VILNIUS UNIVERSITY
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PECULIARITIES OF THE WATER DYNAMICS IN THE SOUTHEASTERN BALTIC SEA

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VILNIAUS UNIVERSITETAS
GEOLOGIJOS IR GEOGRAFIJOS INSTITUTAS

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VANDENS DINAMIKOS YPATUMAI PIETRYČIŲ BALTIJOJE

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INTRODUCTION

Variable distribution of solar energy on the Earth surface causes the energy and matter (heat, moisture, gases, salts etc.) to circulate between atmosphere, ocean sphere and lithosphere. The variation not only highly influences Earth's hydro meteorological conditions but also generates the circulation of water in oceans and seas which, in turn, triggers the turbulent water mixing, redistribution and transportation of a large amount of kinetic energy, dissolved in water gases, salts, biogenic, organic substances, nutrients etc. in different oceanic basins. The abundance of marine biodiversity and its flourishing depend on the active circulation of water masses.

In the study of oceanic sphere and water masses in water basins, the main emphasis is laid on an analysis of currents which, together with some elements of water balance and bottom features define the water circulation system of a distinct marine basin.

Even though major regularities of water circulation in the Baltic Sea were revealed during the hydrodynamic investigation carried out from the mid 19th century, the hydrodynamic regime of distinct water basins such as southeastern part of the Baltic Sea (including Lithuanian waters) is not very well established yet. The hydrodynamics of the whole Sea, ecology of its basin and prediction of its future development are impossible without this knowledge. The recent thesis does not include wave and water level study. The major attention is paid to horizontal water transportation (currents) in the study of water dynamics.

Subject. The multiannual and seasonal water circulation in the southeastern Baltic Sea.

Goal. To investigate multiannual and seasonal hydrodynamic properties of the southeastern Baltic Sea in a stratified water column.

Aims:

1. To investigate the water stratification in the SE Baltic Sea.
2. To define directions of multiannual and seasonal marine currents.
3. To study velocities of multiannual and seasonal marine currents.
4. To model how the distribution of current velocities and directions in the study area depend on hydro meteorological conditions; to compare the modelling results to the natural observations.

Statements to be defended:

1. The water layer in the SE Baltic Sea is made up of water masses with individual thermohalic properties. A number of water masses and their distribution vary during a year.
2. Peculiarities of the water masses and bottom morphology highly influence the spatial and temporal variation of marine current directions in the study area.
3. The temporal and spatial variation of marine current velocities depends on properties of water masses, depth of water basin and distance from the shore.
4. Current velocities at distinct water depths do not depend on current directions.
5. A relationship between the SE Baltic water dynamics and varying hydro meteorological conditions can be evaluated using a 3-D Princeton ocean model (POM) adapted by A. Jankowski.

Novelty. For the first time, the dynamics of the SE Baltic Sea was evaluated using a huge data base of natural observations. Moreover, for the first time in the SE Baltic area, the water masses were distinguished on the basis of hydro physical parameters, as well as their influence on an overall water circulation was defined. It allowed to determine the hydrodynamic regime in stratified water column and to evaluate peculiarities of current dynamics in different water horizons. The relationship between currents at different depths and varying wind directions and velocities in the SE Baltic Sea were modelled for the first time.

Relevance. The water dynamics and stratification of water column are crucial for the study of marine energy and matter circulation, peculiarities of the biosphere evolution and natural marine conditions. The establishment of water masses and study of their characteristic properties have a scientific and practical value. The hydrodynamic regime of the SE Baltic Sea is not well established yet. The study will provide with a new data on distribution of temperature, salinity and other water properties, as well as the influence of the water masses on water dynamics.

Application. The results of the investigation will be useful for a development of oceanology, sedimentology, coastal research, biology and ecology in Lithuania. In cases of hydrocarbon, chemical and other pollutions in the SE Baltic Sea, the revealed hydrodynamic regularities and modelling results will help to assess the impact area with better precision. It will improve considerably the solution of problems related to hydro engineering works etc. in the study area.

Structure and content. The thesis consists of introduction and 6 chapters: first and second chapters give the history of previous studies, highlight the subject, methods and study area; third chapter deals with peculiarities of the water masses in the study area; fourth and fifth chapters based on the results of the third chapter proceed with the multiannual and seasonal variations of current directions and velocities in the study area. A model of the hydrodynamics of the studied basin that resulted from the regularities of varying current directions and velocities and their causes is presented in chapter 6. The major results are given in Conclusions followed by Reference list and List of author's publications. In total, the thesis consists of 171 pages including 12 tables, 59 figures and 196 references.

Scientific results and publications. The results were published in 4 articles, presented in one Lithuanian and 3 international conferences.

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2. STUDY AREA AND METHODS

The study area represents a part of the Baltic basin limited by coordinates 56°30' in the north and 55°00' in the south. The area is limited by a longitude of 19°40' in the west, and by a shore line in the east (Fig. 1). Maximum depth reaches 125 m with an average depth of 47.5 m. The average depth of the study area and profiles was calculated with "ArcGis" programme. The currents were investigated in three transverse A, B and C and four longitudinal D, E, F and G profiles (Fig. 2a) crosscutting different morphologies of the studied basin.

Archive hydrologic and meteorological data. Hydrologic data was collected at archives of the Institute of Marine Research in Klaipėa, Lithuanian Hydrometeorology Survey (LHS) and P. P. Sirsov Institute of Oceanology in Kaliningrad. The data was also obtained from the NOAA-CIRES (National Oceanic & Atmospheric Administration-Cooperative Institute for Research in Environmental Sciences), Climate Diagnostic Center (CDC) and International Council for the Exploration of the Sea (ICES) data bases.

The archive data on current directions and velocities from 12 oceanographic stations in the Baltic Sea (Fig. 2a) acquired in 1951–1975 was selected for this study. The 14 576 measurements of current directions and velocities were used for this study. Current parameters (velocity, direction) were measured from the ships "Jurate", "Geophysicist", "Oceanographer" and autonomic oceanographic stations. The measurements were obtained by BPV-2 and Aleksejev's letter-typing mills.

Field work was performed in the basin of the Southeastern Baltic Sea. Velocities and directions of marine currents, the salinity and temperature were measured during these expeditions.

