Oceanological and Hydrobiological Studies
International Journal of Oceanography and Hydrobiology
Vol. XXXVIII, No.2

Institute of Oceanography (3-16) University of Gdańsk
ISSN 1730-413X 2009 eISSN 1897-3191

DOI 10.2478/v10009-009-0014-8
Original research paper

Received: *March 28, 2008*
Accepted: *June 1, 2009*

Upwelling characteristics in the Puck Bay (the Baltic Sea)

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Key words: the Puck Bay, Southern Baltic, upwelling, sea water properties, numerical modeling

Abstract

The spatial distributions of basic water parameters in the Puck Bay, a small semi-closed water body located on the southern coast of the Baltic Sea, were often typical of upwelling phenomenon. In such situations, like those observed in July of 1999, temperature decreased locally and water transparency increased locally. The present study analyzed conditions under which upwelling occurred using maps of horizontal currents at different depths, which were obtained from an operational hydrodynamic model. With north, northwest winds the upwelling in Puck Bay looked like the shallow-water upwelling arising as a direct dynamic response of the

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water body to the wind direction, without a distinct effect of the Coriolis force. However, upwelling water circulation during other wind directions, i.e. west and northeast winds, did not match this simple scheme and was affected by coastline configuration. The results of many years' measurements pointed at an important role of upwelling in hydrological regime formation in the shallow parts of the Puck Bay.

INTRODUCTION

In the Baltic Sea some mechanisms exist that cause water from deeper sea layers to rise to the surface. This phenomenon is called "upwelling" (Svansson 1975, Myrberg&Andrejew 2003). Upwelling occurs along the southern coast of the Southern Baltic mainly as a result of the east winds blowing parallel to the coastline (Urbański 1995; Kowalewski 1998; Jankowski 2000, 2002; Kowalewski and Ostrowski 2005). Due to the Coriolis force, a surface, offshore transport of water mass is induced and consequently, an inshore compensation current is generated. This mechanism of coastal upwelling evolution is described by Ekman's theory (Pedlosky 1978, Bowden 1983). In this case, adequately deep water is a necessary condition for upwelling formation. An offshore wind is more effective at creating an upwelling in more shallow water bodies (Svansson 1975).

Many field observations corroborate the occurrence of some signs of an upwelling effect in certain coastal and shallow regions of the Puck Bay. They are manifested by a local occurrence of colder waters at the surface or just underneath it during warmer seasons (Nowacki 1980, 1984, 1993a,b,d) and vice versa in winter (Nowacki 1993b**)**. The water at those sites was also more transparent (Krężel&Sagan 1987, 1991; Krężel 1993; Matciak 1998). The occurrence of this phenomena confirmed the results of statistical analysis of the water mass spatial distribution. The water types were classified on the basis of different hydrological and hydrochemical properties. The analysis showed distinct regions of the bay which are different from the rest of the area with respect to water optical state, thermal-salinity characteristics and biogen concentration (Krężel&Sagan 1991, Nowacki&Jarosz 1998, Andrulewicz et al. 2004). Some authors (Krężel&Sagan 1987; Nowacki 1980, 1984, 1993b,c,d) presumed that their observations could be the effect of water rising from deeper sea layers to the surface. However, there is no research devoted entirely to this question. Therefore, the aim of the present work was to investigate the conditions and determine the regions of upwelling occurrence in the Puck Bay.

Morphometric characteristics of the Puck Bay

The Puck Bay is a subregion situated in the western part of the Gdańsk Basin and separated from its deep part by Hel Peninsula (Fig. 1). The bay is

