Fig. 6c), the average climatological inclination of the UP would be +0.10 m km^{-1}. This estimate suggests that on average the UP is 3.1 m higher at the southernmost station than it is at the northernmost station. Without wind forcing, the inclination would be +0.23 m km^{-1}, which would give 7.3 m difference of the UP depth between the northernmost and southernmost edges of the AP transect. Thus, wind forcing reduces the slope on average by 4.2 m. It is noteworthy that the 34-surveys (for one survey the UP was not detected) average UP inclination (+0.24 m km^{-1}) was very close to the value corresponding to windless conditions (+0.23 m km^{-1}). Therefore, it can be assumed that the survey-averaged fields roughly represent the density structure in the layer between the surface and intermediate layers without wind forcing. The regression line suggests that wind stress of –0.023 N m^{-2} (vertical orange line in Fig. 7a) is needed to level the UP.

For the DP, the best fit ($\alpha = -16.20\tau - 0.13$, $r^2 = 0.46$, $n = 31$, $p < 10^{-4}$) was found with the average wind component from NNE 2–6 weeks before the survey. The regression line (Fig. 6d) for the DP is reversed (in comparison with the regression line for the UP in Fig. 6c): a –0.16 m km^{-1} change in the DP slope is associated with wind stress of 10^{-2} N m^{-2}. The average DP-favorable wind stress in the 29 surveys (in two surveys the inclination of halocline was not detected) in May–September was –0.008 N m^{-2} (dashed vertical line in Fig. 7b), which corresponded to the leveled inclination 0 m km^{-1}, i.e. such wind stress (orange vertical line in Fig. 7b) is needed to level the DP. Climatological average for the NNE wind stress was –0.004 N m^{-2} (solid vertical line in Fig. 7b), which suggests –0.07 m km^{-1} for the average climatological slope of the DP. The AP transect length for the typical DP depth (Fig. 6b) is around 17–20 km. Thus, the DP is located on average 1.2–1.5 m shallower near the northern slope of the gulf. For the windless conditions, this difference is slightly steeper, 2.2–2.6 m, which shows that the average wind forcing decreases the slope by about 1 m.

For the UP and DP, the best correlations with wind forcing were found for rather similar wind directions. It appears that the wind from NE generates, though in different time scales, opposite inclination of the two pycnoclines — shallower UP in the southern part of the gulf and shallower DP in the northern part of the gulf (Fig. 6c and d).

Selected UP patterns

Three characteristic stratification patterns were selected to demonstrate cross-gulf distributions during various periods with certain forcing: (1) neutral conditions (Fig. 8a–c), (2) upwelling along the southern coast (Fig. 8d–f), and (3) upwelling along the northern coast (Fig. 8g–i). The idea behind this selection of the surveys was to have similar surveys in terms of the seasonal cycle. As we also aimed to show most distinctive patterns, we selected three summer surveys: 30 July 2013, 15 August 2006 and 20 July 2012.

Neutral conditions

Variable winds from various directions (SE, W and NW) before the survey on 30 July 2013 resulted in a wind stress value (note that wind stress was calculated for 4-day periods, Fig. 7a, red point “1”) and UP inclination (Fig. 6c, red point “1”) close to the long-term average. Thus, this survey exemplifies the UP condition in neutral (long-term average) wind conditions. The applied linear approximation of the UP depth revealed the UP being about 2 m shallower near the southern coast than near the northern coast. However, a locally deeper UP was observed at a distance of 17–21 km from the southernmost station while the UP had a relatively shallow position near the northern coast. This pattern could indicate a westward flow in the southern part and eastward in the northern 1/3 of the profile and can be associated with a subsurface eddy, since isotherms, isohalines and isopycnals were doming in the upper layer in the same distance range of 17–21 km.

Temperature in the upper layer was relatively even (20.1–20.8 °C; Fig. 7a). Salinity was higher near the northern coast (up to 5.8 g kg^{-1}) and at the southernmost station (5.7 g kg^{-1}) while the minimum (5.4–5.5 g kg^{-1}) was found at the distance of 3–17 km (Fig. 7b). The less saline water in the most of the southern and middle part of the profile was probably a result of the westward flow, which was suggested above on the basis of the observed UP inclination. The DP was relatively shallow, especially in the southern part of the profile (51–53 m).