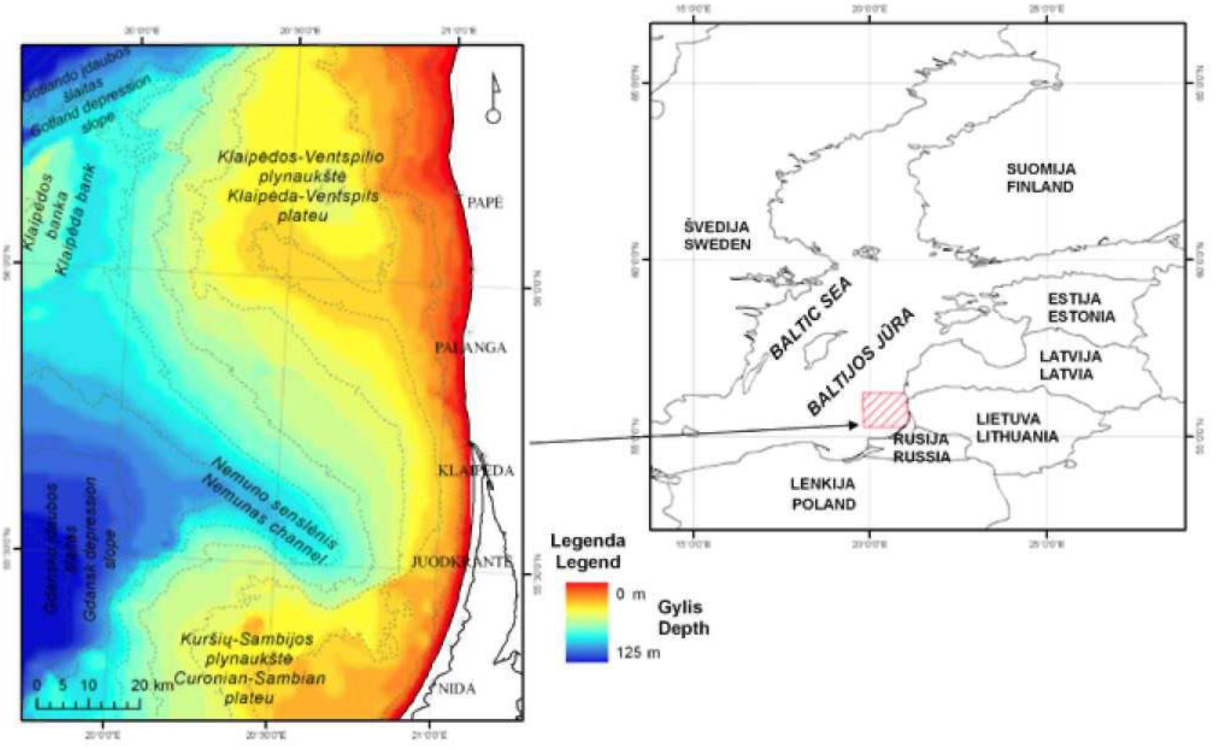

Fig. 1. ***Study area.*** *Izobath every 10 m (Gelumbauskaite et. al., 1998)*

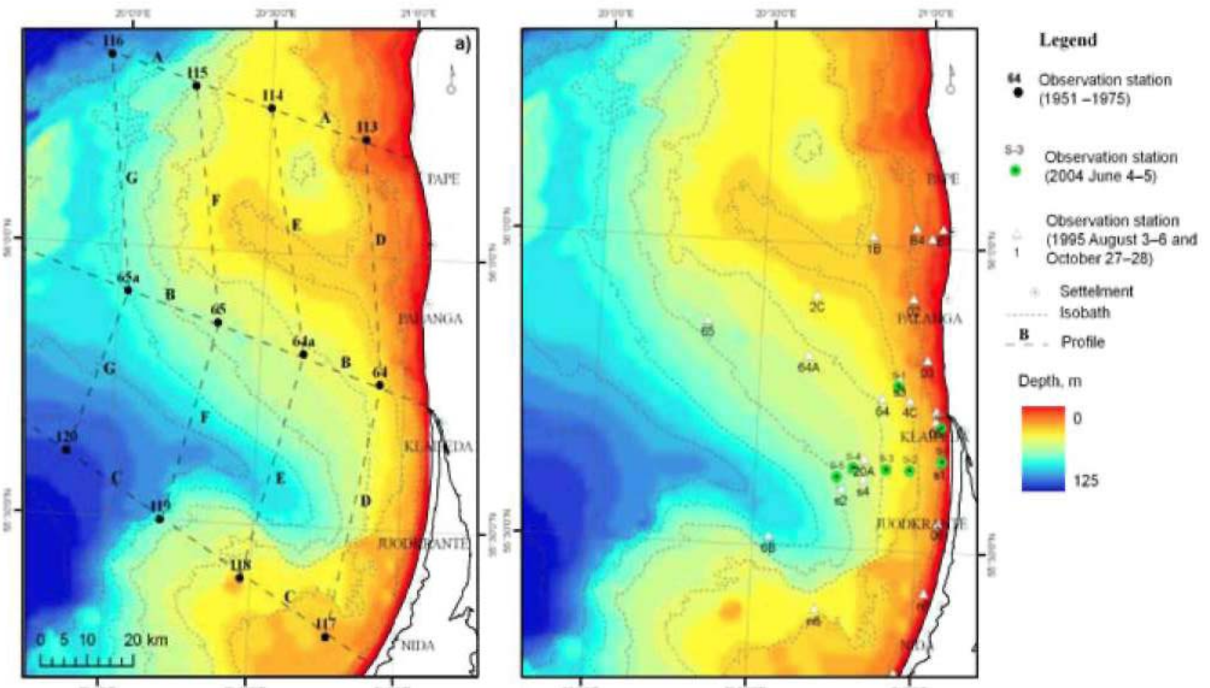

Fig. 2. ***Location of the observation stations in the research area, in which the temperature, salinity and current velocity and direction data was collected in the period 1951–1975 (a); and in 1995 August 3–6 and October 27–28 and in 2004 June 4–5 (b)***

During the winter (February 11–16) and autumn (November 3–7) expeditions of 1998, the Baltic Sea water temperature and salinity were measured from the scientific ship "Vėjas". The measurements were performed by a multifunction probe "Zond-barometer" in stationary horizons. In total, such measurements were performed in 24 oceanographic stations. In summer of 2004 (June 4–5), the current directions and velocities as well as water temperature and salinity in the economical zone of Lithuania in the Baltic Sea were determined in 7 stations (Fig. 2b) using the ship "Darius" belonging to the laboratory of fishery. The current velocity and direction, temperature and salinity were measured by means of multifunction probe RCM 9LW of the Norwegian firm AANDDERAA INSTRUMENTS. The above parameters were measured in a vertical water column each 5 m, the lowest measurement being 1 m above the Sea bottom. The ship "Darius" had been stopped and anchored and coordinates of the stations defined by GPS during the measurements with the multifunction probe.

In order to characterise hydrodynamic processes in the Baltic Sea, following statistic parameters of current velocity were analysed: average (v_{vid}), mode (M), maximum (v_{max}), dispersion $\sigma^2(v)$, standard deviation $\sigma(v)$ and variation coefficient (K). Rose diagrams of marine currents were compiled to define the dominating directions of marine currents in the study area. They showed the general and seasonal (spring, summer and autumn) water circulation. Such rose diagrams are lacking for winter seasons because of insufficient data.

Temperature and salinity data for the characteristics of water masses were taken from the date base of International Council for the Exploration of the Sea (ICES) for the period of 1907–2005 and from the archive of the Klaipėda Marine Research Center for the period of 1991–2005. The 5673 measurements were selected from the both sources. The temperature and salinity data from the newly compiled database allowed defining peculiarities of the water masses. The data was taken using the same criteria: the measurements were performed at the same time and similar weather conditions. The term "at the same time" is "synoptic" and means that the data was obtained in several days and weeks but at similar conditions (Mažeika, 2001).

The modelled data of water temperature and salinity as well as current velocity and direction of the Baltic Sea were used in the study. The Baltic currents were modelled for NW, W and SW winds, which velocity in May, August and November was 5, 10 and 20 m/s respectively. Additionally, in November the current regime was modelled for the velocity of 30 m/s. The Baltic currents were modeled for 162 sites. The model was checked in 15 oceanographic stations in the Lithuanian economical zone of the Baltic Sea.

Mathematical calculations were based on a baroclinic 3-D model of the σ-coordinate of the Baltic Sea with a horizontal resolution of ca. 10 km and vertical one in a range of 24 sigma-levels. A digital model was obtained for the whole Baltic Sea. Open (Skagerrak and water surface) and closed (bathymetry of the Baltic Sea bottom compiled by T. Seifert and B. Kayser) boundaries were used in the model (Seifert, Kayser, 1995; Jankowski, 2000, 2002). The model is limited by the Sea surface, Sea bottom and horizontal boundaries from all sides. The detail description of the POM model is given in works of A. Blumberg and G. Mellor (Blumberg, Mellor, 1987; Mellor, 1993) while a detail version of the Baltic Sea model is described in A. Jankowski's works (Jankowski, 2000, 2002).

3. PECULIARITIES OF THE WATER MASSES OF THE STUDY BASIN

Water masses in the study basin were distinguished according to the two measured parameters of the Baltic Sea water: temperature and salinity. A halocline is unlikely to form because of the shallowness of the Baltic basin. The change of salinity down to 70 m is minute, i.e. 1‰ that is why salinity gradients are so small reaching only hundredths of a promil. The salinity measurements were used only for the correction of the water mass boundaries because of the relatively small change of the Baltic water salinity.

The water masses and their boundaries were defined for different seasons: spring (March–May), summer (June–August) and autumn (September–November). There was no possibility to distinguish water masses for winter because of insufficient data. Horizontal and vertical boundaries of the water masses are usually drown according to the calculated maximum gradients of hydrophysical characteristics (Titov, 2003). Water mass boundaries in the transverse A, B and C, and longitudinal D, E, F and G profiles were drown according to the calculated vertical and horizontal water temperature gradients (ΔT) in a 1 m thick layer.

From two to five water masses of different temperature are forming in the study basin in different seasons. A number of water masses are controlled by the river discharge, shallow medium depth of the Baltic Sea and specific meteorological conditions above the study area.

According to the results of water investigation in the A, B, C, D, E, F, and G profiles, the water masses differ considerably with changing seasons, and their number at a depth is permanently changing. The maximum five water masses are forming in summer while only three are originating in autumn (Fig. 3). A number of water masses decreases in autumn because of the cooling Baltic Sea water and of decreasing temperature difference in a water column caused by water mixing.

The following five water masses were established according to the results of investigation: surface (SWM), changing and migrating (CMWM), transitional (TWM), deep (DWM) and thermoclinic (TRWM).

The most stable are surface, changing-migrating and transitional water masses which are present in all seasons. The deep water masses exist in spring (Fig. 3a) and summer (Fig. 3b) but are absent in autumn (Fig. 3c). The thermoclinic water masses are temporal, forming only in summer. Vertical temperature gradients of the surface, transitional and deep water masses are respectively 0.0–0.02, 0.0–0.1 and -0.1° C/m and do not differ during a year. The vertical gradient of the changing-migrating water masses disappears in spring (0.0° C/m) and reaches 0.5° C/m in autumn. It is important to note that the vertical temperature gradient is stable in the distinct water masses during a year (Table 1).

Apparent boundaries of the water masses and their thickness are dynamic and differ temporally in the study basin. The boundaries and thickness of the deep water masses do not change considerably as was defined by the multiannual temperature analysis of the Baltic Sea water.