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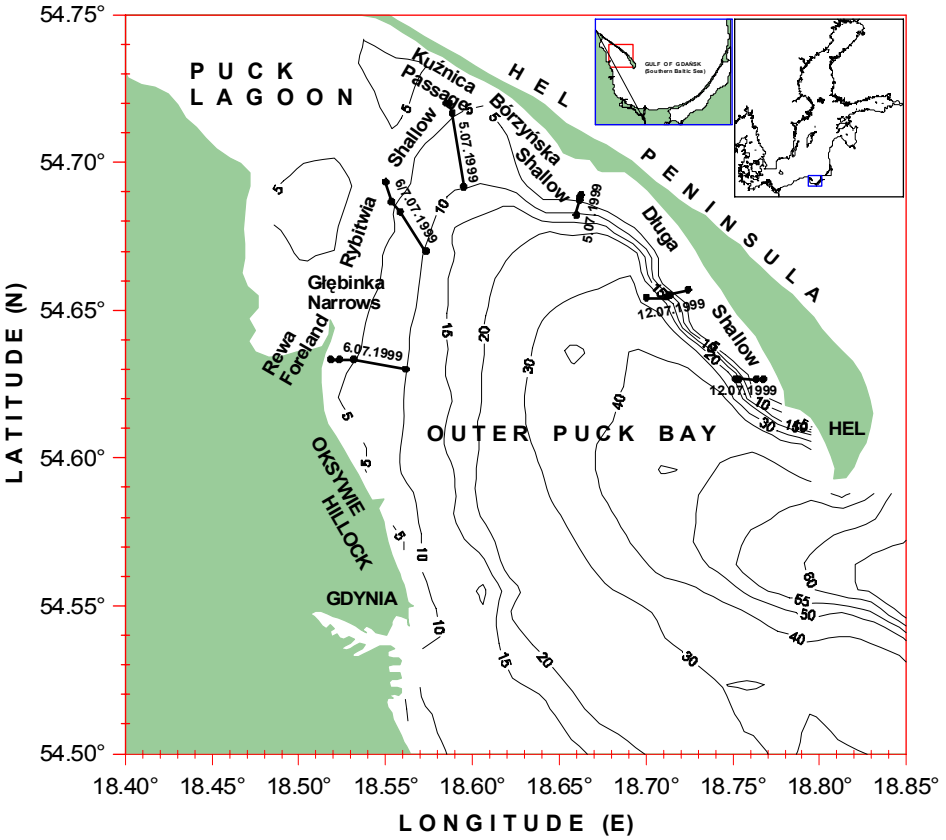


Fig. 1. Study area and location of sampling stations.

divided into two parts: the eastern, deeper one of 20.5 m average depth, called the Outer Puck Bay, and the western, markedly shallower part of 3.1 m average depth, called Puck Lagoon (Nowacki 1993a). Both parts are separated by periodically flooded Rybitwia Shallow running from the Rewa Foreland to Hel Peninsula. Since many parts of Rybitwia Shallow protrude above the water surface, water exchange between the two parts of the Puck Bay is difficult. A passage is situated at each end of Rybitwia Shallow: Głębinka Narrows and Kuźnica Passage, at the southwestern and northeastern ends, respectively (Nowacki 1993a). An intensive water exchange occurs between the Outer Puck Bay and Puck Lagoon through these passages, especially through Głębinka Narrows. Under certain circumstances a considerably smaller water exchange through Rybitwia Shallow could be observed also (Nowacki 1993b). The

important morphological element of the Puck Bay is a remarkable bottom depression. It runs parallel to Hel Peninsula, from the region of maximum depth (54 m) to Rybitwia Shallow.

MATERIALS AND METHODS

Data presented in this study data were collected in the Outer Puck Bay on July 5, 6, and 7, 1999. The measuring stations were situated along the profiles perpendicular to the coast, in the area of 1-10 m depth (Fig. 1). Temperature and salinity were registered at every station, at 0.5 m intervals, by an automatic CTD probe (Meerestechnik GmbH). Water optical state was determined by Secchi disc.