Upwelling near the southern coast

Strong (9–12 m s^{-1}) easterly winds (green dot in Fig. 7a) resulted in upwelling near the southern coast and downward shift of the UP near the opposite coast on 15 August 2006 (Fig. 8d–f). Shoaling of the UP was observed in the central part of the gulf and the accompanied cross-gulf (linear) slope of the UP was 1.59 m km^{-1} (green point in Fig. 6c). The slopes of isopycnals decreased with the depth and at the depth range of the DP, the inclinations of isopycnals were opposite to the UP slope, i.e. the DP was shallower in the northern part of the gulf. The vertical location of the DP was very shallow: it varied between 43 and 53 m throughout the profile (Fig. 8f). In the downwelling area, upper

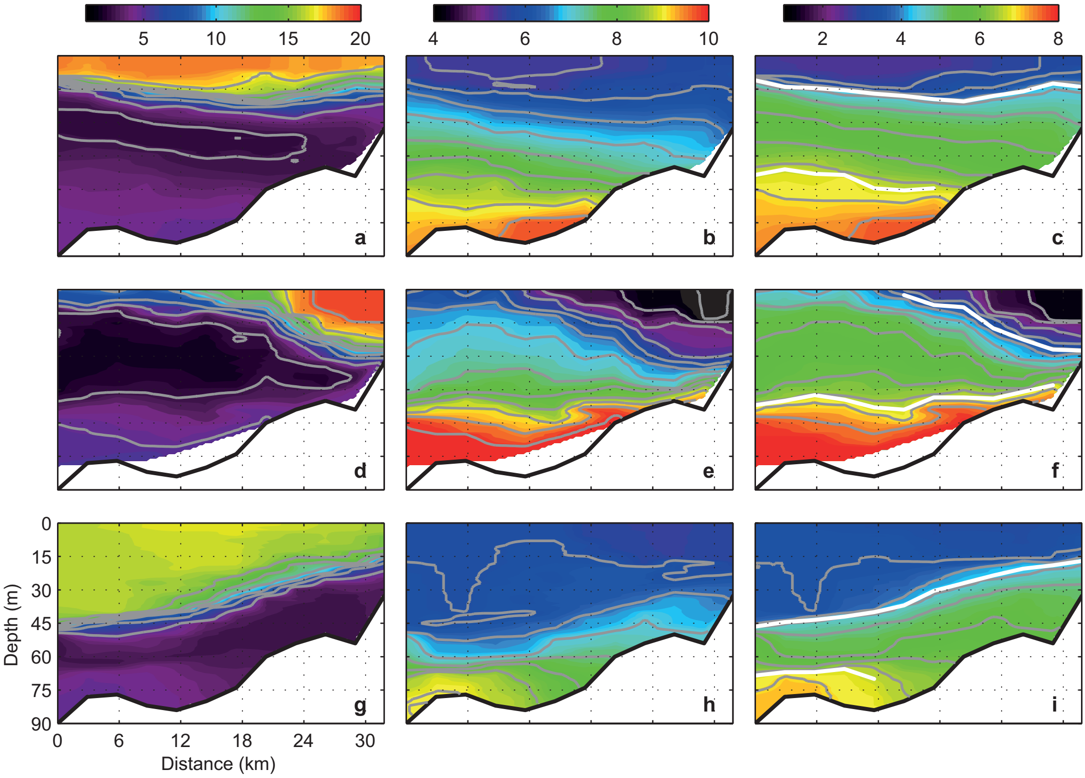

Fig. 8. Vertical profiles of temperature (°C; a, d, g), salinity (g kg^{-1}; b, e, h) and density (kg m^{-3}; c, f, i) in the Gulf of Finland (for locations *see* Fig. 1) on 30 July 2013 (a–c), 15 August 2006 (d–f) and 20 July 2012 (g–i). White lines on the density panels (c, f, i) show the location of the UP and DP.

mixed layer water was unusually fresh. The latter in combination with shoaled cold and saltier intermediate layer water in the south caused very strong lateral gradients of temperature, salinity and density within the upwelling frontal area where these parameters varied in ranges of 8.2–19.5 °C, 3.9–6.2 g kg^{-1} and 1.3–4.7 kg m^{3}, respectively, in the surface layer. Density was very high, up to 8.4 kg m^{-3}, in the deep layer. Thus, strong easterly (seaward) winds caused upwelling near the southern coast and related strong vertical and lateral (cross-gulf) gradients.