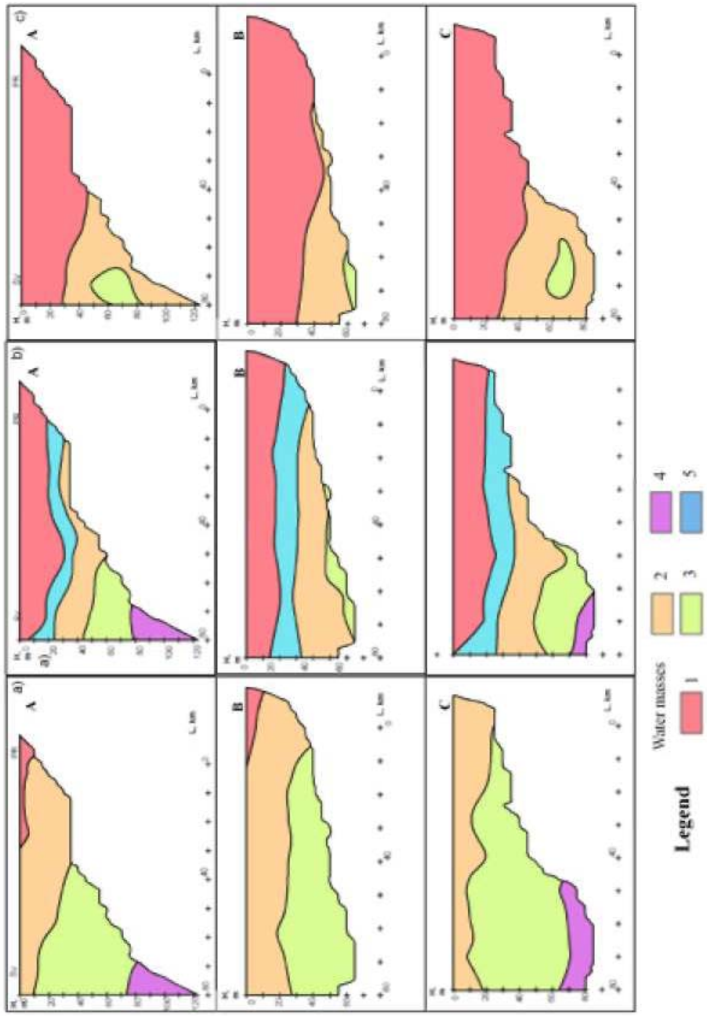

Fig. 3. ***Variability of water masses in measurement profiles: spring (a), summer (b), autumn (c).*** *(Places of profiles showed in Fig. 2).* ***Legend:*** *1 — surface water mass, 2 — changing and migrating water mass, 3 — transitional water mass, 4 — deep water mass, 5 — thermoclinic water mass*

Table 1. ***Water masses' vertical gradients of temperature of study area (°C/m) calculated by author***

Water mass	*Season*		
	Spring	*Summer*	*Autumn*
Surface	0.0–0.2	0.0–0.2	0.0–0.2
Changing and migrating	0.0–0.0	0.2–0.4	0.1–0.5
Transitional	0.0–0.1	0.0–0.1	0.0–0.1
Deep	-0.1	-0.1	–
Thermoclinic	–*	0.5 – 0.8	–

** – no water mass*

4. PECULIARITIES OF THE VARIATION OF THE BALTIC SEA CURRENT DIRECTIONS

As it was obtained from the multiannual analysis of sea current directions, the near-surface water layer (0–10 m) is dominated with north-trending current direction. This was implied from the data coming from the 12 oceanographic research stations. The north trending current direction predominated in the 7 stations (Figs. 4a, b). The average annual repetition of the north trending current is from 17 to 25.4% of all the cases. The current direction in the transitional layer comparing with the near-surface layer varies from 45° to 315°. Small variations of the current direction in shallower part of the study basin are caused by the bottom relief and orientation as well as configuration of a coast line. Wind currents which coincide with the quasi-stationary Baltic Sea circulation dominate the near-surface layer. According to the near-bottom current measurements, the current near the bottom is directed towards north in the five of 12 stations what comprises from 20.6 to 27.6% of all the measurements (Fig. 4c). A flow of near-bottom currents is influenced by the bottom relief and shoreline and therefore is moving along the isobaths following the bottom irregularities. Such currents which move at the same depth (along isobaths) are called counter currents (Holister, Heezen, 1972).

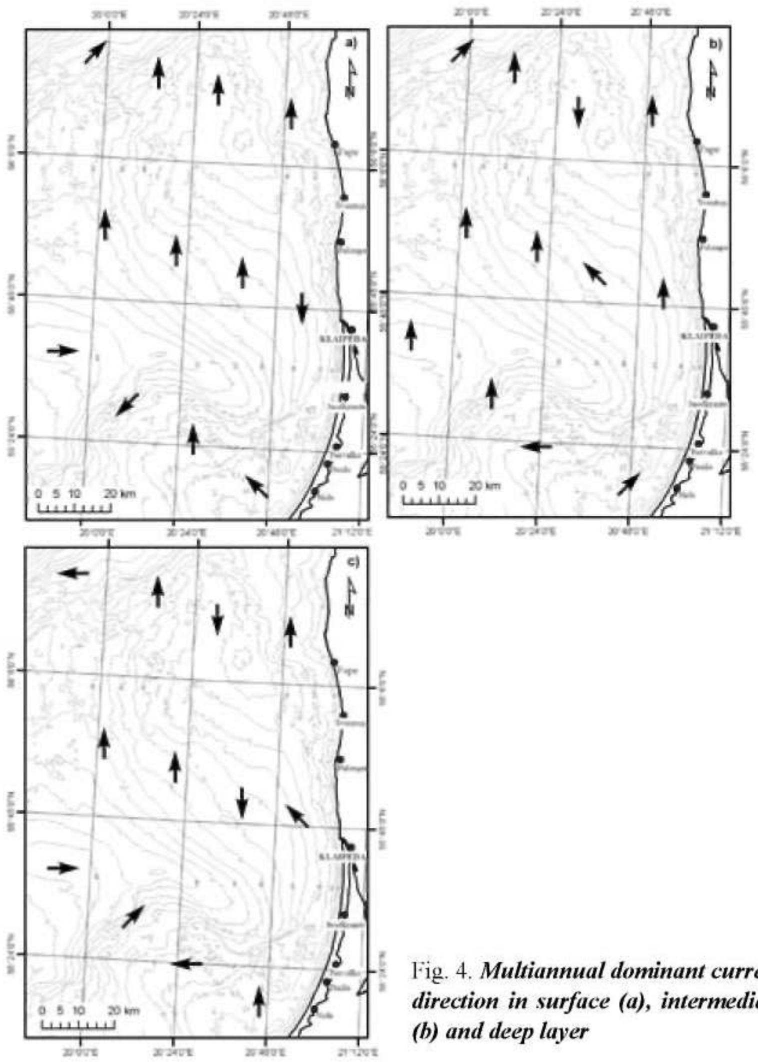

Fig. 4. ***Multiannual dominant current direction in surface (a), intermediate (b) and deep layer***

The variation of seasonal current directions is much more complex. The near-surface layer is dominated with a south trending current direction in spring as it was measured in the eight of twelve stations. In spring time the near-surface (down to 50 m) currents flow southwards following the coastline in the northern and central basin (Fig. 5a). In the central part, near the old Nemunas valley the currents turn towards southwest and flow into the Gdansk trench. It happens because near the Curonian–Sambian plateau they are blocked by the north-eastern currents flowing along the Curonian Spit. In central part of the study basin, beyond the 50th isobath the near-surface currents flow from the south to north turning to the east above the SE slope of the Gotland trench. During springs in the transitional layer, the south trending currents were detected in the five, north trending in six and east trending in one oceanographic station (Fig. 5b). The northern current directions dominate the near-bottom layer in the nine of twelve stations while the currents are directed to south in the remaining three stations (Fig. 5c). It was implied from the near-bottom current direction measurements that the near-bottom currents changed their direction in the ten of twelve stations.

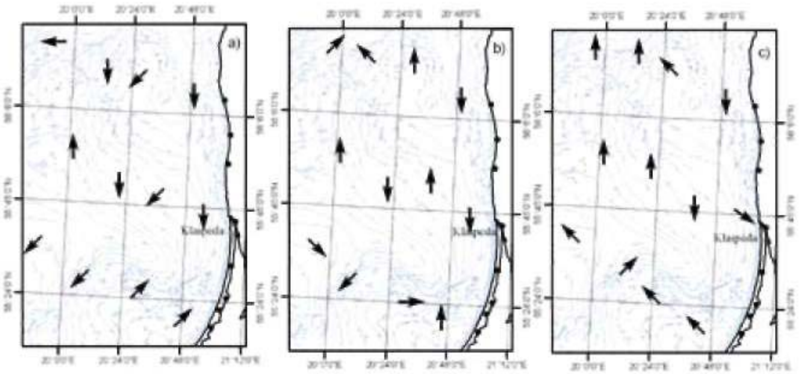

Fig. 5. ***Dominant current direction in spring in surface (a), intermediate (b) and deep layer***

In summer time, the N, NW and NE current directions dominated the near-surface layer as it was measured in the seven of twelve stations (Fig. 6a). The near-surface currents were directed towards S, E and SE in the remaining five stations. The dominating near-surface current direction remained the same in the two stations as was revealed after the comparison of the spring and summer data. It means that the dynamics of the near-surface currents is highly sensitive to seasonal changes. There is no dominating current direction in the transitional layer (Fig. 6b). Unlike in the near-surface water layer, the northern current direction is not so clearly dominating against the southern in the transitional layer. Like in the near-surface layer, the northern current directions dominate the near-bottom layer (Fig. 6c). N, NE, NW directions were measured even in the eight of twelve stations. It was discovered that, unlike in spring, in summer time the dominating current directions have changed in all the stations while the circulation of near-bottom currents became more complex.

