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Seasonal variations in the vertical structure of temperature and salinity fields in the shallow Baltic Sea off the Kaliningrad Region coast

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Abstract. In this paper we describe the seasonal characteristics of the vertical thermohaline structure of the shallow waters of the southeastern part of the Baltic Sea off the Kaliningrad region using the field data of research cruises. The analysis of the original set of experimental data in 2003–2014 confirmed that heating and cooling processes occur, as a rule, at a depth of 30–35 m. The upper 5–10 m layer of water is involved in the heat exchange with the atmosphere. The depth of the thermocline varies from 10–30 m up to 17–35 m in spring and summer. Salinity field of the Baltic shallow water is characterized by a small range of variability in all seasons. Fluctuations in the measured values of salinity in coastal waters do not exceed 0.5 PSU (Practical Salinity Unit). The greatest variations in the salinity of coastal waters (up to 0.7 PSU) are characteristic of the

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upper layer 5 to 10 m thick in winter and summer. Average seasonal linear trends of temperature and salinity variation were obtained.

Introduction

Hydrology of the Baltic Sea basin has been investigated very well [*ESIMO*, 2004; *Mietus*, 1998; *Omstedt et al.*, 2014; *Rak and Wieczorek*, 2012; *Terziev et al.*, 1992; *Wulff et al.*, 2001; *Zakharchuk*, 2007]. However, the waters around the coast of the Kaliningrad region have not received sufficient study and description due to a number of reasons. Climatic description in the atlases (Atlas "Klimat morei Rossii i kluchevykh raionov Mirovogo okeana" [The map "The climate of the seas of Russia and the key areas of the World ocean", electronic source], Integrated national system of the World ocean information (ESIMO), official website URL: http://www.esimo.ru/atlas/Balt/1_1.html, assessed: 27.09.2015), [*Majewski and Lauer*, 1994] does not allow us to see the details and features of the seasonal variability of the thermohaline structure of coastal shallows waters. The HELCOM (Baltic Marine Environment Protection Commission, also known as Helsinki Commission) and ICES databases

(Baltic Sea monitoring data (HELCOM stations) [Electronic resource, The International Council for the Exploration of the Sea (ICES), Official website], URL: http://ocean.ices.dk/Helcom/Helcom.aspx?Mode=1, (accessed: 18.03.2014); CTD and Bottle data [Electronic resource, The International Council for the Exploration of the Sea (ICES), Official website], URL: http://ocean.ices.dk/HydChem/HydChem.aspx?plot=yes, (accessed: 18.03.2014) hardly represent the instrumental measurements in a twelve-mile zone of the Russian sector in the southeastern Baltic Sea at the coast of the Kaliningrad region.

It is also known [*Bowden*, 1988; *Zakharchuk*, 2007; *Zeleny and Smirnova*, 1974] that the regime of the thermohaline structure of the Baltic Sea waters is influenced by the general atmospheric circulation, continental runoff, and water exchange with the North Sea. Shallow coastal waters ranges the factors emphasized in [*Bowden*, 1988; *Omstedt et al.*, 2014; *Wulff et al.*, 2001; *Zakharchuk*, 2007], prioritising air temperature and wind, rainfall and river runoff, coastline exposure, and bottom topography. Water exchange with the North Sea becomes less important for the shallow coastal waters [*Matthäus*, 1992; *Wulff et al.*, 2001]. All these factors inevitably identify the regional specific properties of the coastal waters.

The objective of this paper is to describe the seasonal characteristics of the vertical thermohaline structure of the shallow waters of the southeastern part of the Baltic Sea off the Kaliningrad region.