Upwelling near the northern coast

Downwelling along the southern coast was observed (Fig. 8g–i) on 20 July 2012 after the period of prevailing westerly winds (blue point in Fig. 7a). The upper mixed layer depth exceeded 40 m in the downwelling area while near the northern coast a much shallower UP appeared. The basin-wide slope of the UP was –1.03 m km^{-1} (blue point in Fig. 6c). Intensive shoaling of the UP was not observed probably because the survey (green line in Fig. 1) was not conducted all the way to the Finnish coast. Only slight northward decrease of the upper layer temperature was observed from the central part (16.8 °C) of the transect to the northernmost station (15.8 °C). However, temperature measurements on 20 July 2012 along the Tallinn–Helsinki ferry route at 4 m depth showed that the temperature was lower than 13 °C near the Finnish coast while it was 16–17 °C in the southern and central parts of the gulf (Kikas and Lips 2016). Moreover, the peak of upwelling occurred a couple of days later when water the temperature near the northern coast decreased to 11 °C. Thus, upwelling of colder water took place in the northern part of the gulf and the vertical profile presented here describes the onset of the upwelling. As a consequence of upwelling, slightly saltier water (> 5.7 g kg^{-1}) at the northernmost station was observed as compared with salinity at the four closest stations (in the range 20–29 km; Fig 8h). In the southern part of the transect, the upper mixed layer salinity up to 6.0 g kg^{-1} was observed. The saltier water in the southern part was probably an outcome of eastward advection along the coast. Thus laterally three water types with different properties were observed in the upper layer: warm and saltier in the southern half of the transect, cold and fresher at the northernmost edge of the transect, and warm and freshest water in between (Fig. 8g–i). The latter warmer and fresher water appeared as lateral density minimum zone in the upper layer. It is noteworthy that the temperature (15.8–16.8 °C), salinity (5.5–6.0 g kg^{-1}) and density (3.1–3.5 kg m^{-3}) ranges in the upper layer in this survey were much narrower than they were in the previously-described case, when upwelling along the southern coast was observed. The center of the DP was located at around 70 m depth, and it was present only in the southern part of the transect. Thus, the cross-sectional area occupied by water beneath the DP was much smaller than in the previous case when upwelling near the southern coast appeared. Likewise, the density range was smaller — maximum density along the transect was 7.2 kg m^{-3}.

In conclusion, opposite to easterly winds, westerly winds were resulted in upwelling along the northern coast and caused much weaker lateral and vertical density gradients in the profile. Lateral (in the surface layer), and vertical density differences throughout the transect during southern upwelling on 15 August 2006 were 3.3 kg m^{-3} and 7.1 kg m^{-3}, respectively. In the case of upwelling along the northern coast on 20 July 2012, corresponding values were 0.4 kg m^{-3} and 4.0 kg m^{-3}; and in the case of neutral situation on 30 July 2013, 0.5 kg m^{-3} and 5.2 kg m^{-3}.

Moreover, wind forcing had a great effect on the cross-sectional areas occupied by different layers. We considered the upper layer from the surface to the UP depth, mid-layer from the UP to the DP and deep layer from the DP to the bottom. The largest area was occupied by the mid-layer, it covered 55% of the cross-section during neutral conditions and 43% (56%) during upwelling near the northern (southern coast), respectively. The share of the upper-layer water and deep-layer water was nearly equal during neutral conditions: 23% and 21%, respectively. In case of upwelling near the southern coast, the upper layer occupied only 14% and the deep layer 30% of the section. During upwelling near the northern coast, situation was reversed: the upper layer covered 48% of the section while the deep layer only 9%. This pattern can also be seen in other upwelling events near the northern and southern coast (Figs. 2–3).

Pycnocline variations in 1981–2013

In order to estimate past inter-annual pycnocline variations, the Kalbådagrund wind data from 1981–2013 were used in the regression equations derived for the data presented in Fig. 6c and d. Only the data from the period with seasonal thermocline (May–September) were used. The UP neutral and upwelling conditions near both coasts were distinguished using criteria for wind stress based on pycnocline slopes defined in this study (*see* Fig. 6c). Analogously, the 2–6 day mean ENE wind stress was used. Neutral conditions were assumed for wind stress > –0.04 and ≤ 0.02 N m^{-2}, southern upwelling for wind stress > 0.02 N m^{-2} and northern upwelling for wind stress ≤ –0.04 N m^{-2}. Inter-annual variations in the occurrence of favorable winds for northern and southern upwellings as well as for neutral conditions are shown in Fig. 9a.

