Estonian Journal of Engineering, 2008, **14**, 1, 29–41 doi: 10.3176/eng.2008.1.03

On the influence of the sequence of coastal upwellings and downwellings on surface water salinity in the Gulf of Finland

Lembit Talpsepp

Institute of Marine Systems, Tallinn University of Technology, Akadeemia tee 21, 12618 Tallinn, Estonia; talpsepp@sea.ee

Received 26 April 2007, in revised form 31 January 2008

Abstract. The results of the observations of upwellings and downwellings near the southern coast of the Gulf of Finland in the Pakri Bay region in 1995–1996 are presented. Long-term currents, temperature and salinity measurements at single points and repeated CTD-castings on the transects perpendicular to the coastline show that the average properties of the water masses across the Gulf of Finland may be substantially modified by sequences of upwellings and downwellings of different extent. In particular, fresher water patches in the middle of the Gulf of Finland apparently have been formed as a result of a sequence of upwellings in 1987 and 1990.

Key words: Gulf of Finland, Pakri Bay, upwelling, downwelling, water salinity, surface layer.

1. INTRODUCTION

The upwelling-downwelling phenomena are often observed in many regions of the Baltic Sea [1–4]. The majority of relevant articles are devoted to the study of single events. The situation where a sequence of upwellings is followed by downwellings of comparable extent is rarely observed; for example, upwelling-downwelling cycles in a sensitive coastal system are modelled in [5]. Sequences of upwellings and downwellings have a more complicated influence on the water structure than a single event. In the present study we observe the sequence of upwelling-downwelling cycles in the Gulf of Finland in summer period caused by variable wind. We rely on the data gathered in the summer periods of 1995 and 1996 and use field measurements data from 1987 and 1990.

Coastal upwellings and downwellings are generally not periodic phenomena. In the conditions of the Gulf of Finland they are mainly generated by the influence of specific large-scale patterns of wind stress, induced by cyclones and anticyclones with spatial extent of 1000–3000 km. A chain of such structures, running over the Gulf of Finland, may generate upwellings or downwellings near the coasts of the Gulf with a certain periodicity. Elaborating the ideas of recent investigations [6,7], in this paper we concentrate on the sequence of these phenomena and their influence on the water body. The single upwellings in observed sequences are of different extent and magnitude, depending on weather conditions, but always influencing the water properties in the surface layer. Based on the analysis of historical experimental measurements we show how water temperature and salinity vary under the influence of sequent upwellings and under intermittent upwellings and downwellings. As an example, we show that the formation of the water structure with less saline water in the middle of the Gulf, observed during field experiments, is probably the result of a cycle of sequential upwellings near the southern coast and after that near the northern coast of the Gulf of Finland.

2. MEASUREMENTS

The present study of the influence of upwellings and downwellings on water properties in the Gulf of Finland partly relies on the data from the mooring stations near the southern coast of the Gulf in 1995–1996. The devices measured the speed and direction of currents, the water temperature and salinity. The region of measurements was near Pakri Bay (Fig. 1). As the thickness of the upper mixed layer in the Gulf of Finland was up to 10–20 m in summertime [8], in order to describe the dynamics and properties of water masses in both surface and deeper layers, one Aanderaa current meter was deployed at the 7 m level below water surface and the other at the 37 m level, about 3 m above the sea bottom. The CTD-castings at stations, shown in Fig. 1, were carried out every 2–3 days. The measurements were performed from 7 July to 14 August in 1995 and from 22 August to 14 September in 1996. A gap of nearly two weeks in the CTD-measurements in 1995 was covered by current and temperature measurements at the mooring station. The CTD-castings were performed with one nautical mile distance between two neighbouring stations along two lines, perpendicular to the axis of the Gulf. The data were used to study the time dependence and spatial distribution of water masses during upwelling and downwelling events.

Another source of data of the present paper are weekly repeated CTD-mappings, carried out in the central part of the Gulf of Finland (region 2 in Fig. 1) in the summers of 1987 and 1990. The CTD-castings covered the Gulf of Finland from the Estonian coast up to the Finnish coastal area with the distance of two nautical miles between the stations. More than 300 CTD-castings in 1987 and nearly 400 CTD-castings in 1990 enabled to get detailed pictures of water temperature and salinity distribution and of water circulation in the central part of the Gulf of Finland. The data of current measurements at the mooring station supported the circulation schemes, constructed from CTD-measurements, but are not analysed in this paper.