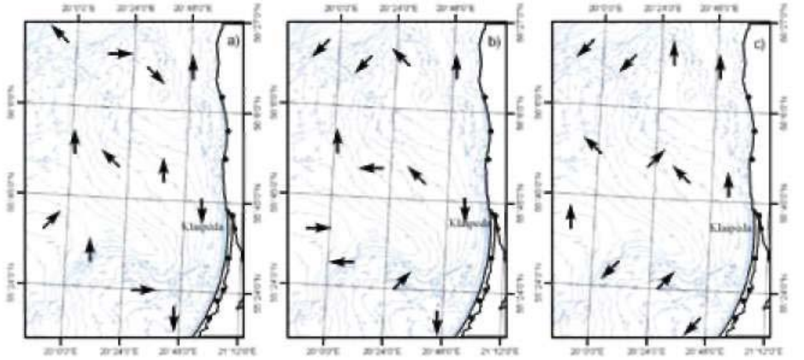

Fig. 6. ***Dominant current direction in summer in surface (a), intermediate (b) and deep layer***

In autumn time, the northern current directions predominate (Fig. 7a). The currents flew northwards in the seven and northeastwards in one of twelve stations. Unlike in spring time when the near-surface currents flew towards south, the currents changed their direction towards north in autumn time. Like in the near-surface layer, the currents flew to the north in the transitional layer too (Fig. 7b). This direction has been repeatedly measured in the eight stations of twelve. Circulating cycles are much weaker in the transitional layer in autumn than in spring or summer. Besides, unlike in spring and summer when currents near the shoreline flew to the north as well as to the south, only the north directed currents dominated this area in autumn time. The northern directions were measured in the near-bottom layer in many stations (Fig. 7c). The currents in the near-bottom layer flew also westwards (three stations) and southwards (one station) in autumn time. When the water gets cooler it sinks moving westwards, in the direction of sloping bottom.

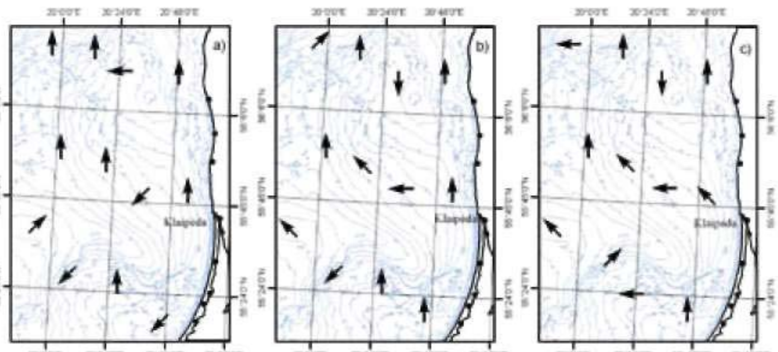

Fig. 7. ***Dominant current direction in autumn in surface (a), intermediate (b) and deep layer***

The variation of current directions gets more complex because of the water masses. An analysis of current directions in summer when the five water masses form is given separately (Fig. 8). The obtained results revealed that the currents had different directions in the near-surface water masses: northern direction in the four, NE, NW, S, SE and E directions in the other stations (Fig. 8a). In summer, the currents in near-surface water masses change their direction and flow southwards from the Klaipėda strait, along the Curonian Spit. The latter fact may be also explained by the decreasing discharge of fresh water through the Klaipeda strait in summer time. It is interesting to note that circulating cycles are forming above the Klaipeda–Ventspils and Curonian–Sambian plateaus, the first being of cyclone and the second of anticyclone type. The northern (NW, N, NE) current directions dominate the offshore waters, beyond the 45th isobath. Western current directions are common for the thermoclinic water masses (Fig. 8b) since the W, SW and NW directions were measured in the eight of eleven oceanographic stations. While atmospheric processes governed the current directions in the near-surface water masses, the inner processes (inner waves) depending on hydro physical properties of water masses were crucial for the thermoclinic water masses (Sustavov et al., 1980). In summer time, the changing-migrating water masses (CMWM) occur below the thermoclinic ones. Like in the near-surface water masses, north trending current directions are characteristic for the CMWM (Fig. 8c). N, NE, NW directions were fixed in the six of eight

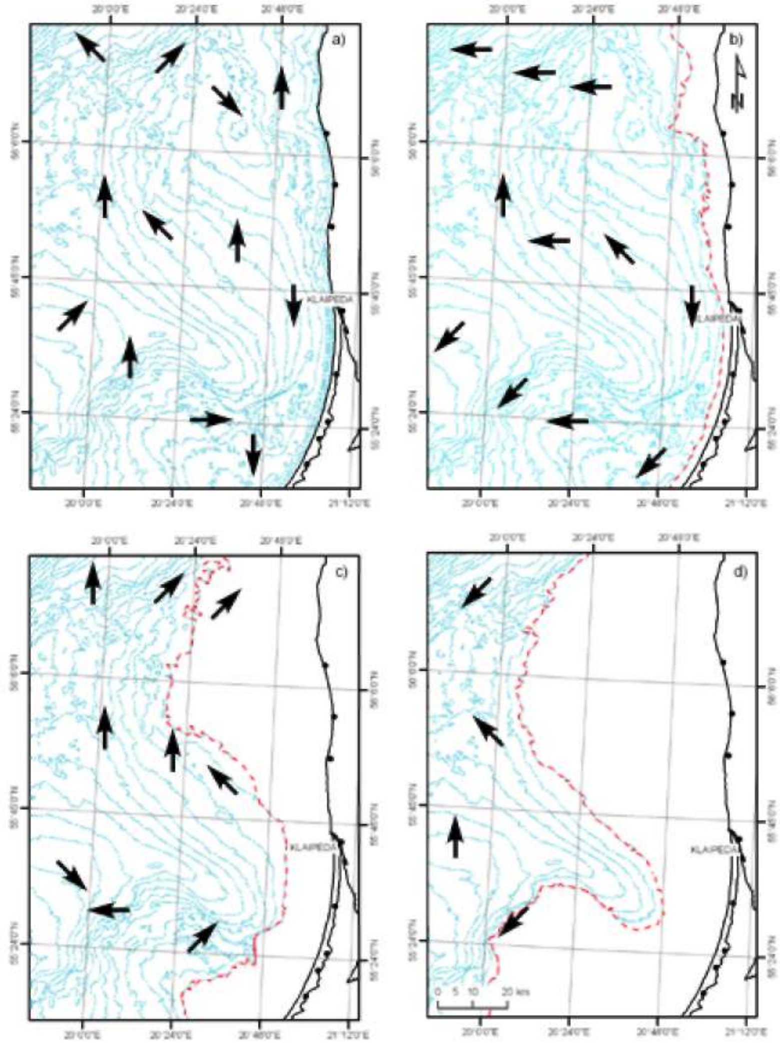

Fig. 8. ***Dominant current direction in summer in surface water mass (a), thermoclinic water mass (b) changing and migrating water mass (c), transitional water mass (d)***

stations. The bottom relief is responsible for the great majority of current directions in the transitional water masses (Fig. 8d). The dependence on the bottom relief was implied from the obtained data showing that dominating current directions followed the isobaths. In summer time, the deep water masses (DWM) are present only in the deepest parts of basin where only two stations are installed. It was discovered that currents trend northwards in the southern whereas they flow to the SW in northern parts. The great percentage of recurrent current directions (over 27%) evidences the stability of currents in the deep water masses. Thus the currents retain their properties (trajectory) better in the colder and denser water masses.

To sum up, the northern (N, NE and NW) current directions are most common in the near-surface, transitional and near-bottom layers of the study basin. The quasi stationary circulation of the Baltic Sea currents is of the same direction. However, the currents are affected by different factors in distinct water layers. In all the layers the currents partly depend on bottom relief, shoreline configuration and orientation. The current direction in the near-surface, transitional and near-bottom water masses is highly affected by a shape and orientation of shoreline and bottom relief in the near shore area; however their influence decreases considerably with the depth and is detected only in the near-bottom water masses. The circulation of the measured near-surface currents in spring, summer and autumn is similar to this shown on the sketches compiled by I. M. Soskin (Soskin, 1963). It was discovered that the current flow in stratified water masses is getting more complex leading to the variation of current directions in distinct water masses during a year:

- a two-layered circulation is forming in the study basin in spring time; currents trend southwards near the surface, northwards near the bottom;
- in summer time when the thermoclinic water masses are forming, the northern discharge gets complicated in the study area: water currents trend to the west in the thermoclinic water masses while they flow northwards above and below them;
- in autumn, the discharge to the north is dominating, nevertheless it is complicated by the circulating cycles and countercurrent streams in the changing-migrating and transitional water masses.

5. PECULIARITIES OF THE VARIATION OF CURRENT VELOCITIES IN THE STUDY BASIN

The current velocity decreases from the south to north as it was revealed by the multiannual analysis of average current velocities in the near-surface, transitional and near-bottom layers. The average velocity varies because of the decreasing current inertia. The maximum current velocities near the surface were measured 48–49 km far from the coast in the A and B profiles and 79 km far in the C profile. According to J. D. Michailov, the maximum velocities were detected 28 km far from the coast (Michailov, 1972). The most common current velocities vary from 6 to 11 cm/s in the near-surface, from 4 to 8 cm/s in the transitional, from 4 to 11 cm/s in the near-bottom layers. The average current velocity in the near-bottom layer decreased from 11.3 (near-surface layer) and 10.8 (transitional layer) to 9.8 cm/s.