There was a slight seasonality in the occurrence of different patterns. Winds producing neutral conditions in the gulf were more frequent in summer (June–August, 19–20 days in a month), whereas in May and September they occurred on 15–16 days in a month. Southern upwelling occurred on 3–7 days in a month, with minimum in July (3.5 days) and maximum in May (7.5 days). Northern upwelling had lowest occurrence in April–May (6–6.5 days in a month) while in summer its occurrence increased and in September it was 9 days.

All three types of pycnocline slopes can had considerably different occurrence rates. In several months, northerly upwelling-favorable winds did not occur at all, but months with > 20

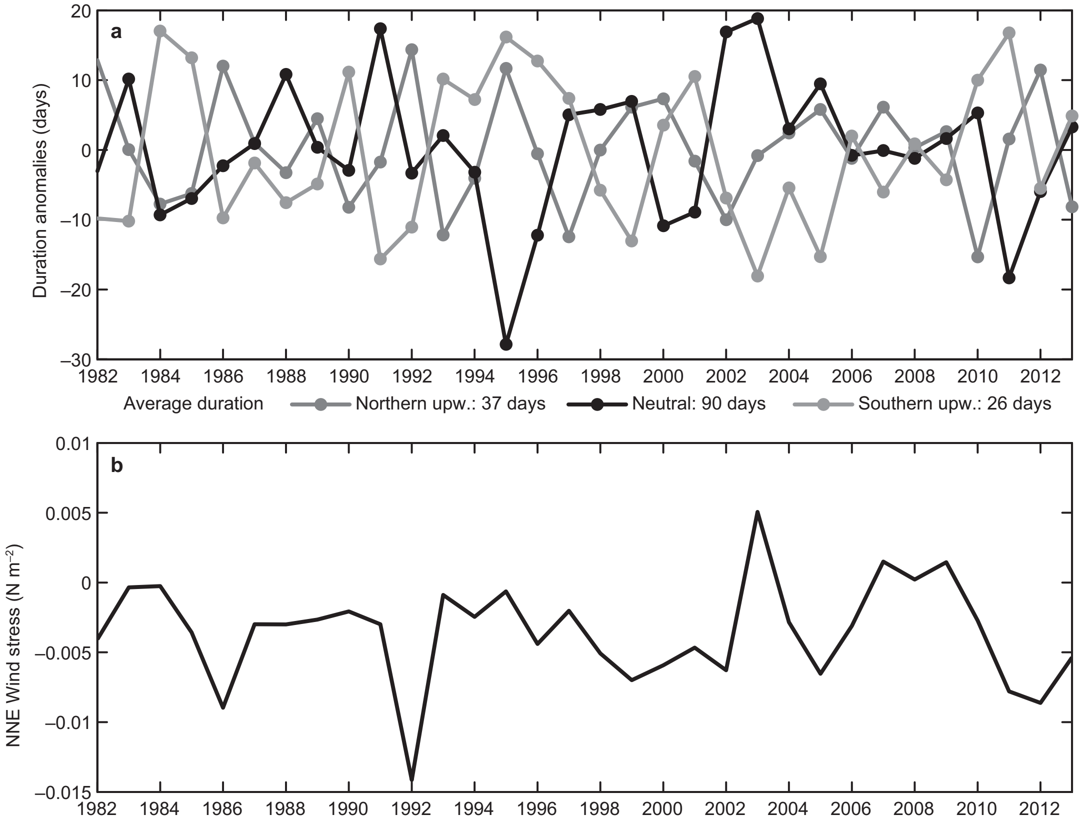

Fig. 9. (**a**) Inter-annual variations in the duration of favorable wind for northern and southern upwellings as well as for neutral conditions. Average durations are shown in the legend and are subtracted from the data series, which are presented as deviations from the average. (**b**) Inter-annual variations in average seasonal NNE wind stress (N m^{-2}) that represents wind stress affecting DP inclination. Calculations were made only for May–September.

days with such winds can be found from time series as well (July 1987, July 1995 and September 2005). Months without winds generating southern upwelling were even more frequent. The highest occurrences (> 17 days month) of southern upwelling were found for May 1984, September 1990, May 1996, and August 2006. High occurrence was also found for September 2001, however only 65% of the wind data were available for that month.