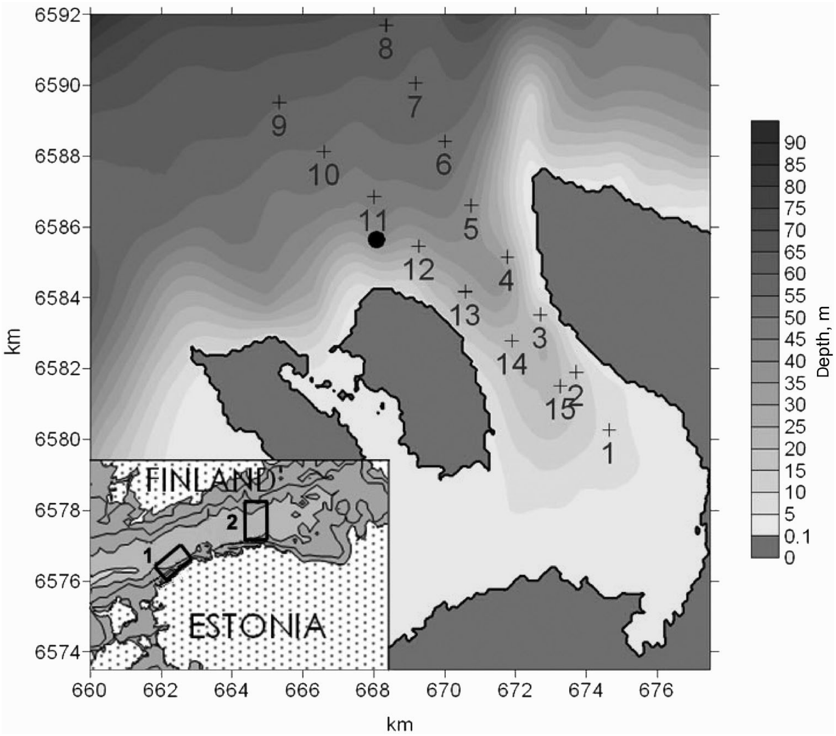

Fig. 1. The location of CTD-castings and mooring station (black circle) in the summers of 1995 and 1996 in the Pakri Bay region (region 1 in the small map), where upwelling observations were carried out. Region 2 in the small map shows the location of the CTD-mapping grid in the middle part of the Gulf of Finland in 1987 and 1990.

3. RESULTS

Four strong upwellings, bringing the near-bottom more saline and colder water to the surface, were observed near the southern coast of the Gulf of Finland (Fig. 2) during the summer period of 1995 on the basis of water temperature and salinity measurements at mooring stations. The resulting salinity front in the surface layer was situated at 5–8 km from the coast. The upwelled water did not reach the sea surface at the site of the mooring station. Thus this upwelling was not present on the sea surface but was rather strong in the subsurface layer. The observed upwellings are of different extent, for example, during upwellings on 17 July and 31 August the water with the temperature of about 4 °C is lifted to the 7 m level, but on 4 August the temperature of the lifted water is about 6 °C and on 17 August only 9–10 °C. After the relaxation of upwellings, more saline water remained in the surface layer, which warmed up in some days without a sharp temperature front.

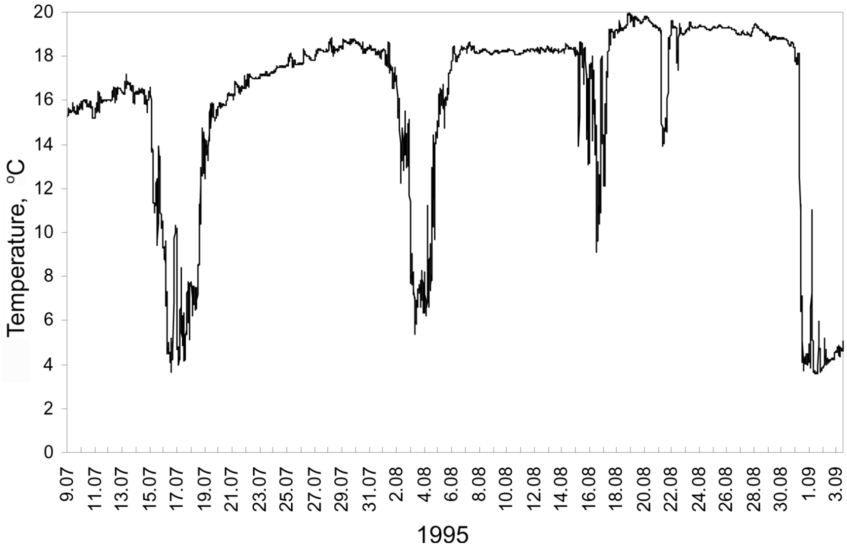

Fig. 2. The temperature variation in 1995 at the depth of 7 m near the southern coast of the Gulf of Finland at 59N 22, 27′, 23E 57, 26′, measured by an autonomous mooring station with Aanderaa current meter.