In respect to the factors which may influence average velocities in the near-surface layer, the correlative relationship ($r = 0.72$) between the variation of average current velocities and distance from the shore is quite important. The correlative relationship between the average current velocity and depth of the Baltic Sea is weaker ($r = 0.64$). The correlative relationship between the vector of dominating near-surface currents and average current velocity is statistically unimportant ($r = 0.14$; Fig. 9). There were no statistically reliable correlative relationships between the maximum current velocities and distance from the shore ($r = 0.31$), depth of the Baltic Sea ($r = 0.45$) and vector of the dominating current direction ($r = 0.24$).

The correlative relationship between the variation of average current velocity and distance from the shore ($r = 0.67$) is important in the transitional layer. Similar relationship is between the average current velocity and depth of the Baltic Sea ($r = 0.68$). The correlative relationship between the vector of dominating current and average current velocity is statistically unimportant in the transitional layer ($r = -0.09$; Fig. 10). It occurred that the correlative relationship between the maximum current velocity and distance from the shore ($r = 0.54$) as well as depth of the Baltic Sea ($r = 0.57$) are important. Again, there is no important correlation between the vector of dominating current and maximum average current velocity ($r = 0.32$).

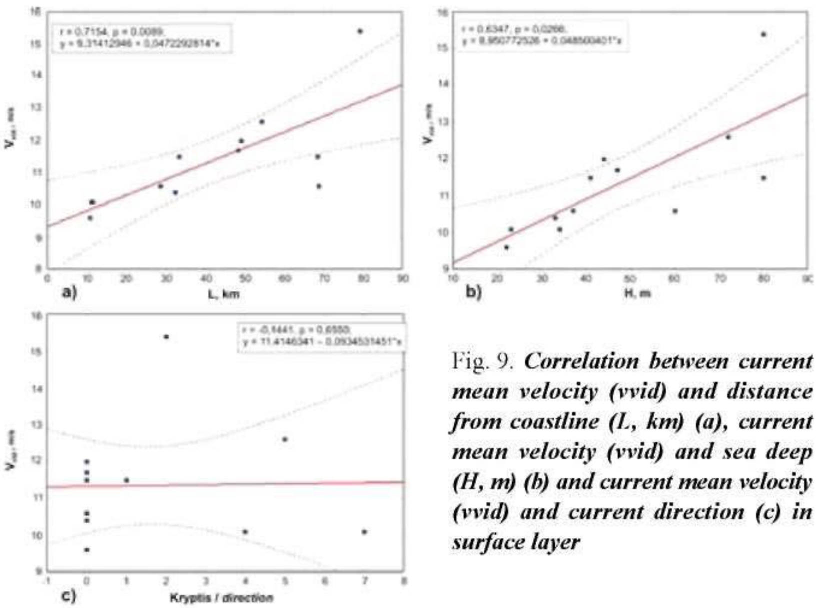

Fig. 9. ***Correlation between current mean velocity (vvid) and distance from coastline (L, km) (a), current mean velocity (vvid) and sea deep (H, m) (b) and current mean velocity (vvid) and current direction (c) in surface layer***

There is no statistically reliable correlation between the above factors and average as well as maximum current velocities near the bottom. Thus, the correlative relationship between the average current velocity near the bottom and distance from the shore (r = 0.36), depth of the Baltic Sea (r = 0.41), vector of dominating current (r = 0.19) are statistically unimportant (Fig. 11). Similarly unimportant is the correlation between the maximum current velocity near the bottom and distance from the shore (r = 0.07), depth of the Baltic Sea (r = 0.02) as well as vector of dominating current (r = 0.35). Thus, the current velocity near the bottom depends on other factors such as peculiarities of the bottom relief, sloping and roughness. The data is insufficient to assess the influence of these factors.

A seasonal analysis of current velocities has revealed that their distribution is extremely complex in vertical and horizontal directions. The largest amount of fresh water discharges in the Baltic and the Black Sea in spring and summer times (Dubra, 1970; Titov, 2003). As well as in the Black Sea, currents flow faster in the refreshed water of the Baltic Sea, however their velocity in the latter depends on the debit of incoming water from

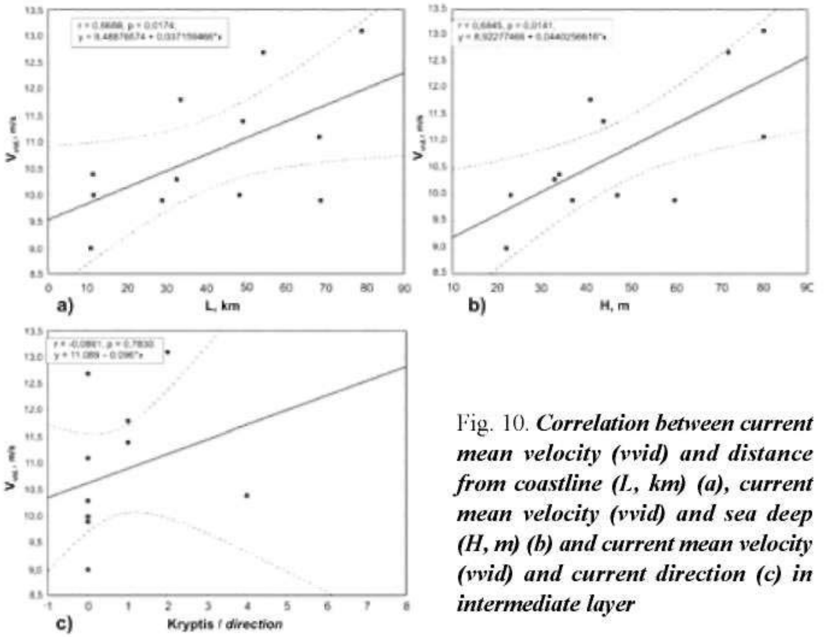

Fig. 10. ***Correlation between current mean velocity (vvid) and distance from coastline (L, km) (a), current mean velocity (vvid) and sea deep (H, m) (b) and current mean velocity (vvid) and current direction (c) in intermediate layer***

the Curonian Lagoon. The current velocity and direction may be different even in the same water masses here. The difference may be caused by the properties of water masses and depth of the Sea. Currents flow slower in the changing-migrating and transitional water masses because of the influence of the Baltic Sea bottom. Therefore the current velocity gets slower near the shore because of the friction. This factor does not work in the near-surface water masses where the debit of refreshed water is much more important.

The average velocity in all the layers increases in summer time. The current velocity increases by 3 cm/s near the surface and only by 0.6 cm/s near the bottom. The velocity also slightly increases in the transitional layer where the velocity 2.2 cm/s higher than in spring time was fixed. The average velocities vary from 11.3 to 12.4 in the transitional and from 9.0 to 11.5 cm/s in the near-bottom layers (Fig. 11).

In summer, the current velocity does not change in the near-surface layer (0–10 m) as well as in near-surface water masses. For the distribution of current velocities in the deep water masses, the influence of wind

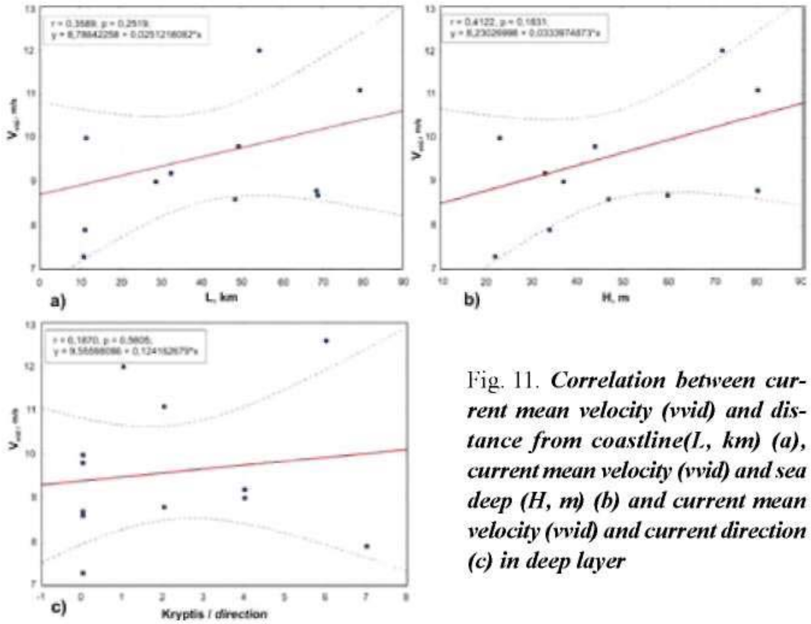

Fig. 11. ***Correlation between current mean velocity (vvid) and distance from coastline(L, km) (a), current mean velocity (vvid) and sea deep (H, m) (b) and current mean velocity (vvid) and current direction (c) in deep layer***

decreases, and such factors as properties of water masses (thickness, depth) play. The lowest current v_{av} for thermoclinic water masses occur near the shore. They vary from 7.5 to 7.8 cm/s. It is believed that the current velocity decreases because of the friction with the Baltic Sea bottom. The highest up to 11.9 and 16.3 cm/s velocities were measured in the thermoclinic water masses at the greatest distance from the shore. It appeared that the diversity of the distribution of current velocities in the study basin depends not only on the wind field but also on depth of the Baltic Sea, properties of water masses, their vertical thickness and position in the water column (Fig. 12). The results of the velocity study in summer time showed that the average current velocity in the thermoclinic and changing-migrating water masses is higher in the profiles above the plateaus and lower in the central part of the study area.