A three-dimensional hydrodynamic model developed by Kowalewski (1997, 2002) was applied to reproduce water circulation. The model works in an operational system (i.e. it reproduces daily maps of sea currents) at the Institute of Oceanography, University of Gdańsk. The model was verified in the investigations of upwellings in the whole Baltic area, and especially of the one that occurs at the outer side of Hel Peninsula (Kowalewski 1998). Input meteorological conditions, i.e. air temperature, atmospheric pressure and wind field, were derived from a mesoscale operational weather forecast model UMPL (Herman-Iżycki et al. 2002). The data on wind direction and velocity were positively verified based on the results from field measurements. The hydrodynamic model enabled one to obtain an approximate pattern of spatial distributions, with grid steps of 1 nautical mile, of current velocity horizontal components, temperature and salinity in the surface layer (0-2.5 m) and in the following water layers of 5 m thick, at noon, between July 1 and 12, 1999.

RESULTS

The analysis of the spatial distribution of water temperatures in the study area showed colder waters (17 – 20°C) in the surface layer of these coastal zone regions as compared to the surrounding waters (ca. 21°C) (Fig. 2a). The colder waters were noted mainly along the middle and northeastern parts of Rybitwia Shallow and the middle section of Hel Peninsula (Bórzyńska Shallow) (Fig. 2a). They could be characterized by higher salinity (6.5-6.7 PSU) as compared to the salinity of the surrounding waters (ranging from 5.7 to 6.4 PSU) (Fig. 2b). On July 6 and 7, 1999 vertical distributions at the transect perpendicular to Rybitwia Shallow showed that the colder and more saline waters were upwelled to the surface from deeper sea layers (Fig. 2c, 2d). Areas with thermal and salinity differences were also characterized by an increase in water transparency. Secchi depth was ca. 4 m and 3.5 m at most places along

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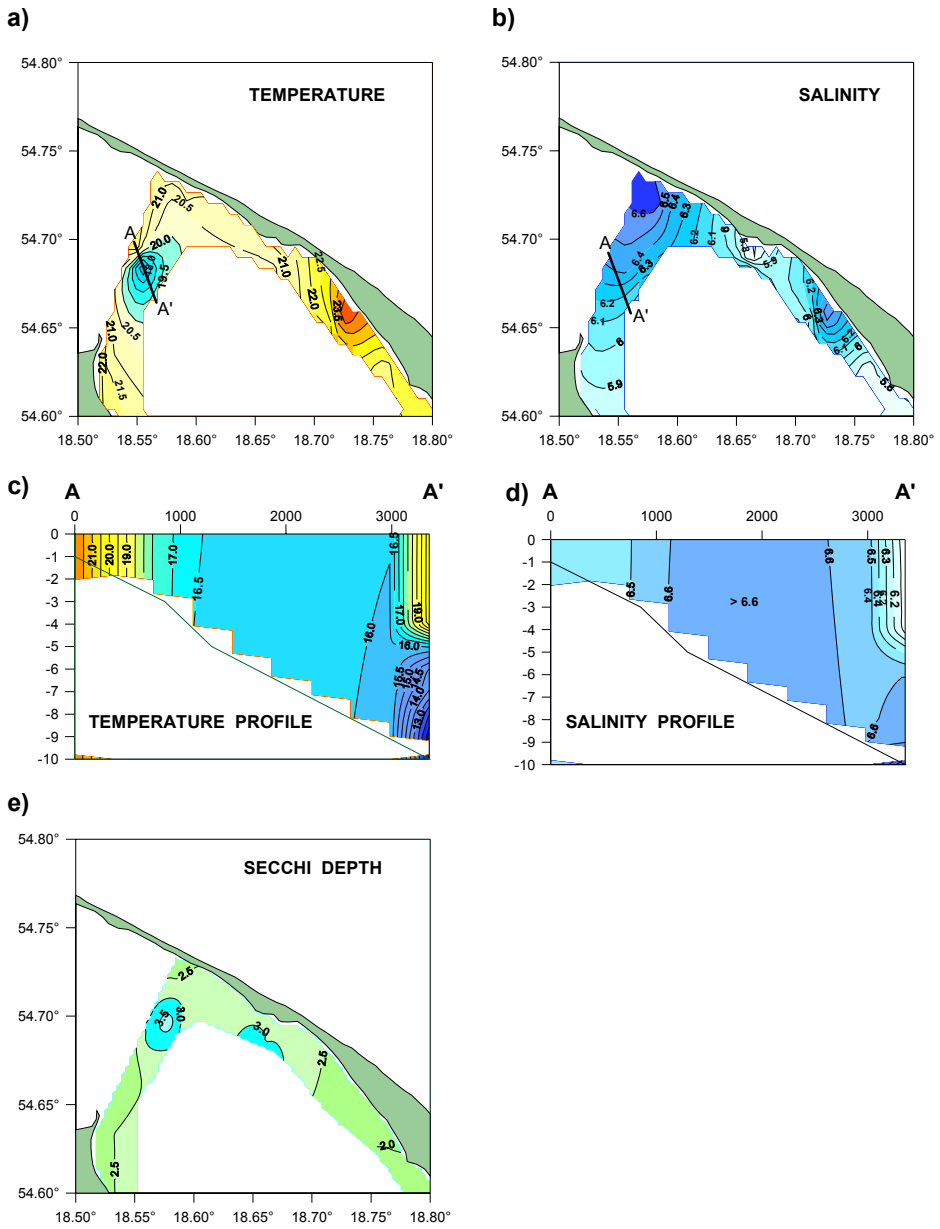