Two strong downwellings (on 24 July and 27 August) and two smaller ones (on 9 July and 20 July) were observed in the same regions during the period of observations in 1995 (Fig. 3). Due to the position of the mooring instrument near the bottom, only stronger downwellings were detected. The vertical structure of water masses during the experiment is presented in Figs. 4 and 5 at two different

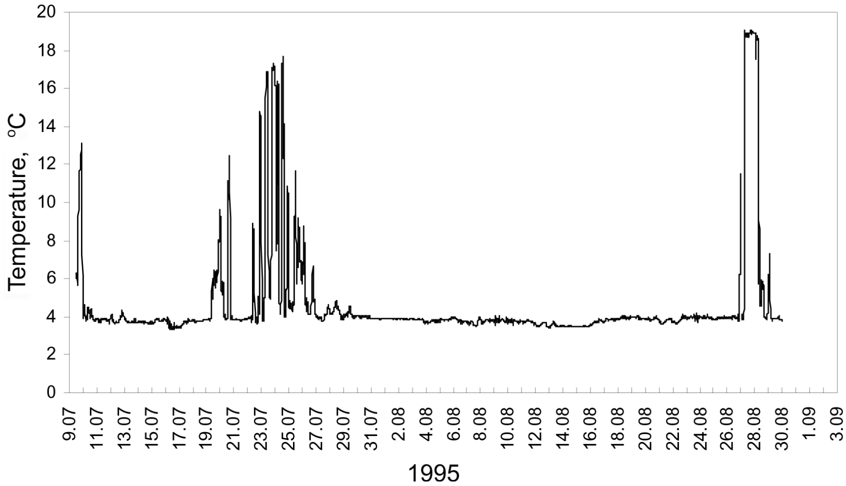

Fig. 3. The temperature variation at the depth of 38 m near the southern coast of the Gulf of Finland at 59N 22, 27′, 23E 57, 26′, measured by an autonomous mooring station with Aanderaa current meter.