The average current velocities increased in almost all the profiles and their layers in autumn time. Thus the general current v_{av} increased in all the layers from 2.8 cm/s in spring to 3.3 cm/s in autumn. As compared to

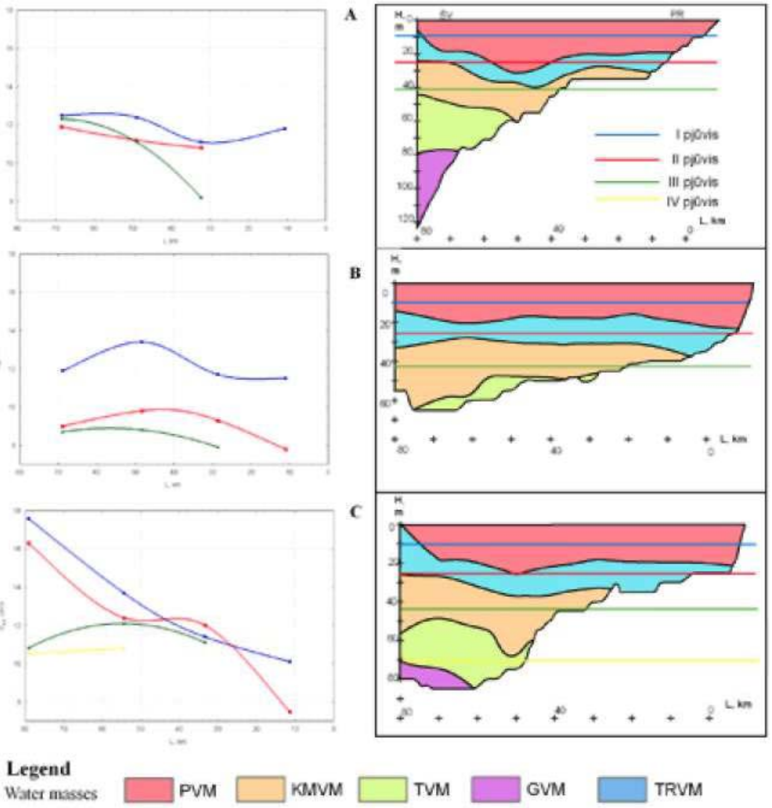

Fig. 12. ***Variability of summer current mean velocity in measurement profiles (A, B, C) in stratification water thickness*** *(Places of profiles showed in Fig. 2)*

summer time, the general current v_{av} remained the same near the surface while it increased from 1.2 to 3.2 cm/s in the transitional and near-bottom layers. Maximum current velocities were measured at the same localities in the near-surface and transitional layers. The average velocity in autumn time is only slightly lower than in summer time when the velocity was higher near the surface in the two profiles. The cases when current velocities near the bottom exceeded those near the surface and in the transitional layer may be explained by the formation of inertia currents. Besides, the current velocity near the surface depends on weather conditions. Therefore near-surface currents may be subdued and their velocity decreased when wind changes its direction and speed. As it was implied from the data on the maximum current velocity in autumn, the currents reach their maximum in the transitional layer. To sum up, throughout all the seasons the highest maximum velocity was in the transitional layer, than near the surface and lowest near the bottom. In autumn the maximum current velocity near the bottom was 1.7 and 1.4 times higher than in spring and summer.

The average current velocity is distributed in the water masses according to the certain rules. First of all, the greater the number of water masses, the more complex the distribution of current velocities in the water column (Fig. 13). The average current velocity changes at the boundaries of water masses leading to the break of velocity lines in such places.

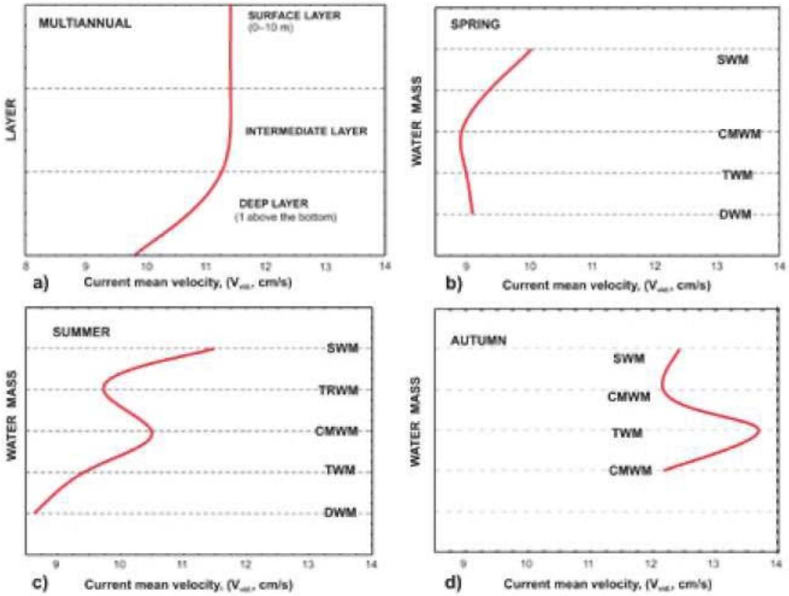

Fig. 13. ***Multiannual (a) and seasonal variability of vertical current mean velocity in spring (b), summer (c) and autumn (d).*** *SWM – surface water mass, CMWM – changing and migrating water mass, TWM – transitional water mass, DWM – deep water mass, TRWM – thermoclinic water mass*

6. THE MODELLING OF HYDRODYNAMIC REGIME OF THE STUDY BASIN

The obtained in field current measurements and compiled sketches of current circulation do not allow to characterize the hydrodynamic regime of the Baltic Sea in extreme (storm) conditions. Moreover, despite the relatively dense net of research stations and great number of field measurements used in the study, the obtained results do not fully highlight the hydrodynamic regime of the study basin.

The results of the hydrodynamic modeling revealed that the surface currents depend on the wind direction and speed. They usually flow in wind's direction slightly declining from it to the right (Krauss, Brugge, 1991). The current directions stabilize with the increasing wind. Similar modelling results were obtained for the near-surface currents in the Baltic Sea by a great number of investigators (Soskin, Denisov, 1957; Falzenbaum, 1976; Kovalik et al., 1977; Hydrometeorological…, 1983; Gailušis et al., 2002; Davulienė, Trinkūnas, 2004; Zurbas et al., 2004).

The greater increases the wind speed in the same direction, the faster flow the currents near the surface. The distribution of average current velocities near the surface differs very much as it was implied from the comparison of average velocities in the transverse profiles. J. D. Michailov thinks that the current average velocity near the surface of the Baltic Sea increases up to 28 km far from the shore and farther decreases (Michailov, 1972). By the way, similar tendency was obtained for the distribution of current velocities in the Black Sea (Ivanov, Bogdanov, 1953; Konovalova, Lagutin, 1968). The modelling results of the surface currents as well as field investigations in the study basin showed that the distribution of current velocities near the surface is different and much more complex (Fig. 14). The current velocity near the surface modelled at different western winds with a speed not exceeding 10 m/s was in many cases higher than the measured one. The modelled velocities are higher than measured because the measurements were performed in the 0–2 m thick layer while the thickness of this layer was 0 m in the model (Rukovodstvo…, 1954; Spravochnik…, 1971; Spravochnik…, 1973).

The current circulation gets more complex in the transitional layer where the winds affect increases. Currents flow in different directions and their velocities vary considerably. The most remarkable feature of the transitional layer is its ability to form circulating cycles which usually appear above the Klaipėda–Ventspils and Curonian–Sambian plateaus and their slopes. As it was implied from the model for the transitional layer with westerly winds, the anticyclone cycles more often appear in the northern part, above the Klaipėda–Ventspils plateau while the cyclones form in the south, above the Curonian–Sambian plateau.

The near-surface current velocity modelled for the westerly winds with a speed not exceeding 10 m/s turned to be higher than the measured one. However the modelled near-surface current velocity for the same westerly (NW, W, SW), 10 m/s blowing winds in the transitional and near-bottom layers is lower than the average measured velocity. This may have happened because the self-writing BPV-2 most frequently used for the current measurements does not measure currents slower than its sensitivity, i.e. 2 cm/s (Spravochnik…, 1971, 1973). The hydrodynamic model allows to model currents slower than 2 cm/s. That is why the measured velocities are usually higher than the modelled ones.