Fig. 2. Spatial distributions of sea water properties determined by in situ measurements in Outer Puck Bay on July 5,6,7, and 12, 1999: a) surface temperature [°C], b) surface salinity [PSU], c) temperature [°C] vertical distribution at the AA' transects on July 6 and 7, 1999, d) salinity [PSU] vertical distribution at the AA' transects on July 6 and 7, 1999, e) Secchi depth [m].

Rybitwia Shallow and the middle part of Hel Peninsula, respectively, whereas the values were ca. 2.5 m in the surrounding waters (Fig. 2e).

During in situ measurements moderate winds from the north and east prevailed (Fig. 3). Their life-span was between several and 24 hours. The numerical model circulation showed that the east wind on July 5 resulted in surface water inflow from the Gulf of Gdańsk into the Puck Bay and water outflow from Puck Bay at deeper layers (Fig. 4a, 4b). The general pattern of water circulation generated by the north and northwest (Fig. 4c, 4d) winds on July 6 and 7 was exactly the opposite. The wind drove the water in the surface layer approximately according to wind direction toward the open border of the Puck Bay. It caused the formation of a reversible compensation current from a depth of ca. 10 m. As a consequence, the water flow exhibited the opposite direction to the surface one. With a northwest wind this current originated along the marine coast of Hel Peninsula, then turned at its end and flowed into the bay, where it headed mainly northward. It should be noted that part of the current continued a circular motion flowing finally to Hel Peninsula. However, with a north wind the current at a depth of 10 m flowed from the south part of the Gulf of Gdańsk towards Rybitwia Shallow. Except for the east wind, there were favourable conditions for upwelling evolution since the water withdrawn from the surface of Rybitwia Shallow and the Hel Peninsula coast could be replaced by water from deeper sea layers.