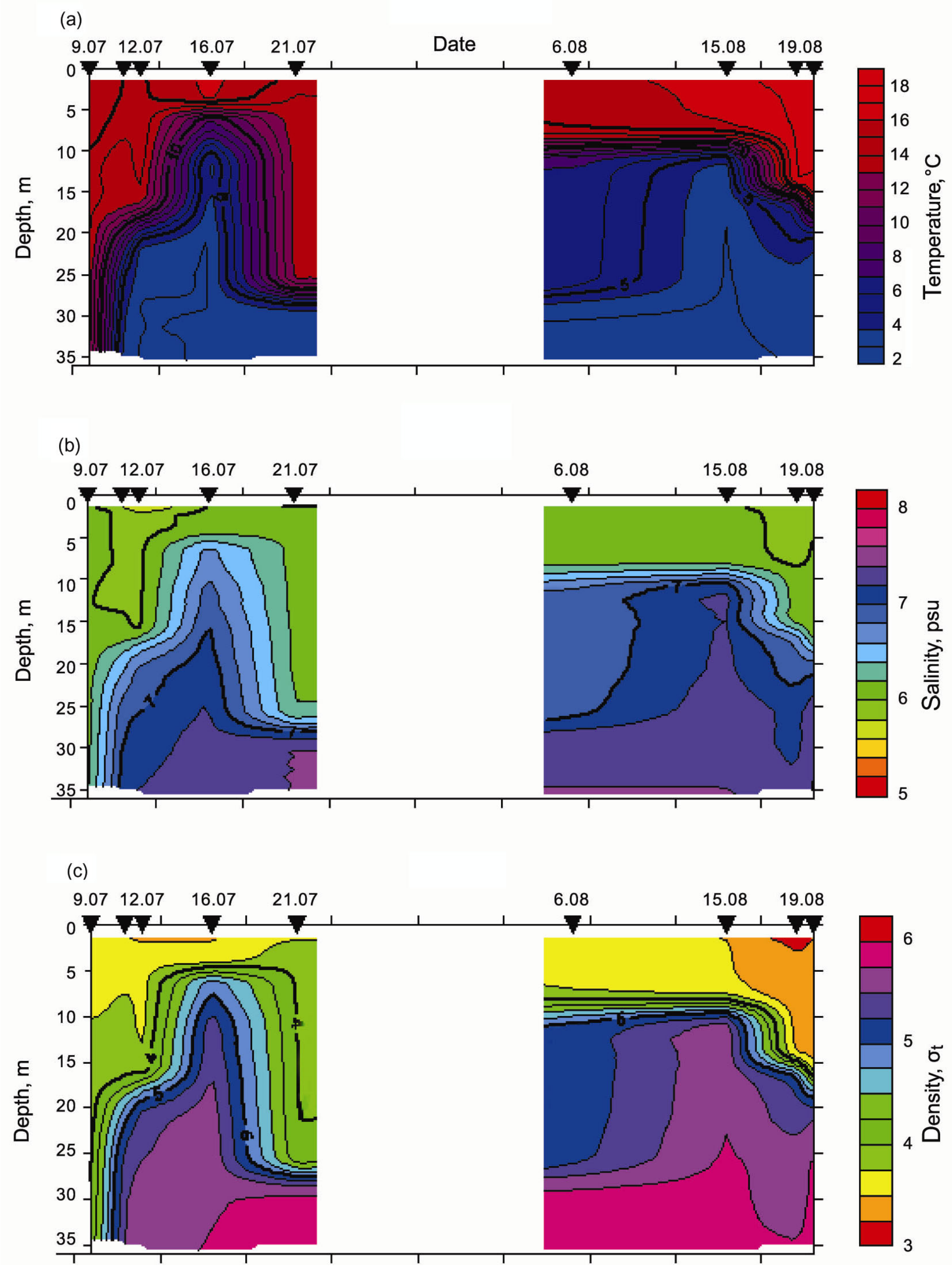

Fig. 4. Vertical profiles of temperature (a), salinity (b) and density (c) at station 4 in the Pakri Bay in July–August 1995.