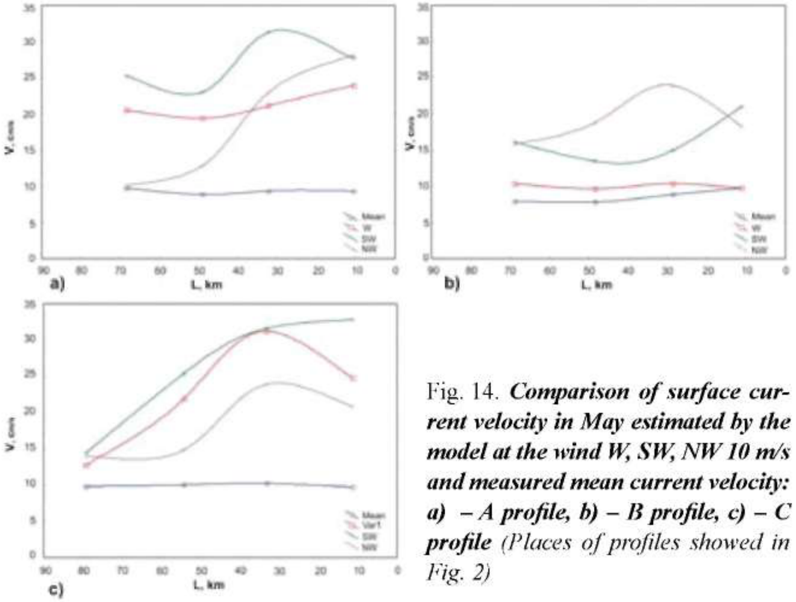

Fig. 14. ***Comparison of surface current velocity in May estimated by the model at the wind W, SW, NW 10 m/s and measured mean current velocity: a) – A profile, b) – B profile, c) – C profile*** *(Places of profiles showed in Fig. 2)*

The maximum velocity (198.9 cm/s) of the near-surface currents was obtained from the model with the SW blowing, 30 m/s fast wind. However the highest measured current velocity did not exceed 54 cm/s in spring. It is understandable that there is a lot of risk to measure current velocities during the storms. That is why we lack such measurements. Nevertheless, the current measurements in the Baltic Sea showed that the high current velocities were obtained quite often in quiet conditions.

The model confirmed the fact that the circulation of water masses in the study basin is defined by the bottom morphology. An area between the Klaipėda–Ventspils and Curonian–Sambian plateaus is assumed to be a submarine bay of the old Nemunas valley. Currents move from promontories (Klaipėda–Ventspils and Curonian–Sambian plateaus) into the depression (old valley of the Nemunas river). Such the current system can be defined as a macro circular cell (Fig. 15). It is interesting to note that similar circular cells emerge during the storms in the higher part of nearshore (Shepard, Inman, 1951; Sonu, 1972; Shchadrin, 1972; Žilinskas, 1993).

CONCLUSIONS

1. Water masses with individual thermohalic properties (near-surface, transitional, changing-migrating, deep and thermoclinic) were distinguished in the water column of the southeastern Baltic Sea. Their number varies from three (autumn) to five (summer).
2. The near-surface, transitional and deep water masses retain their properties, especially the vertical thermo gradient (0.0–0.2° C/m, 0.0–0.1° C/m and -0.1° C/m respectively) throughout changing seasons. Properties of the changing-migrating water masses vary: their vertical temperature gradient ranges from 0.0° C/m in spring to 0.5° C/m in autumn. The thermoclinic water masses forming only in summer have the highest vertical thermo gradients of 0.5–0.8° C/m.
3. Boundaries of the deep water masses do not change. Their thickness reaches 10–15 m in summer and 25–30 m in autumn. The near-surface and transitional water masses vary considerably in location and thickness which amplitude reaches 35 and 40 m respectively. The near-surface water masses are the thinnest in spring and the thickest in autumn while the transitional water masses are vice versa.

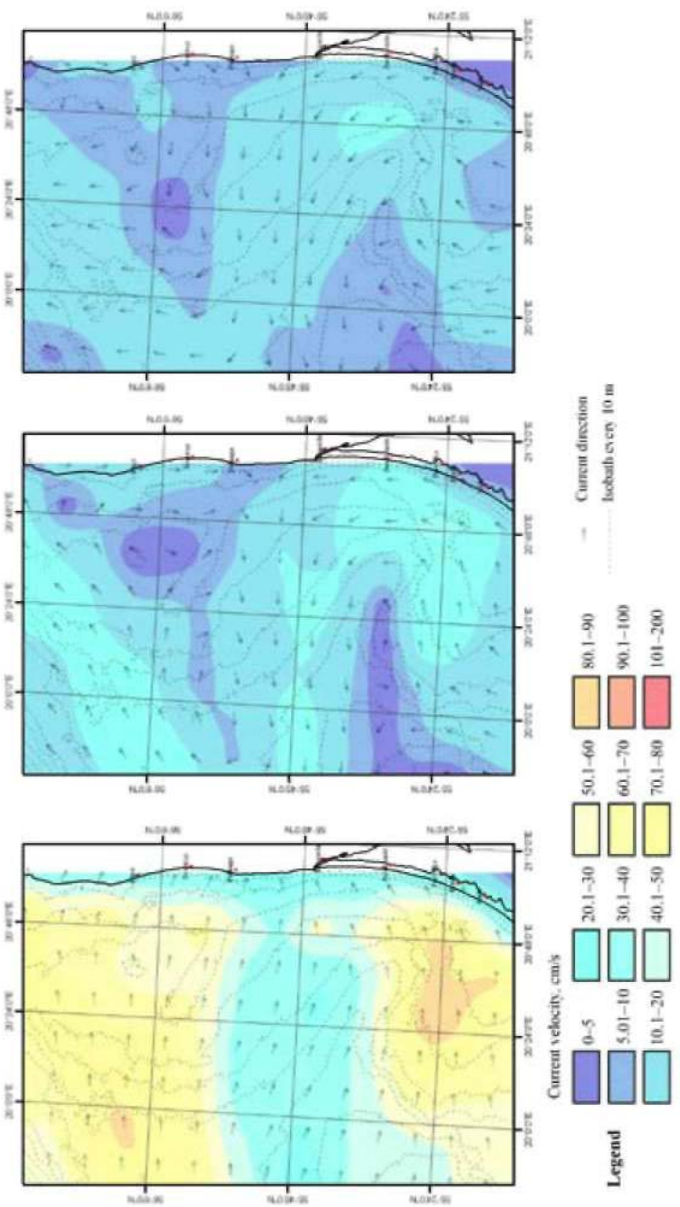

Fig. 15. ***Current vector and velocity in the research area in May estimated by the model at the wind W 20 m/s: surface (a), intermediate (b) and deep (c) layer***

4. The resultant direction of multiannual water discharge in the study basin is pointed towards north, in the same direction as quasi stationary circulation of the Baltic Sea currents.
5. The dominant current directions vary in the distinct water masses according to changing seasons. The two-layered circulation dominates the basin in spring time: currents are directed to the south in the near-surface and changing-migrating and to the north in the transitional and deep water masses. In summer when the thermocline is formed the northwards directions dominate the water masses above and below it. The currents flow to the west in the thermoclinic water masses. North directed currents dominate the water masses in autumn. The northern directions are complicated by the circulating cycles and head streams forming in the changing-migrating and transitional water masses.
6. Near the shore, the current flow direction in the transitional and near-bottom layers depends on the configuration and orientation of shore line and bottom relief. The latter do not influence the current direction farther offshore except for the near-bottom water masses.
7. The current velocity increases in the near-surface and transitional water layers with the distance from the shore and depth of the Sea.
8. The vertical distribution of current velocities in the basin of the Southeastern Baltic Sea depends on water masses. The current velocity epiuras change with the increasing number of water masses.
9. Multiannual and seasonal current velocities in the Southeastern Baltic Sea do not depend on dominant current directions.
10. In normal weather conditions (wind speed up to 10 m/s), the repetition of current-absent situations did not exceed 1% of all the measurements, however it increased to 16.9% in the transitional and to 29.8% in the near-bottom layers.
11. The digital 3-D baroclinic (POM) model can be used for the assessment and prediction of the water dynamics in the SE Baltic Sea as it was confirmed by the comparison of the field measurements and results of hydrodynamic modelling.
12. The results of hydrodynamic modelling proved the hypothesis based on the field measurements stating that a macro circular cell emerges between the Curonian–Sambian and Klaipeda–Ventspils plateaus at westerly winds.