Average May–September occurrences in 1981–2013 were 90, 37 and 26 days for neutral conditions, northern upwelling and southern upwelling, respectively. It can be expected that in those years when winds generating neutral conditions had low occurrence (Fig. 9a), the gulf was more dynamic and hydro-physical fields were generally more variable. Interestingly, there is not always clear negative correlation between inter-annual occurrence of upwelling near the northern and southern coast. There were several years when upwellings at both sides of the gulf were more frequent than normally (1995, 2000, and 2011) and, therefore, neutral conditions were less common. In contrast, occurrences of neutral conditions were higher than long-term average in several years (1991, 2002–2003) as well.

Based on the regression calculated in this study (Fig. 6d), corresponding wind stress for the leveled DP is –0.008 N m^{-2}. Monthly average wind stress was below this value in 25% of cases. Annual (May–September) averages were in most cases in the range from –0.008 N m^{-2} to 0.002 N m^{-2} (Fig. 9b), which gives the inclination from 0 to –0.16 m km^{-1}. The two most extreme years were 1992 (–0.014 N m^{-2} corresponding to the DP slope of 0.10 m km^{-1}) and 2003 (0.005 N m^{-2} corresponding to the DP slope of –0.21 m km^{-1}). It means that in 1992 the halocline was on average 1.6–1.9 m higher near the southern coast while in 2003 it was 3.6–4.2 m higher near the northern coast.

Nevertheless, no significant long-term trend in inclinations of the DP and UP could be detected in the wind data analysed by us.

Discussion

In our study we found considerable variations in temperature and salinity, as well locations of the two pycnoclines.

Winds from ENE were the most favorable for the upwelling-event generation along the southern coast, but those winds also supported westward advection of fresher, riverine water in the upper layer and, thus, strengthened the UP. WSW winds had an opposite effect: saltier water was transported into the gulf in the upper layer and haline stratification was reduced. In spring, when thermocline was absent, westward advection of low-salinity water stabilized the water column and separated the upper layer from the intermediate layer. Such vertical (haline) buoyancy gradient may create pre-conditions for spring algal-bloom initiation before the water temperature has increased above the temperature of maximum water density (2.5–2.9 °C) (Kahru and Nõmmann 1990, Lips *et al*. 2014).

In our study, we found that in summer the UP could either shoal to the surface or penetrate down to 46 m. It means that in the latter case, nutriclines were well below the euphotic zone (Luhtala and Tolvanen 2013) and, therefore, nutrients were not available for primary production.

Upwelling at one coast usually means downwelling near the opposite coast, hence, primary production is affected in different ways near the southern and northern coasts of the gulf. As the effects of upwelling near the southern and northern coasts differ in terms of the salt flux and resulting buoyancy flux along the gulf, also its effects on primary production differ.

In the deep layer, the most prominent feature is the penetration/relaxation of the salt wedge (Elken *et al*. 2003), which has lower oxygen concentration and might be hypoxic (Liblik *et al*. 2013). In the present study, we found that DP depth considerably varies across the gulf. Thus, depending on wind conditions, hypoxic salt wedge might have considerably different vertical location near the northern and southern coasts. Long-lasting north-easterly winds might lift up the salt wedge towards the northern coastal slope to 43 m depth while south-westerly wind pushes the salt wedge deeper there. In conclusion, the wind not only affects the location of the hypoxic salt wedge along the thalweg (Liblik *et al*. 2013) but across the gulf as well.

The mean UP inclination found in this study was 0.10 m km^{-1}, i.e. on average the UP was approximately 3 m shallower near the southern coast. This corresponds to the general circulation scheme in the gulf where the residual circulation pattern includes outflow in the upper layer as expected from semi-analytical solutions (e.g. Valle-Levinson 2008) and as it is observed in various locations in the gulf (Liblik and Lips 2012, Liblik *et al*. 2013, Suhhova *et al*. 2015). The average inclination of the UP (and the regression line in Fig. 7c) might indicate that in general, less wind forcing is needed to generate upwelling near the southern coast. Laanemets *et al*. (2009) suggested that wind forcing with the same strength generates more intense upwelling near the southern coast as compared with that near the northern coast due to the steeper bottom slope along the southern coast.

In the Gulf of Finland salty-water inflows from the Baltic Proper in the deep layer, freshwater flux is from atmosphere and rivers and outflow of the mixture of the two water masses is through the upper layer. Water renewal time in the gulf is an important factor for many, also ecological, processes (e.g. Andrejev *et al*. 2004b).