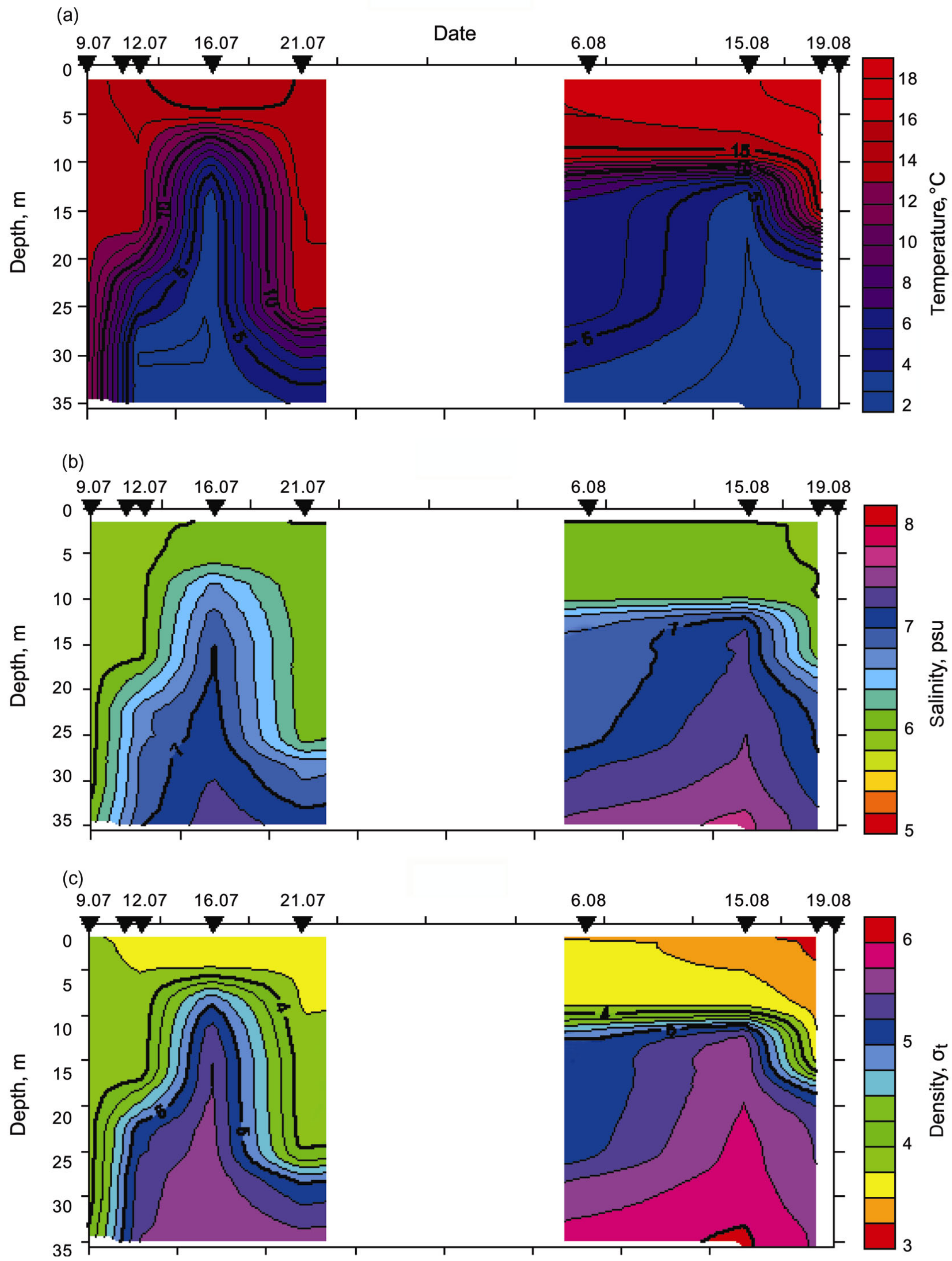

Fig. 5. Vertical profiles of temperature (a), salinity (b) and density (c) at station 12 in the Pakri Bay in July–August 1995.