LIST OF PUBLICATIONS ON DISSERTATION SUBJECT

Articles:

1. Žaromskis R., **Pupienis D.** (2003). Srovių greičio ypatumai skirtingose Pietryčių Baltijos hidrodinaminėse zonose. *Geografija (1)*. 16–23
2. Žilinskas G., Jarmalavičius D., **Pupienis D**. (2003). Jūros priekrantės sąnašų papildymo poveikis kranto būklei. *Geografijos metraštis 36, (1)*. 89–98
3. **Pupienis D.**, Žilinskas G. (2005). Specific features of morphodynamic processes in the dumps in the Lithuanian offshore. *Baltica 18, (1)*. 29–37
4. **Pupienis D.**, P. Jalinskas, Vyšniauskas I. (2007). The influence of currents on possible dispersion of oil products in the South-East Baltic. *Acta Zoologica Lituanica 17, (2)*. 160–172

Conference:

1. Žilinskas G., Jarmalavičius D., **Pupienis D.** (2003). **Эксперимент рекультивации прибойной зоны.** *Обсуждение материалов схемы противооползневых и берегоукрепительных сооружений на побережье Балтийского моря, Куршского и Вислинского заливов в пределах Калининградской области.* Kaliningradas. 2003 03 11–14.
2. **Pupienis D.** (2004). Hydrodinamic processes and their lithodynamic role in the coastal zone of the Southeast Baltic. *Lietuvos Baltijos jūros krantotvarkos problemos.* Vilnius. 2004 04 16.
3. **Pupienis D.** (2005). Jūros dugno morfologijos pokyčiai dampingo rajone ties Alksnyne. *Meteorologija ir hidrologija Lietuvoje: raida ir perspektyvos.* Vilnius. 86–87
4. **Pupienis D.**, Jankowski A. (2006). Modelling of sediment transport in the dumps in the Lithuanian offshore. *9th Marine Geological Conference, August 27 – September 3, Jūrmala, Latvia: Extended abstracts.* Riga. 79–81

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VANDENS DINAMIKOS YPATUMAI PIETRYČIŲ BALTIJOJE

REZIUMĖ

Netolygus Saulės energijos pasiskirstymas Žemės paviršiuje iššaukia energijos bei medžiagų apykaitą (šilumos, drėgmės, dujų, druskų ir kt.) tarp atmosferos, okeanosferos ir litosferos, formuoja ir keičia hidrometeorologines sąlygas Žemėje, o tuo pačiu ir generuoja vandens cirkuliaciją vandenynuose bei jūrose. Šios cirkuliacijos dėka įvairaus dydžio okeanosferos baseinuose vyksta turbulentinis vandens maišymasis, didelio kinetinės energijos kiekio, vandenyje ištirpusių dujų, druskų, biogeninių, organinių ir maistinių medžiagų persiskirstymas bei pernaša ir t. t. Aktyvi vandens masių cirkuliacija – viena iš svarbiausių vandens faunos ir floros gausos bei įvairovės klestėjimo sąlygų.

Pasaulinėje praktikoje tiriant tiek visos okeanosferos, tiek ir atskirų jos baseinų vandens masių cirkuliaciją pagrindinis dėmesys skiriamas srovių analizei, kurių apibendrinta visuma kartu su vandens balanso elementais ir baseino dubens ypatybėmis dažniausiai ir nulemia kiekvieno jūrinio baseino vandens apykaitos sistemą.

Nors Baltijos jūroje hidrodinaminiai tyrimai vykdomi nuo XIX a. vidurio ir yra žinomi bendriausi jos vandens cirkuliacijos dėsningumai, tačiau atskirų akvatorijų, tarp kurių paminėtinas ir Pietryčių Baltijos regionas (su Lietuvos vandenimis), hidrodinaminis režimas nėra pakankamai ištirtas. Tokių žinių trūkumas trukdo geriau pažinti ir visos Baltijos jūros hidrodinamikos ypatumus, įvertinti ekologinę šios akvatorijos būklę bei prognozuoti tolimesnę raidą. Atsižvelgiant į ribotą šio darbo apimtį, darbe nenagrinėjamos bangos ir vandens lygis. Tiriant vandens dinamikos ypatumus didžiausias dėmesys skiriamas horizontaliai vandens pernašai (srovėms).

Darbo objektas. Daugiametė ir sezoninė vandens cirkuliacija Pietryčių Baltijoje.

Darbo tikslas. Ištirti Pietryčių Baltijos jūros daugiamečius ir sezoninius hidrodinamikos ypatumus stratifikuotoje vandens storymėje.

Darbo uždaviniai:

1. Ištirti PR Baltijos vandens storymės stratifikaciją.
2. Ištirti jūros srovių krypčių daugiametės ir sezoninės kaitos ypatumus.
3. Ištirti jūros srovių greičių daugiametės ir sezoninės kaitos ypatumus.
4. Sumodeliuoti tiriamojo rajono srovių greičių ir krypčių pasiskirstymą, esant įvairioms hidrometeorologinėms sąlygoms bei palyginti modeliavimo ir natūrinių tyrimų rezultatus.

Ginami teiginiai:

1. Pietrytinėje Baltijos jūros dalyje vandens storymę sudaro vandens masės, pasižyminčios individualiomis termohalinėmis savybėmis. Vandens masių skaičius ir jų išplitimo ribos keičiasi metų bėgyje.
2. Tiriamojo rajono jūros srovių krypčių kaitai erdvėje ir laike ženklų poveikį daro vandens masės ypatumai ir dugno morfologija.
3. Tiriamojo rajono jūros srovių greičių kaita erdvėje ir laike priklauso nuo vandens masės ypatumų, akvatorijos gylio ir atstumo nuo kranto.
4. Įvairiuose jūros gylio horizontuose srovių greičiai nepriklauso nuo srovių krypties.
5. Taikant, tridimensinį baroklininį POM (*Princeton ocean model)* modelį aprobuotą A. Jankowskio, galima įvertinti PR Baltijos vandens dinamikos ypatumus esant įvairioms hidrometeorologinėms sąlygoms.

Išvados:

1. Pietrytinės Baltijos jūros vandens storymėje išskirtos individualiomis termohalinėmis savybėmis pasižyminčios vandens masės (paviršinė, tarpinė, kaiti-migruojanti, giluminė ir termoklininė), kurių skaičius kinta nuo trijų (rudenį) iki penkių (vasarą).
2. Paviršinė, tarpinė ir giluminė vandens masės pasižymi gebėjimu keičiantis sezonams išlaikyti savo savybes, ypač vertikalų temperatūros gradientą (atitinkamai 0,0–0,2 °C/m, 0,0–0,1 °C/m ir -0,1 °C/m). Kaičios-migruojančios vandens masės savybės keičiasi: jos vertikalus temperatūros gradientas kinta nuo 0,0 °C/m – pavasarį iki 0,5 °C/m – rudenį. Termoklininė, kuri susidaro tik vasarą, turi didžiausius vertikalius temperatūros gradientus 0,5–0,8 °C/m.
3. Mažiausiai kinta giluminės vandens masės paplitimo ribos. Jos storis pavasarį siekia 10–15 m, o rudenį 25–30 metrų. Didžiausia ribų ir storio kaita pasižymi paviršinė ir tarpinė vandens masės, kurių storio kaitos amplitudė siekia atitinkamai 35 m ir 40 metrų. Paviršinė vandens masė būna ploniausia pavasarį ir storiausia rudenį, o tarpinė vandens masė būna storiausia pavasarį ir ploniausia rudenį.

4. Tiriamos akvatorijos daugiametės vandens pernašos krypties atstojamoji, vyraujanti visoje vandens storymėje, nukreipta į šiaurę. Jos kryptis sutampa su kvazistacionaria Baltijos jūros srovių cirkuliacija.
5. Vyraujanti srovių tekėjimo kryptis atskirais sezonais priklauso nuo vandens masių. Pavasarį tiriamoje akvatorijoje vyrauja dvisluoksnė cirkuliacija: paviršinėje ir kaičioje-migruojančioje vandens masėje srovės dažniausiai nukreiptos į pietus, o tarpinėje ir giluminėje – į šiaurę. Vasarą, susidarius termoklinai, aukščiau ir žemiau jos esančiose vandens masėse vyrauja į šiaurę nukreiptos srovės, o termoklininėje – į vakarus. Rudenį vandens masėse vyrauja šiaurinės krypties tėkmės, kurias komplikuoja cirkuliaciniai žiedai ir priešpriešiniai srautai, susidarantys kaičioje-migruojančioje ir tarpinėje vandens masėse.
6. Priekrantėje srovių tekėjimo kryptį paviršiniame, tarpiniame ir priedugniniame sluoksniuose apsprendžia kranto konfigūracija ir orientacija bei dugno reljefas, tuo tarpu gilėjant jūrai dugno reljefo poveikis srovių tekėjimo krypčiai jaučiamas tik priedugniniame sluoksnyje.
7. Paviršiniame ir tarpiniame sluoksniuose tiriamoje akvatorijoje srovių greičiai didėja, tolstant nuo kranto ir didėjant gyliams.
8. Vertikalus srovių greičių pasiskirstymas Pietryčių Baltijos vandens storymėje priklauso nuo vandens masių. Didėjant vandens masių skaičiui srovių greičių epiūros pobūdis kinta.
9. Daugiamečiai ir sezoniniai srovių greičiai Pietryčių Baltijos vandens storymėje nepriklauso nuo vyraujančių srovių krypčių.
10. Ramiu oru (vėjo greitis iki 10 m/s) paviršiuje srovių tykos pasikartojimas neviršijo 1% visų matavimo atvejų, tarpiniame sluoksnyje – padidėjo iki 16,9%, o priedugnėje iki 29,8%.
11. Atliktas natūrinių duomenų ir hidrodinaminio modeliavimo rezultatų palyginimas parodė, kad skaitinis tridimensinis baroklininis (POM) modelis gali būti taikomas PR Baltijos vandens dinamikos vertinimui ir prognozavimui.
12. Hidrodinaminis modeliavimas patvirtino natūrinių duomenų analizės metu iškeltą hipotezę, kad tiriamajame rajone, pučiant vakarų krypties vėjui, tarp Kuršių–Sambijos ir Klaipėdos–Ventspilio plynaukščių susidaro makrocirkuliacinė celė.

Donatas Pupienis

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