Without wind forcing, the UP would be approximately 7 m shallower near the southern coast, which is very close to the average inclination obtained from the 34 surveys. Thus, we can assume that the 34-surveys average thermohaline structure roughly represents windless situation and baroclinic part of the circulation in the gulf. Applying the Cunningham (2000) geostrophic stream function to the mean temperature–salinity field gives the average seaward velocity of 3.6 cm s^{-1} in the upper 30-m layer if considering the reference pressure at 30 db. In reality, the prevailing wind forcing slows down the estuarine circulation (Elken *et al*. 2003) and reduces the UP difference between the two coasts to 3 m since the average airflow is towards NE (Keevallik and Soomere 2010). Considering that wind slows down the estuarine circulation by approximately 50% and the area of the cross-section from Aegna to Porkkala is about 1.05 km^2, the outflow from the gulf would be 600 km^3 y^{-1}. This value agrees with the earlier water-balance estimation by Alenius *et al*. (1998) and suggests the water residence time in the gulf to equal 2 years. Anyhow the outflow is not uniform throughout the gulf. This stems from the fact that the isopycnals are not straight lines across the gulf (*see* Fig. 5 and Stipa 2004). Likewise, Elken *et al*. (2011) suggested that density distribution averaged over several years have curve-like shape, especially in the upper layer.

Andrejev *et al*. (2004a) and Elken *et al*. (2011) suggested that the residual flow field in the gulf is characterized by several circulation cells. We found variability of local inclinations to be high; the strongest UP inclinations that correspond to the strongest seaward flow tended to be in two ranges: 3–9 km and 15–26 km. Thus, a quite persistent outflow area, as was suggested by Andrejev *et al*. (2004a), might exist in the Gulf of Finland while in some cases the most intense outflow could exist in the southern part of the gulf. Our data, however, did not allow us to confirm the findings of Andrejev *et al*. (2004a) with high confidence. Current measurement campaign or long-lasting salinity measurements across the gulf (Kikas and Lips 2016) probably can confirm/refute the existence of a persistent residual flow system. It should to be noted that our study area is topographically very complicated. Peninsulas, islands and shoals in combination with strong thermohaline gradients create conditions favorable for eddies (e.g. Zhurbas *et al*. 2008). Thus, on top of the estimated basin-wide baroclinic flow, strong mesoscale variability exists.

The mean DP slope found in our study was –0.07 m km^{-1}, which means that the DP is located on average 1.2–1.5 m shallower near the northern coast. However, due to high variability of the DP depth (*see* Fig. 6d) we cannot confirm that this difference between the two coasts really exists. The absence of the DP slope means that the approximately-same-velocity inflow to the gulf exists in the intermediate and near-bottom layers.

Pycnoclines inclined across the gulf occur regularly, as the UP (DP) slopes were in 59% (50%) of the cases lower than –0.20 m km^{-1} or higher than +0.20 m km^{-1}. Both pycnoclines are sensitive to changes in wind forcing, but their reaction times are quite different and the inclination directions opposite. The shallower UP near the southern coast was associated with the seaward (ENE) wind a few days before the survey, which is the result of northward, cross-gulf Ekman drift in the upper layer. Likewise, the DP inclination correlated with the seaward (NNE) wind, but the reaction time was few weeks and as a result the DP was shallower near the northern coast. This indicates that the exchange flow between the Gulf of Finland and the Baltic Proper cannot always be considered a two-layer system as in many other estuaries in the world (Geyer and MacCready 2014). Three-layer estuarine circulation systems exist in Juan de Fuca Strait (Thomson *et al*. 2007) and several fjords (Valle-Levinson *et al*. 2014). However, the leveled average DP slope suggests that three-layer circulation is not stationary and depends largely on prevailing wind forcing.

Explanation for saltier water appearance at the northern coast might be a cyclonic circulation scheme in the deep layer. It implies that if the salt wedge is thick enough it does not mix (diffuse) vertically in the inner (eastern) part of the gulf and the return (seaward) flow can be observed at the northern coast as higher salinity in the near-bottom layer. Note that sea depths at the northern coast of the gulf are smaller than at the southern coast. Another explanation might be the specific chain of water movements across the gulf in the case of easterly winds (Fig. 10): (1) the northward Ekman transport in the upper layer near the southern coast is compensated by (2) upwelling of the intermediate layer water near the southern coast and (3) southward flow in the intermediate layer which in turn is compensated by (4) the northward flow in the deep layer and its upward movement along the northern coastal slope.