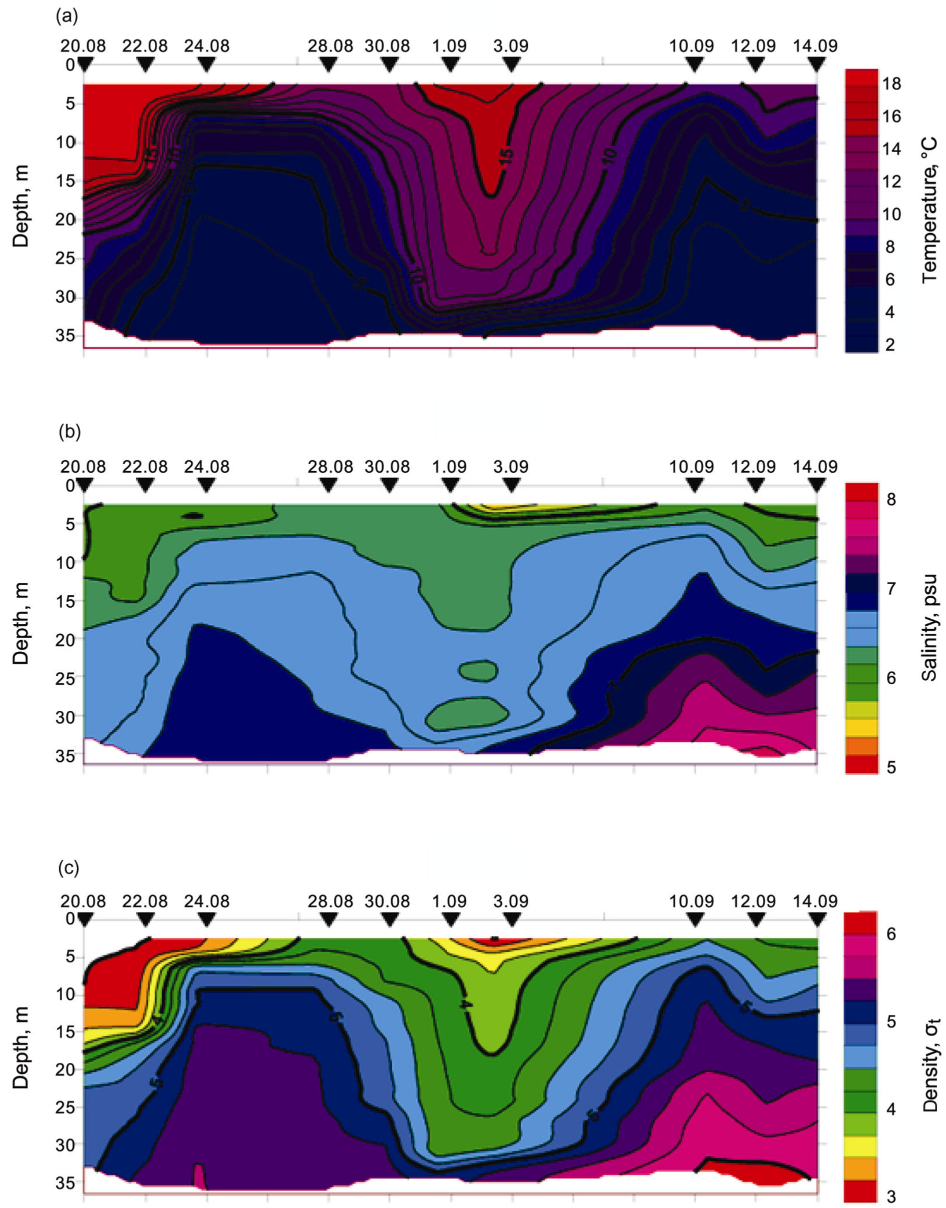

Fig. 6. The time-series of the temperature (a), salinity (b) and density (c) profiles, plotted on the basis of CTD-castings at the mouth of the Pakri Bay near the southern coast of the Gulf of Finland in 1996.

stations (Nos. 4 and 12 in Fig. 1) at the mouth of the Pakri Bay, situated at the distances of 2 or 6 km to the east from the mooring station, respectively. The measurement dates are shown in the figures. The temperature, salinity and density data are interpolated between single measurements. During the experiment there was a gap in measurements due to technical reasons, thus some results are extrapolated.

We observed two strong upwellings during the period of CTD-measurements. The upwelling on 6 August is different from the earlier one (Figs. 3, 4), because it brought bottom layer water into the intermediate layer. Due to the gap in measurements, the starting date of the second upwelling cannot be exactly determined.

The temporal course of the water temperature, salinity and density, reflecting the influence of two upwellings at the entrance of the Pakri Bay in 1996, is presented in Fig. 6. These upwellings are stronger than those observed a year before, so the water with the temperature lower than 10 °C was lifted to the surface. Figure 6 clearly indicates that the salinity and temperature distributions in the surface layer are substantially modified as a result of the upwellings.

The presented results of field measurements confirm that sequences of upwellings and downwellings are rather common phenomena in the summertime near the southern coast of the Gulf of Finland. Unfortunately, no similar data are available about the situation near the northern coast of the gulf. Relying on the Ekman theory [9] and accounting for the extent of wind effects, necessary for producing a strong up- or downwelling [4,6], we may assume that simultaneously with a strong downwelling near the Estonian coast, near the Finnish coast an upwelling took place and saline water was lifted to the surface there. A similar situation was observed in Figs. 4c and 5c of [10] and during field measurements carried out by U. Lips in the Gulf of Finland (unpublished results, personal communication). Consequently, one may assume that simultaneously with two strong downwellings in 1995 (Fig. 3) near the Estonian coast, upwellings near the Finnish coast occurred. This description suggests that the hydrography in the Gulf of Finland is at times substantially influenced by intermittent upwelling-downwelling cycles.

A similar conclusion may be derived from the results of hydrophysical measurements of 1987 and 1990. The phenomena observed during these measurements are apparently in direct correlation with upwelling-downwelling cycles. In 1987 a strong upwelling was observed near the Finnish coast between 7 and 11 July (see Figs. 4 and 5 in [10]). Another, weaker upwelling started before 17 July. It pushed fresher water back northwards from the southern coast of the gulf. As a result of these two events, more saline water was brought to the surface layer near both of the coasts. Accordingly, fresher water was observed outside the coastal area of the Gulf of Finland (but still near to the southern coast).

Further evidence of the influence of the up- and downwellings provide measurements, made in 1990, when a fresher water stripe was observed in the middle of the gulf. In the summer of 1990, repeated CTD-castings covered a whole cross-section of the Gulf of Finland, except very shallow coastal areas. As an example, Fig. 7 presents the observed salinity distribution along meridian 26°E (region 2 in Fig. 1). The data show that the less saline water existed in the surface layer in the middle part of the gulf and more saline water was observed both near the southern and the northern coasts. At the same time there was no remarkable difference in the temperature across the gulf. Similar stripe-like water structure is presented in Fig. 4 of [10]. The stripes, observed in 1987 and 1990, were about 10 miles wide with prolonged shape and extended to about 100 km along the axis of the Gulf of Finland.

The situation presented in Fig. 7 was observed 5–7 days after a strong upwelling event near the southern coast. It pushed the resulting salinity front in the surface layer nearly to the middle of the gulf. After relaxation of the upwelling, the salinity front moved southwards to some extent; however, more saline water stayed near the southern coast and was warmed up in the surface layer. A few days before this event, our observations showed that the water with a salinity of 3.8 psu covered the southern part of the Gulf of Finland whereas after relaxation the salinity was 4.2 psu.