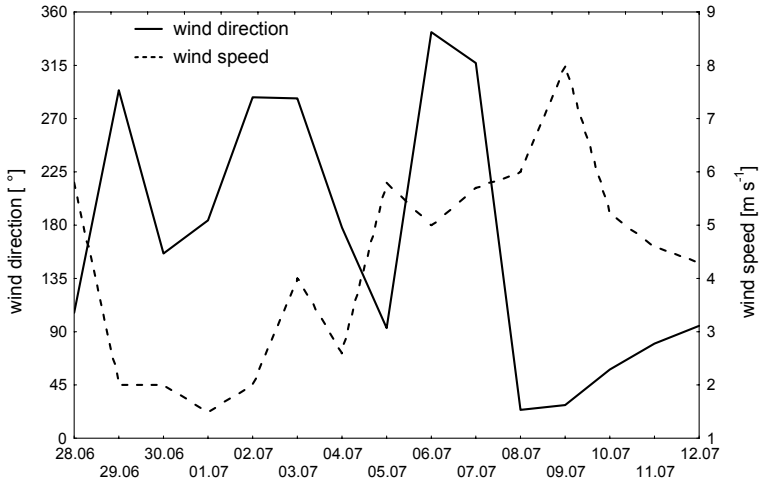


Fig. 3. Wind conditions (June 28 – July 12, 1999) in the Puck Bay area obtained from the mesoscale operational weather forecast model UMPL (Herman-Iżycki et al. 2002).

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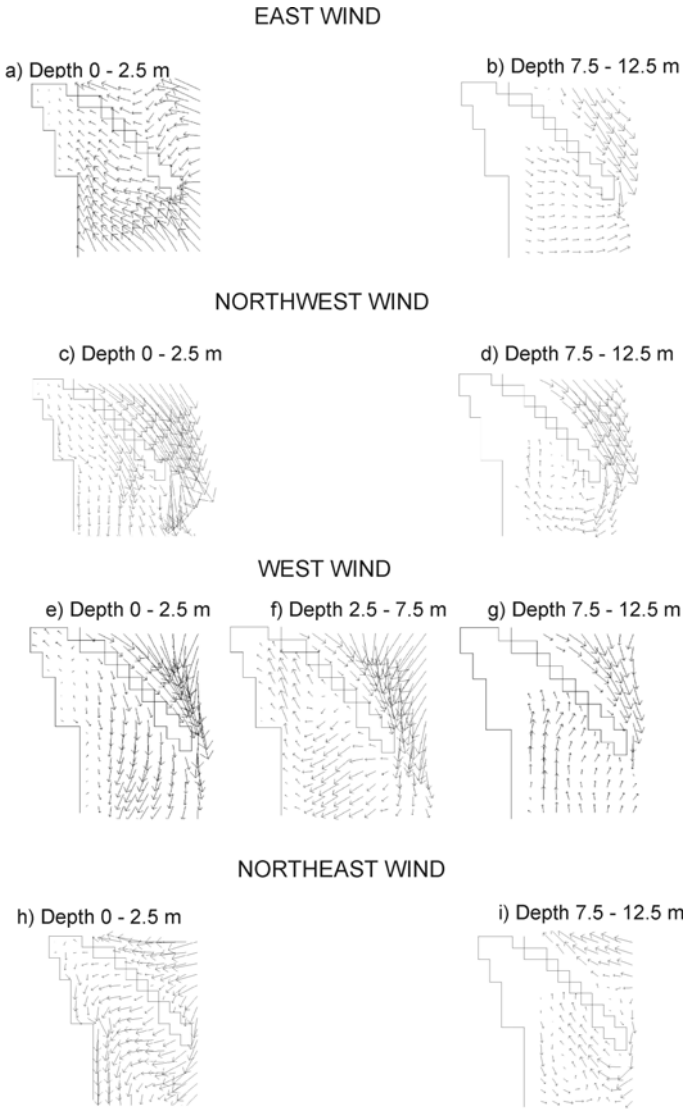


Fig. 4. Sea currents in Outer Puck Bay obtained with the use of the numerical model: a) in the surface layer (0-2.5 m) with a east wind (July 5, 1999); b) in the water layer from 7.5 to 12.5 depth with a east wind (July 5, 1999); c) in the surface layer (0-2.5 m) with a northwest wind (July 7, 1999); d) in the water layer from 7.5 to 12.5 depth with a northwest wind (July 7, 1999); e) in the surface layer (0-2.5 m) with a west wind (July 3, 1999); f) in the water layer from 2.5 to 7.5 depth with a west wind (July 3, 1999); g) in the water layer from 7.5 to 12.5 depth with a west wind (July 3, 1999); h) in the surface layer (0-2.5 m) with a northeast wind (July 9, 1999); i) in the water layer from 7.5 to 12.5 with a northeast wind (July 9, 1999).