The Data

The results of our study are based on the field data of 81 research cruises (20 cruises of the R/V "Professor Shtokman", 33 monitoring cruises to "Kravtsovskoye" oil field and 28 trips of smaller vessels and boats) and 45 purposeful observations on the oil D-6 oil platform. The works were carried out between May 2003 and December 2014. The total number of stations used in the study is 1263. A general scheme of the stations is shown in Figure 1. Geographically, the study site belongs to the Gdańsk basin of the Baltic Sea. Instrumental measurements of coastal waters parameters were conducted using the CTD90M probes manufactured by the Sea & Sun Technology (Germany) and Italian Idronaut 316 profilers, as well as the Russian-made hydro miniprobe STD-2a. Low draft of small ships allowed us to carry out the measurement, from

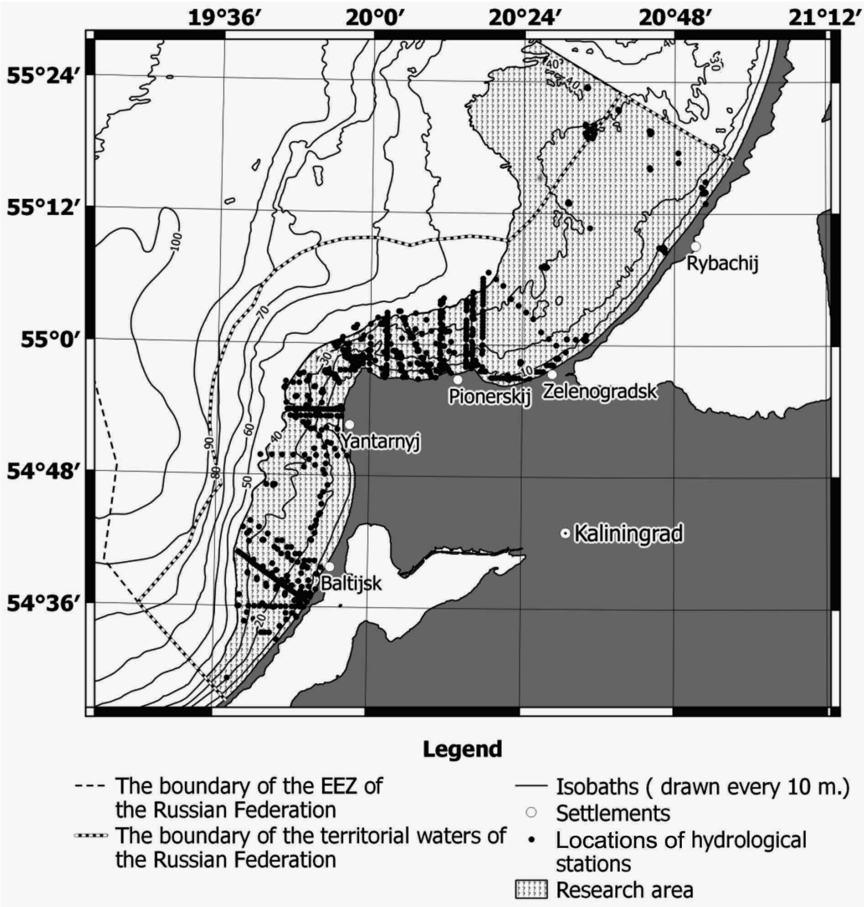

Figure 1. General scheme of the research site and locations of hydrological stations.

the 3-meter isobath.

The depth at the outer limit of the coastal zone is considered to be equal to half-wavelength of the largest storm waves [*Leontiev*, 2001]. In the Gdańsk basin this boundary is located along the 30–35 m isobath [*Babakov*, 2012]. In this paper, we assume that the outer research boundary corresponds to the 40 m isobath, which separates the shallow and open sea waters.

At the initial stage of experimental data processing the whole set of measurements was sorted according to the seasons. Hydrological seasons in this paper do not coincide with climatic ones; they have a one month forward chronological shift. In other words, winter includes the months from January to March, spring corresponds to April to June, and so on. Such climatic seasons better correspond to the conditions in the Gdańsk Basin [*Wulff et al.*, 2001; *Zakharchuk*, 2007; *Zeleny and Smirnova*, 1974].

Averaging of the seasonal data was used to form seasonal profiles. In this research, the commonly used mean arithmetic value was replaced by the median average. The median value, due to its resistance to abnormal emissions, is the main alternative to the arithmetic mean value of [*Piterbarg and Gritsenko*, 1983; *Sizova*, 2005]. The idea of the stratified median filtering approach implemented in the research [*Belkin*, 1991] is calculating the median value of seasonal temperatures and salinity in an arbitrary layer (up to 1 m thick). This procedure yielded seasonal mean profiles of the depth distribution of hydrological parameters.