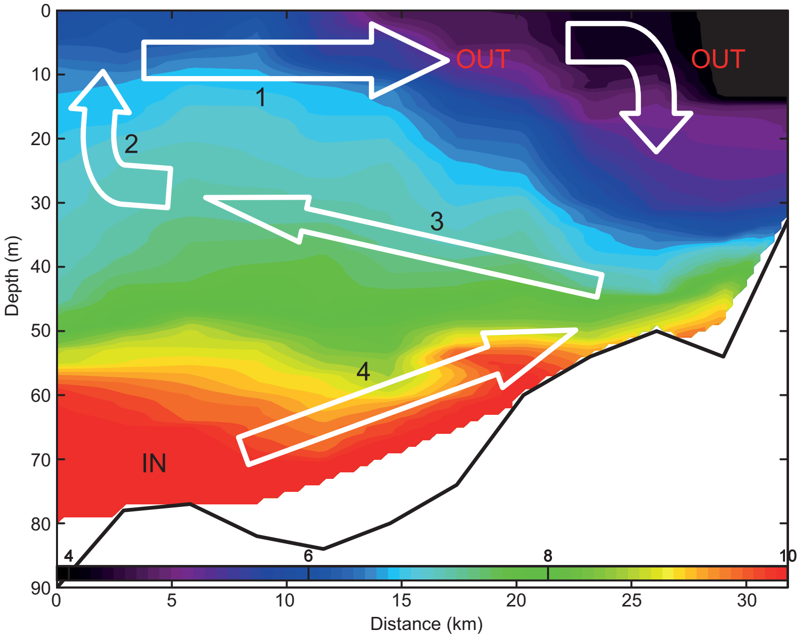

Fig. 10. Salinity distribution and water circulation in the Gulf of Finland during upwelling along the southern coast on 15 August 2006. (1) The northward Ekman transport in the upper layer near the southern coast is compensated by (2) upwelling of the intermediate layer water near the southern coast and (3) southward flow in the intermediate layer which in turn is compensated by (4) northward flow in the deep layer and its upward movement along the northern slope. Inflow (IN) and outflow (OUT) regions were found based on the salinity change in comparison with the previous surveys on 25 July and 8 August 2006.

Upwelling-favoring winds for the southern and northern coasts had distinct effects on the share of water masses in the gulf. Due to different characteristics of the upper and deep layers, wind generated transport had a pronounced effect on water and matter exchange with the Baltic Proper. In the case of upwelling near the southern coast, outflow prevails in the upper layer and cross-sectional area occupied by the upper layer water decreases while the area occupied by deep layer water increases (Fig. 11, left-hand-side panel). Due to different properties of the upper-layer water (high temperature, low salinity, nutrient depleted and high oxygen) and the deep-layer water (low temperature, high salinity, nutrient rich and low oxygen) in summer, positive flux of nutrients and salt can be expected from the Baltic Proper during easterly winds. On the other hand, heat and oxygen fluxes are likely negative.

In the case of upwelling near the northern coast, inflow to the Gulf of Finland prevails in the upper layer. However, this eastward transport is impeded as the gulf fills with water and sea level rises in the easternmost part of the gulf. Consequently, not only water transported towards the south (which results in upwelling near the northern coast) causes downwelling near the southern coast, but also the convergence of the inflowing water contributes to it (Fig. 11, right panel). As a result, the area occupied by warm and fresher upper-layer water increases in the case of upwelling near the northern coast. Thus, downwelling near the southern coast penetrates deeper and causes accumulation of the warm upper layer water in the gulf. As a result, upwellings near the northern coast create positive lateral heat and oxygen fluxes from the open Baltic Sea while salinity and nutrients in the gulf decrease due to outflow in the deep layer. Downwellings near the southern coast probably reach deeper also because of the steeper coastal slope (Laanemets *et al*. 2009).

In the chapter "Selected UP patterns", we analysed one prominent upwelling event near the southern coast and one near the northern coast. However, as seen in Fig. 7a, even stronger wind