Numerical simulations of west and northeast winds pointed also at the water motion which could promote the upwelling as well. Unfortunately, there were no accompanying in situ measurements since the west wind was only noted on July 2 and 3, just before fieldwork began. On the first day the wind was initially light (2-3 m s^{-1}), and on the next day it freshened to ca. 4 m s^{-1}, which resulted in southerly water flow in the surface layer of Outer Puck Bay (Fig. 4e). However, at a depth of 5 m the current flowed toward the western coast of the bay where it turned to the north (Fig. 4f). Deeper water flowed north, to Rybitwia Shallow and Hel Peninsula (Fig. 4g). The northeast wind (8-9.07) blew perpendicular to Hel Peninsula pushing the surface water away from the peninsula to the western coast of the Puck Bay where it turned south (Fig. 4h). From a depth of about 5 m, the northwesterly wind directed water flow along Hel Peninsula, whereas on the other side of the bay the current was directed southward (Fig. 4i). All water circulation patterns were characterized by relatively low current speeds, which generally did not exceed 20 and 5 cm s^{-1} in the surface and deeper layers, respectively. Outside the bay the water could move faster, particularly along Hel Peninsula.

The modeled course of temperature spatial changes with a west wind demonstrated that the lowest temperature values occurred at both ends of Rybitwia Shallow, i.e. Rewa Foreland and in the region of Kuźnica Passage (Fig. 5a). With a northwest wind the zone of lower temperature was noted in the northeastern part of Rybitwia Shallow and along Bórzyńska and Długa Shallows (Fig. 5b). In both cases regions of colder water also occurred with a northeast wind (Fig. 5c).

DISCUSSION

The Outer Puck Bay is a small water body of ca. 20 m average depth. Because of its shallow depth, upwelling induced by along shore wind and a distinct influence of the Coriolis force on the surface flow of water mass could not be expected. At shallow depths (on the order of 10 m) the occurrence of offshore wind results in compensatory water inflow at the deeper sea layers directly to the coast (Svansson 1975) and the combination of horizontal current speed and the water depth decrease is the reason for the upward water motion (Lund-Hansen&Vang 2003). Morphometric features of Outer Puck Bay create favorable conditions for the upwelling induced by offshore wind, as the bay is surrounded on two sides by land, and an underwater barrier, i.e. Rybitwia Shallow, occurs on the north. In such a situation upwelling would occur with almost all wind directions, except for those from the south. With north and northwest winds reversible compensation current, which causes upwelling, overlapped approximately the wind direction. When the withdrawn surface