Properties of the Thermohaline Structure of Coastal Waters

Let us describe the vertical structure of temperature fields and salinity of the coastal shallow waters of the southeastern Baltic Sea off the coast of the Kaliningrad region for seasonal pairs: cold and warm seasons (winter, summer) and transitional seasons (spring, autumn).

TS-fields in winter and summer.

Figure 2 shows the vertical profiles of temperature and salinity in cold (winter) and warm (summer) seasons with their linear trends. In winter, the active development of convective processes under the influence of surface cooling contributes to inverse thermal stratification (Figure 2a).

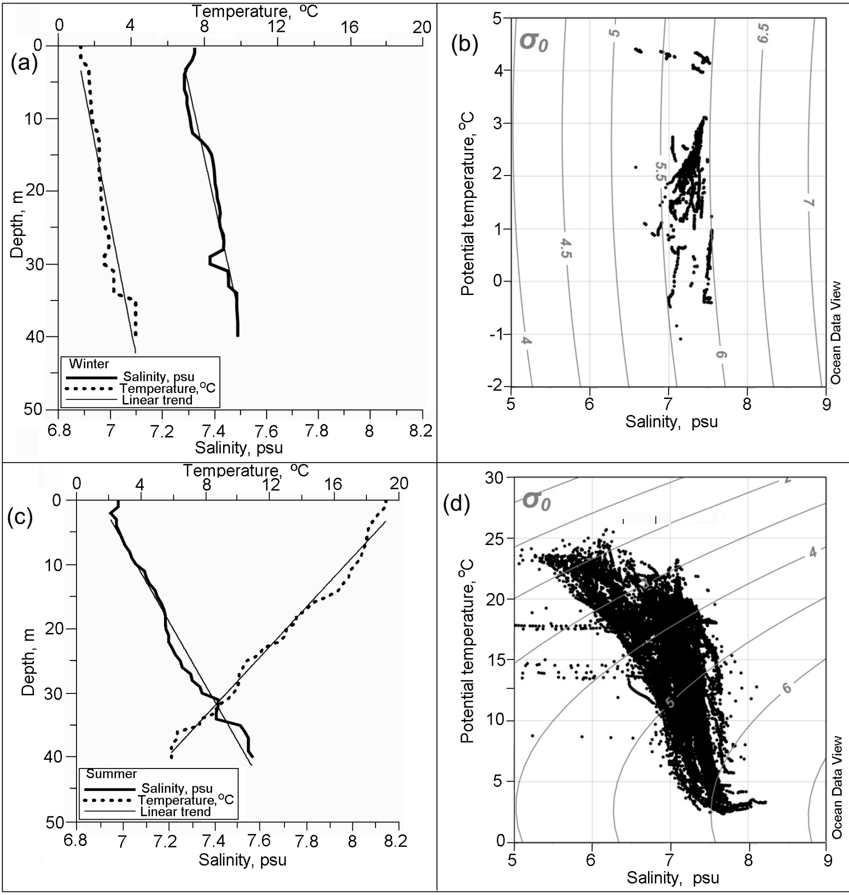

Figure 2. Mean vertical seasonal profiles of temperature and salinity of the Baltic shallow waters off the coast of the Kaliningrad region (thick solid and dotted lines) together with their linear trends (thin solid lines) in winter (a) and summer (c), and a scattergram of the original field data in TS-coordinate system [*Mamayev*, 1987] in winter (b) and summer (d).

In winter water temperature increases with depth from 1.5°C at the sea surface to 4.2°C at the bottom; the gradient is 0.067°C/m. At a depth of about 30 m a temperature jump is found (about 1.0°C), caused by colder water (about 2.5°C), which is close to the temperature of the maximum density and low salinity. Such a combination of thermohaline water parameters is characteristic of the coastal processes of alongslope convection [*Chubarenko*, 2010]. These values are significantly different from the corresponding indices for the open waters of the Baltic Sea. In particular, the minimum temperature of water at the surface in winter is higher than 3°C. Water temperature in the bottom layer is also notably higher than 7°C. The minimum temperature of about 4°C is found in the cold intermediate layer, which is also well above the minimum temperature of coastal waters.