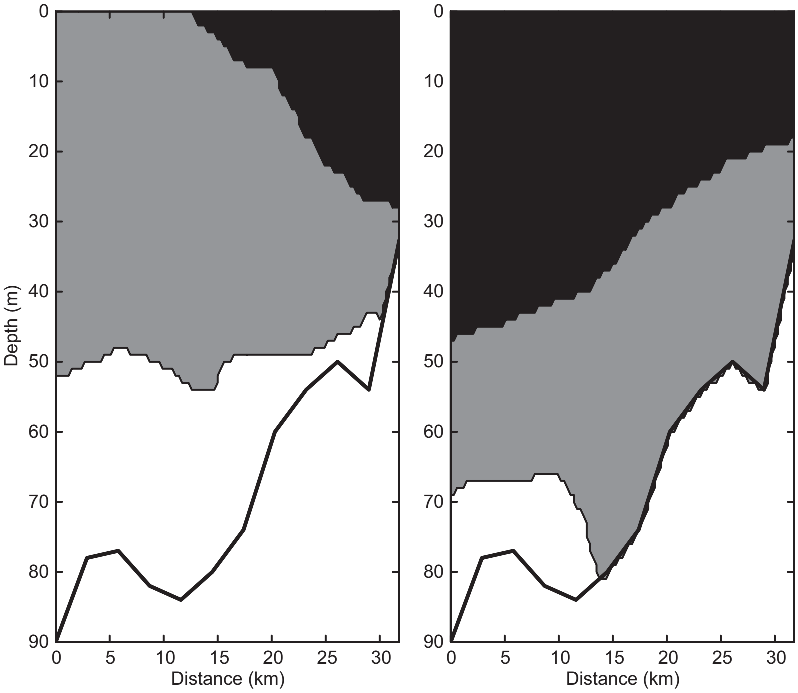

Fig. 11. Distribution of different water masses: upper mixed layer (above the UP, black), cold intermediate layer (between the UP and DP, grey), and deep layer (below the DP, white) in the case of easterly winds on 15 August 2006 (left) and westerly winds on 20 July 2012 (right).

impulses that those can occur. Ferrybox measurements along the Tallinn–Helsinki transect (Kikas and Lips 2016) indicated that the peak of the northern upwelling (*see* also Fig. 8g–i) occurred a few days later. Moreover, Uiboupin and Laanemets (2009) showed by remote sensing that northerly upwelling could cover around half of the gulf surface area.

Past pycnocline variations were estimated using regression analysis (*see* Fig. 6c and d) and the Kalbådagrund wind data from 1981–2013. For the UP, three different conditions were separated: neutral, upwelling near the northern coast and upwelling near the southern coast. Thresholds between the different conditions were chosen on the basis of observed pycnocline slopes and they were in accordance with remote sensing observations (*see* Table 1 in Uiboupin and Laanemets 2009). We found no clear trend in occurrences of different conditions.

Conclusions

The two pycnoclines showed considerable variations in inclination, strength and depth in response to wind forcing in the Gulf of Finland. The most conspicuous result was different behavior of the two pycnoclines. The shallower UP near the southern coast was associated with the seaward (ENE) wind few days before the observation. DP inclination correlated best with seaward (NNE) wind as well, but the reaction time was few weeks and as a result the DP was shallower near the northern coast.

In addition, the following conclusions can be drawn from our study:

- Pycnoclines inclined across the gulf occur regularly, the UP (DP) slopes were in 59% (50%) of the cases smaller than -0.20 m km^{-1} or greater than $+0.20$ m km^{-1}.
- On average, the UP was 3 m shallower near the southern coast. This result might indicate that less wind force is needed to cause upwelling near the southern coast.
- On average, inclination of the DP did not differ much from zero, which indicates that average velocities of inflow were rather similar in the deep and intermediate layers.
- The greatest inclinations of the UP and DP were steeper than 1.5 m km^{-1} and 0.6 m km^{-1},

respectively.

- The UP penetrated down to 46 m near the southern coast as a result of a downwelling event.
- The DP was lifted up to 43 m depth at the northern coast.
- Haline stratification stabilized the water column and separated the upper layer from the intermediate layer in spring when seasonal thermocline was not present.
- Easterly winds that generated upwellings near the southern coast also caused stronger stratification and horizontal temperature, salinity and density gradients across the gulf while during westerly winds and upwelling near the northern coast, the horizontal and vertical gradients were weaker.
- Easterly winds caused outflow in the upper layer and relatively shallow downwelling along the northern coast while westerly winds caused inflow in the upper layer and deep downwelling along the southern coast.
- Less wind force was needed to generate upwelling along the southern coast of the gulf as compared with wind force needed to generate upwelling along the northern coast of the gulf.
- The average density distribution and respective geostrophic current estimate confirmed the earlier estimates of annual outflow of 600 km^3 in the upper 30-m layer and water residence time of 2 years in the gulf.
- No clear trend was found in occurrences of wind conditions favorable for different inclinations of the UP and DP.

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