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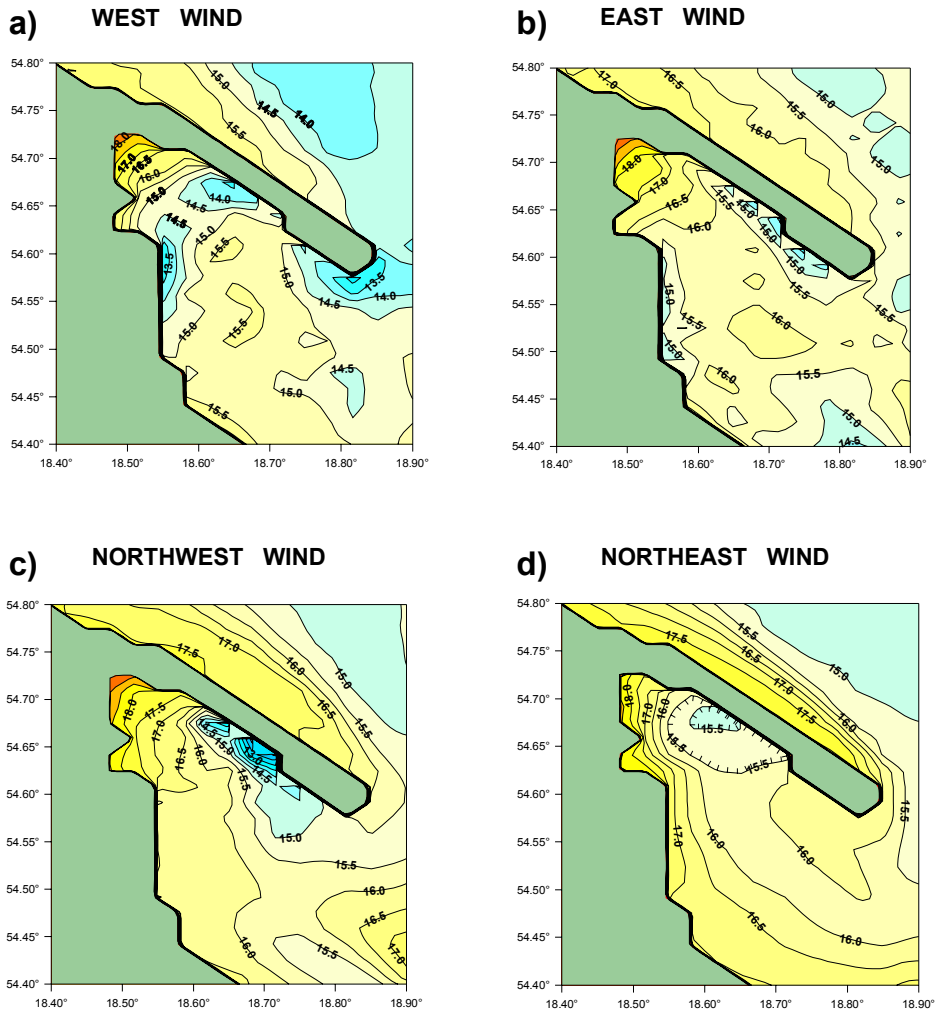


Fig. 5. Spatial distributions of sea water temperature [°C] in the subsurface layer (2.5-7.5 m) determined with the use of a numerical model in Outer Puck Bay: a) with a west wind (July 3, 1999); b) with a northwest wind (July 7, 1999); c) with a northeast wind (July 9, 1999).

waters were replaced by the waters from deeper sea layers, upwelling was expected to occur along the northeastern part of Rybitwia Shallow and Hel Peninsula, i.e. Bórzyńska and Długa Shallows. It was evidenced by the results of field investigations as well as by sea current and temperature distributions derived from the hydrodynamic model.

The dynamic response of the bay at deeper water layers was different from the mechanism suggested earlier with northeast and west winds. With a northeast wind the subsurface compensating current (to 20 m depth) did not direct towards the coast of the peninsula but ran approximately parallel to it in the northwestern direction. When the current reached Borzyńska shallow and the northeastern part of Rybitwia Shallow the water finally moved toward the surface. When winds blew from the west the subsurface current at ca. 5 m of depth flowed to the west whereas at deeper layers the current ran northwards. The western, relatively wide and shallow coastal zone of the bay, Rybitwia Shallow and the coast of the peninsula were the regions where upwelling were expected. The results in both simulated cases should be verified based on *in situ* investigations. It seems that the upwelling usually occured when the surface waters flowed outside the Puck Bay through its open border with the Gulf of Gdańsk while underneath, water flowed into the bay. With east and south winds the water was pushed into the bay in the surface layer, which caused the outflow at greater depths. A pool of more transparent water observed on July 5, 1999 along Bórzyńska Shallow with an east wind (Fig. 2e) might still have been the effect of the upwelling caused by the west wind, which prevailed earlier on July 2 and 3 (Fig. 3).