Water salinity at the surface is slightly higher in winter (more than 7.3 PSU) than at a depth of about 5 meters (slightly less than 7.3 PSU). Salinity gradient is very low (0.0054 PSU/m). Apparently, this feature is associated with a decrease in the river runoff in winter and ice formation in the nearshore zone. At a depth of about 12–14 m there is a layer, in which salinity increases with a gradient of 0.03 PSU/m. Salinity at the bottom is about 7.5 PSU. Recorded salinity variation range is consistent with the overall pattern of salinity field evolution in the open waters of the Baltic Sea. Changes in the salinity of coastal waters are small; the typical value is about 7.3 PSU. However, salinity of coastal waters is somewhat higher ($\sim$ 0.3 PSU) than in the open waters of the Baltic Sea at the same depths.

In the bottom layers, deeper than 35 m, the temperature in winter and summer differs slightly: from the values higher than 4°C in winter and lower than 5°C in summer. Salinity in these layers is even less variable: approximately 7.45 PSU in winter and 7.55 PSU in summer. The basic mechanism of a slight decline in salinity of water at the bottom is, apparently, the nearslope convection developed in autumn and winter seasons, which allows the descent of coastal and near-surface cooler and less salty waters into the deep layers of the sea.

Thus, distribution of the temperature and salinity fields is quite homogeneous. Vertical gradients of temperature and salinity are low, except for the coastal zone of the inverse image of the cold intermediate layer of the Baltic Sea at a depth of 30–35 m. The vertical variability of the coastal waters properties is observed primarily in the temperature field; this variation is determined by the processes of surface cooling and near slope convection (Figure 2b).

Water warming from the surface in summer reaches its annual natural maximum warming the average seasonal water temperature at the surface up to 19°C. In the open waters of the Baltic Sea the surface temperature is below 17°C. The water temperature almost gradually reduces towards 30–35 m, reaching a minimum of 6°C at a depth of 40 m. The vertical temperature gradient is significant with its average values of -0.36°C/m and a maximum value at -1°C/m. The seasonal thermocline is well pronounced; it is located at depths from 14–17 to 30–35 m (Figure 2). In the open waters of the Baltic Sea the displacement range of thermocline is different: from 30–35 m (in June) to 50 m (in August).

The summer values of salinity in the surface layer to the depths of 4–5 m may be lower than 7 PSU, which is caused by high rainfall, the maximum regional amount of which is in summer (see The Baltic Sea hydrology, electronic source URL: http://portal.esimo.ru/portal/), [*HELCOM*..., 2006; *Mietus*, 1998; *Terziev et al.*, 1992]. There is a small salinity jump and decrease in the subsurface layer. Below this layer there is a slight increase in salinity towards the bottom (7.5 PSU), from a depth of 30 m the gradient increases to 0.1 PSU/m. A linear trend of increase in salinity with depth is 0.016 PSU/m. The salinity profile shown in Figure 2c demonstrates the main features of the summer vertical structure of the Baltic Sea salinity field in the coastal shallow waters offshore the Kaliningrad region.

Winter and summer profiles share approximately constant rate of temperature variation and salinity with depth. However, in winter the temperature and salinity of coastal waters increase with depth, while in summer they decrease.

Specific winter properties of temperature and salinity distribution plotted in the TS-coordinate system [*Mamayev*, 1987] make it possible to clearly see and analyse the ranges of variability in sea water parameters (see Figure 2b). In particular, in winter, all the measured values of coastal water temperature and salinity (dots in the graph) are concentrated within a rectangle with a range of changes from -0.5 to 4.5°C in temperature and from 7.0 to 7.5 PSU in salinity. It should be noted that water temperature values mainly remain within 2–3°C.

The distribution of summer values is strongly different; the TS-curves have an S-form (Figure 2d). The scatterogram bends at the surface and at the bottom:

salinity at the surface decreases relatively to the mean values while at the bottom it increases. The values of the basic sea water parameters in summer vary from $2^\circ$to 25°C in temperature and from 5.5 to 8.2 PSU in salinity.

TS-fields in spring and autumn.

Let us now study (Figure 3) the seasonal mean temperature and salinity profiles of coastal waters in the transitional seasons, i.e. spring and autumn.