The presented results suggest that the observed cross-sectional distribution of water properties with the stripe of less saline water in the middle of the gulf represents a generic feature of surface water of the eastern and central part of the Gulf of Finland after spring ice-melting in summer and autumn. (The salinity of the surface layer on 5 May, 1987, is shown in Fig. 4 of [10], where the section of salinity along the axes of the Gulf of Finland just after ice melting is presented.)

The presence of the fresher water body in the middle of the gulf is traditionally attributed to the Neva River runoff into the eastern part of the gulf. The above observations suggest an alternative explanation. Most probably, the fresher water is a sort of "remnant" of original relatively fresh water that is preserved after strong upwelling near the southern coast. If it was created by river runoff,

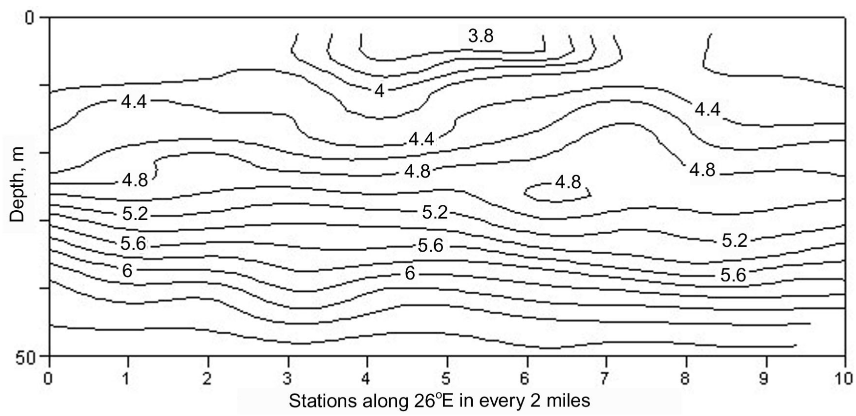

Fig. 7. The distribution of salinity (in psu) in the central part of the Gulf of Finland in summer 1990 after passing a cascade of cyclones and anticyclones. North (the Finnish coast of the Gulf) is on the right.

intense mesoscale dynamics [7] should have destroyed it soon. As our observations in 1995–1996 were carried out near the southern coast of the Gulf of Finland, they apparently reflected only the southern part of a similar structure. Also in [11], less saline water was discovered in the middle of the gulf.

4. DISCUSSION AND CONCLUSIONS

This investigation supports the opinion that sequences of up- and downwellings are the most probable mechanism explaining the existence of the fresher water observed in the middle of the Gulf of Finland. A strong upwelling near any coast of the gulf causes an increase of the salinity along this coast. After upwelling relaxation, more saline water remains in the surface layer near the coast. Thus a sequence of upwellings at the opposite coasts leads to the stripe of fresher water in the middle of the gulf.

This explanation implies that the fresher water stripes is a non-permanent phenomenon. Relying on numerous CTD-castings in the Gulf of Finland, we found that fresher water stripes in the middle of the gulf occur during the second half of the summer after a sequence of two upwellings, one near the northern coast and another near the southern coast of the gulf. Experiments in 1995 and 1996 show that such sequences of upwellings can often take place, because up- and downwelling usually mirror each other at the opposite coasts.

A sequence of downwellings and upwellings produces more saline coastal waters. The less saline surface water remains intact only in the central part of the gulf, forming a “stripe” of “original” less saline water from the surface layer that was formed before the cycle started. The less saline water, observed in the middle part of the gulf, is thus apparently the surface water, which covered the eastern part of the gulf in spring before any upwelling started.

Although some stages of the generation of the fresher water stripes are not properly documented, several arguments favour the presented mechanism. First, observed sequences of upwellings near both coasts of the Gulf of Finland. We have observed that these upwellings push fresher water far away from the coast. An observation of the situation confirmed that fresher water existed outside the coastal area. We have observed many fresher water stripes in the middle of the Gulf of Finland after sequent upwellings near both coasts. Thus, the presented hypothesis on the generation of fresher water stripes in the middle of the gulf is rather justified.

As the results of modelling show (Zhurbas, personal communication), the upwelled water as well as the surface water move away from the coast and may create meanders, mushroom- and tongue-like structures and patches. Thus the regular stripes of fresher water, observed in 1987 and 1990 (Fig. 7), may have acquired a different shape after some days or some weeks and therefore may not be recorded by other earlier measurements.

The measurements show that sequences of upwellings and downwellings along both coasts of the Gulf of Finland is a frequent phenomenon, having a remarkable influence on water masses near the coast. The observed upwellings and downwellings were of different extent, some lifted the near-bottom water to the near-surface layer, and others pushed the surface water far to the open part of the gulf.