Spring warming of coastal waters increases temperatures in the entire depth up to 30–35 m. In April, the seasonal thermocline begins to form. The thickness of the upper quasi-uniform layer is about 10 m, mean seasonal water temperature is about 14.5–15.0°C. Seawater temperature decreases with depth, the average vertical rate is -0.32°C/m with a maximum of -1.2°C/m at a depth of about 30 m. At the bottom, water temperature drops below 4°C (Figure 3a).

Salinity at the surface in spring is 7.15 PSU, increasing gradually with depth to 8 PSU. Stratification is stable; the average increase rate with depth is 0.024 PSU/m with a maximum of 0.05 PSU/m at a depth of 28–33 m.

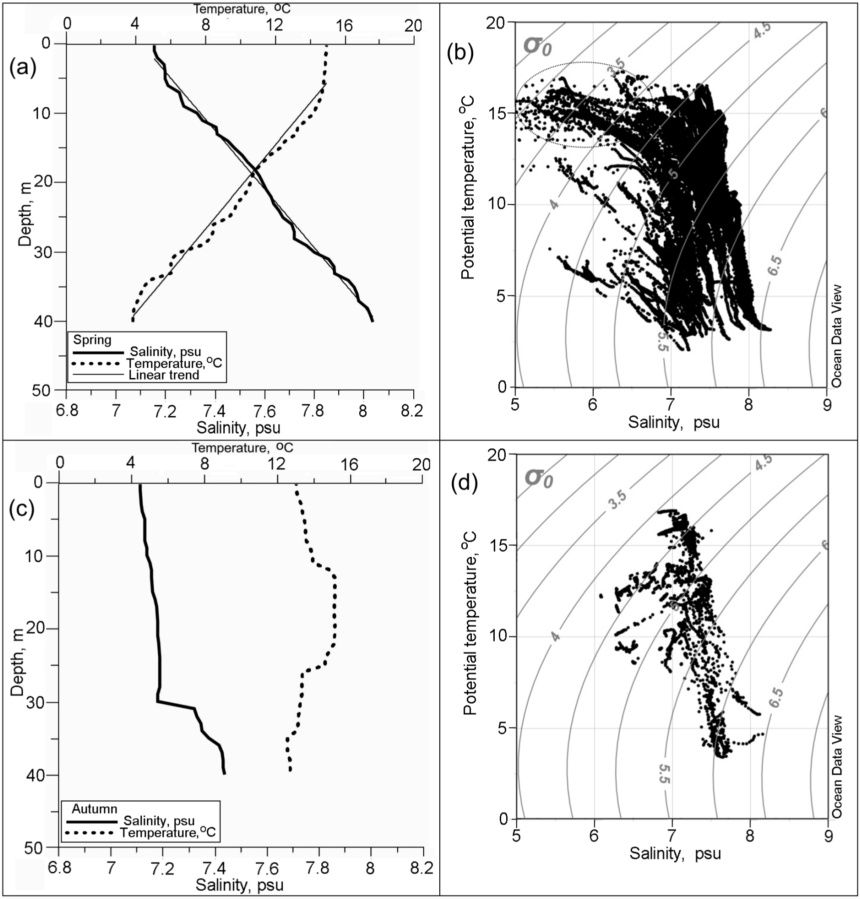

Figure 3. Vertical seasonal mean profiles of temperature and salinity of coastal waters of the Southeastern Baltic (thick solid and dashed lines, respectively) together with their linear trends (thin solid lines) in the spring (a) and autumn (in) periods, and a scattergram of the original field TS-data in the coordinate system suggested in [*Mamayev*, 1987] in the spring (b) and autumn (d) periods.

In general, the spring season is characterized by an increase in water temperature with a slight decrease in salinity caused by the increase in continental runoff. In the areas located near the mouths of rivers and the Baltic Strait, local lenses of low saline water appear at the surface, the corresponding regions are marked with an oval in Figure 3b.

The autumn season is characterized by the beginning of an intense process of cooling from the sea surface, which establishes reverse thermal stratification in the surface layer up to 10 m depth. Lower, in the range of 12–27 m depth, the water layer is warm. Thermal gradients at the upper boundary of this layer reach 1.2°C/m. Water temperature gradually drops in the deeper waters up to a depth of 35 m where another temperature jump is found: it decreases by 0.5°C over each linear meter. The temperature in the bottom layer is 12.7°C (Figure 3c).

A distinctive feature of the autumn season is a quasi-uniform layer in the salinity field which is formed under the influence of powerful convection processes; it extends to a depth of 30 m. A notable increase in salinity is found deeper. Salinity at the bottom is about 7.4 PSU.

The difference in temperature and salinity in the bottom layers at depths of 35–40 m is significant. Spring water temperatures at these depths are close to the maximum density temperature of $\sim 4^{\circ}$C. In autumn, the temperature at these depths is maximum; it reaches about 13°C. Salinity of water in spring at the same depths is maximum; it is slightly higher than 8 PSU. In autumn at these depths, it decreases to its regular value of 7.45 PSU. Such a difference may be due to the different rates of convective alongslope processes in autumn and spring [*Chubarenko*, 2010].

In general, the autumn distribution of the vertical thermohaline structure is characterized by a layered character of temperatures and homogeneous field of salinity. The temperatures are more variable under the influence of seasonal cooling (Figure 3c).

Scattergram of repeated CTD-measurements in the coastal area in spring (Figure 3b) is characterized by a high degree of salinity variation ranging from 5 to 8 PSU. This is probably defined by a significant continental runoff in the form of spring floods and melting snow. The temperature also varies in a wide range: from 2.5 to 17.0°C, and it is not possible to clearly identify the prevalence of any temperature and salinity values. This difference may be explained by the fact that water gets heated unevenly during this period and the main meteorological parameters are highly variable.

In autumn, the scattergram (Figure 3d) is more spatially localized than in spring due to the intensification of convective mixing process through surface cooling. Salinity ranges between 7–8 PSU, temperature increases from 3°C (at the bottom) to 17°C (in the surface layer). Salinity increases with depth, the chart shows individual measurements, which spread beyond the basic line of the distribution of thermohaline indexes. Basically, this is due to the low salinity values in the region.

Conclusions

The instrumental measurements of temperature and salinity of the Baltic Sea waters off the coast of the Kaliningrad region completed in 2003–2014 allowed us to describe the properties of the seasonal vertical structure of temperature and salinity fields of the Baltic Sea shallow waters. Therefore the seasonal variation in temperature and salinity of the waters of the Baltic Sea received a better and more detailed description.

The analysis of the seasonal characteristics of the vertical thermohaline structure of coastal waters showed that heating and cooling processes occur, as a rule, at a depth of 30–35 m (in the open Baltic sea at 50–60 m). The upper 5–10 m layer of water is involved in the heat exchange with the atmosphere. The depth of the thermocline varies from 10–30 m up to 17–35 m in spring and summer.

Salinity field of the Baltic shallow water is characterized by a small range of variability in all seasons. Fluctuations in the measured values of salinity in coastal waters do not exceed 0.5 PSU. The greatest variations in the salinity of coastal waters (up to 0.7 PSU) are characteristic of the upper layer 5 to 10 m thick in winter and summer. These patterns of salinity of coastal waters complement the previously known features of the seasonal values of the open Baltic Sea waters.

The average seasonal linear trend of temperature variation in winter, spring, and summer are 0.067, -0.36, and -0.32°C/m, respectively; the trends in the salinity field are 0.0054, 0.016, and 0.024 PSU/m, respectively. In autumn, the vertical thermohaline structure of coastal waters has a two or three-layer structure.

The measurements in the study site showed that 30–35 m water layers are characterized by local changes of temperature and salinity in all seasons.

The analysis of the original set of experimental data in 2003–2014 confirmed that the main factors determining salinity field in winter are the minimum of the continental runoff and processes of ice formation, and the governing processes in summer are the flow of water from the mainland and large amounts of atmospheric precipitation from July to September.

The assessment of the degree of temperature and salinity variations in the Baltic shallow waters off the coast of the Kaliningrad region confirmed the dominant role of heat and moisture from the atmosphere and continental runoff in forming the vertical thermohaline structure.

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