The central conclusion from the observed phenomena is that specifically the normal less saline surface water remained only in the central part of the gulf, forming a stripe of fresher water that was well observed in 1990 [11] and 1987 [10]. We have observed also tongue-like salinity patterns and patches of water with different water properties [11], which are generated, to our opinion, by the sequence of upwelling-downwelling cycles in the Gulf of Finland. Finally, it should be noticed that upwelling-induced structures are modelled [5,6] and often observed from satellite images [12]. The vertical structure of water masses, presented in Figs. 4 and 5 at two different stations at the mouth of the Pakri Bay, shows that upwellings can not always be observed from the satellite. Therefore numerical modelling together with field measurements is needed for understanding the nature and history of specific cross-sectional distribution of salinity in the Gulf of Finland.

ACKNOWLEDGEMENTS

This paper was partly supported by the Estonian Science Foundation (grant No. 5869). The author thanks Tarmo Soomere for substantial suggestions for improving the manuscript. The author thanks also Svetlana Verjovkina and Tõnn Talpsepp for help in data processing.

REFERENCES

1. Gidhagen, L. Coastal upwelling in the Baltic Sea. Satellite and in situ measurements of sea-surface temperatures indicating coastal upwelling. *Estuarine Coastal Shelf Sci.*, 1984, **24**, 449–462.
2. Fennel, W. and Seifert, T. Kelvin wave controlled upwelling in the western Baltic. *J. Mar. Sci.*, 1995, **6**, 289–300.
3. Jankowski, A. Wind-induced variability of hydrological parameters in the coastal zone of the southern Baltic Sea – a numerical study. *Oceanol. Studies*, Gdansk, 2000, **29**(3), 5–34.
4. Haapala, J. Upwelling and its influence on nutrient concentration in the coastal area of the Hanko Peninsula, entrance of the Gulf of Finland. *Estuarine Coastal Shelf Sci.*, 1994, **38**, 507–521.
5. Carbonel, C. A. A. H. Modelling of downwelling-upwelling cycles caused by variable wind in a very sensitive coastal system. *Cont. Shelf Res.*, 2003, **23**, 1559–1578.
6. Myrberg, K. and Andrejev, O. Main upwelling regions in the Baltic Sea – a statistical analysis based on three-dimensional modelling. *Boreal Environm. Res.*, 2003, **8**, 97–112.
7. Andrejev, O., Myrberg, K., Alenius, P. and Lundberg, P. A. Mean circulation and water exchange in the Gulf of Finland – a study based on three-dimensional modelling. *Boreal Environm. Res.*, 2004, **9**, 1–16.

8. Alenius, P., Myrberg, K. and Nekrasov, A. The physical oceanography of the Gulf of Finland: a review. *Boreal Environm. Res.*, 1998, **3**, 97–125.
9. Lacombe, H. *Cours d'Oceanographie Physique*. Mir, Moscow, 1974 (in Russian).
10. Talpsepp, L., Nõges, T., Raid, T. and Kõuts, T. Hydrophysical and hydrobiological processes in the Gulf of Finland in summer 1987 – characterization and relationship. *Cont. Shelf Res.*, 1994, **14**, 749–763.
11. Talpsepp, L. Investigations of mesoscale hydrophysical processes in the Gulf of Finland in 1985–1990. *Proc. Estonian Acad. Sci. Ecol.*, 1993, **3**, 137–148.
12. Bychkova, I. A. and Viktorov, S. V. Use of satellite data for identification and classification of upwelling in the Baltic Sea. *Oceanology*, 1987, **27**, 158–162.

Rannalähedaste ap- ja daunvellingute vaheldumise mõjust Soome lahe pinnakihi soolsusele

Lembit Talpsepp

On toodud Soome lahe lõunaranniku lähedal aastatel 1995–1996 teostatud apvellingute (süvaveekergete) ja daunvellingute (pinnavee sukeldumiste) pika-ajaliste vaatluste tulemused. Lisaks pinnakihi ja põhjalähedase kihi hoovuste, temperatuuri ning soolsuse mõõtmisele poijaamade abil teostati korduvad CTD-sondeerimised kahel lõikel. Saadud tulemused näitavad, et korduvad apvellingud mõjutavad oluliselt vee omadusi Soome lahe ranniku lähedal. Tugevate ap- ja daunvellingute vaheldumine tekitab Soome lahe keskosas ulatuslikke magedama vee laike ning teisi struktuure. Apvellingute tulemusena jääb mõlema ranniku lähedale suhteliselt soolasem vesi.