The upwelling zones differ from the surrounding waters particularly in terms of colder temperatures (Bowden 1983). This phenomenon is relatively frequent in the Outer Puck Bay and could be confirmed by the occurrence of a low temperature zone in the foreland of Rybitwia Shallow. The zone could be observed in spatial temperature distributions in the water body obtained from many years' measurements (Fig. 6a, b). It is worth noting that in the Outer Puck Bay the waters are most probably upwelled from relatively shallow depths, c.a. 10-15 m, because they do not differ significantly in their physical properties from the surrounding waters. For comparison, during the upwelling occurring along the outer, marine side of Hel Penisula, the temperature in its centre could be lower even by about 15°C (Krężel et al. 2005, Matciak et al. 2005). Since the water circulation in the surface layer of the Puck Bay strongly depends on the wind direction it is important to look at the wind conditions throughout a year in this area. They were analyzed by Cyberski and Szefler (1993). The north and northeast winds dominate in spring whereas the west and northwest ones dominate from summer until the end of the year. The annual rhythm of prevailing wind directions could be reflected in quarterly mean fields of water transparency (Fig. 7). Depending on wind conditions the areas of higher water transparency were observed at the locations already described above, i.e. at the eastern coast of the bay in spring and also along Rybitwia Shallow in the summer and autumn. From January until March, when the west winds are accompanied by the south ones and the water column is optically homogenous,

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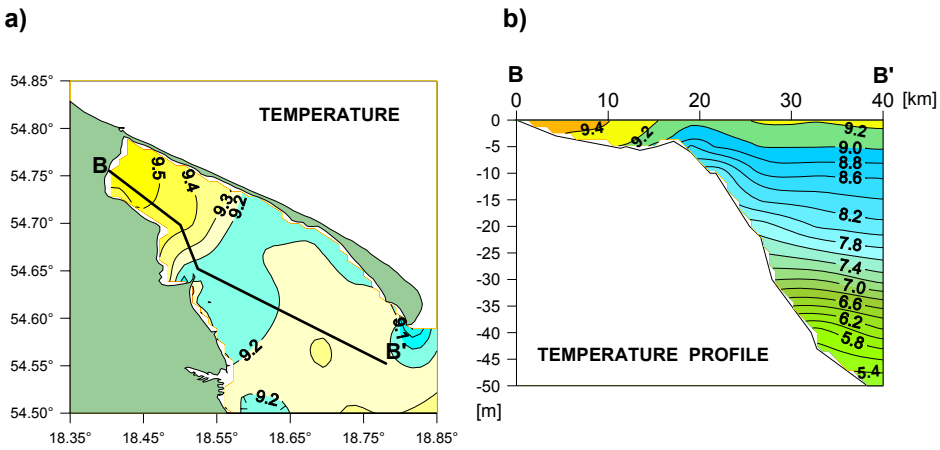


Fig. 6. Spatial distributions of the mean temperature values [°C] (1981-1996) at the surface (a) and in the water body along the transect BB' (b) in Outer Puck Bay.

isolated areas of higher mean Secchi depth were not revealed. In this case the water of increased transparency could be noted in the whole central part of the bay.

It appears that the influence of upwelling water circulation in the Puck Bay was not restricted only to its outer part. Based on data collected during the years 1975-87 it was noticed (Nowacki 1980; Krężel 1993; Nowacki 1993b, c) that in the inner, shallow part of the Puck Bay (ca. 3 m average depth), which is separated from the rest by Rybitwia Shallow, the water was often characterized by relatively high salinity and, throughout vegetative season, it had a higher transparency as compared to the surface waters in the outer part of the bay. In particular the last fact is surprising because shallow water bodies are usually the least transparent due to intensive resuspension processes as well as enhanced biological productivity. There were attempts to explain these observations by the distinct difference in the morphological conditions between the two parts of the bay and by the role of Rybitwia Shallow, which impedes free water flow. It was also supposed that the waters upwelled from deeper areas along Hel Peninsula may play a certain role in limiting the water exchange between these bodies of water (Krężel 1993). In light of the results presented here, a hypothesis could be made that the direct cause of the observed differentiation could be the compensation current flowing up to Rybitwia Shallow from the south and flowing into Puck Lagoon mainly by Głębinka Narrows. Nowacki (1993c) observed this type of current in Głębinka Narrows. The water inflow to the lagoon through the whole cross-section of the narrow

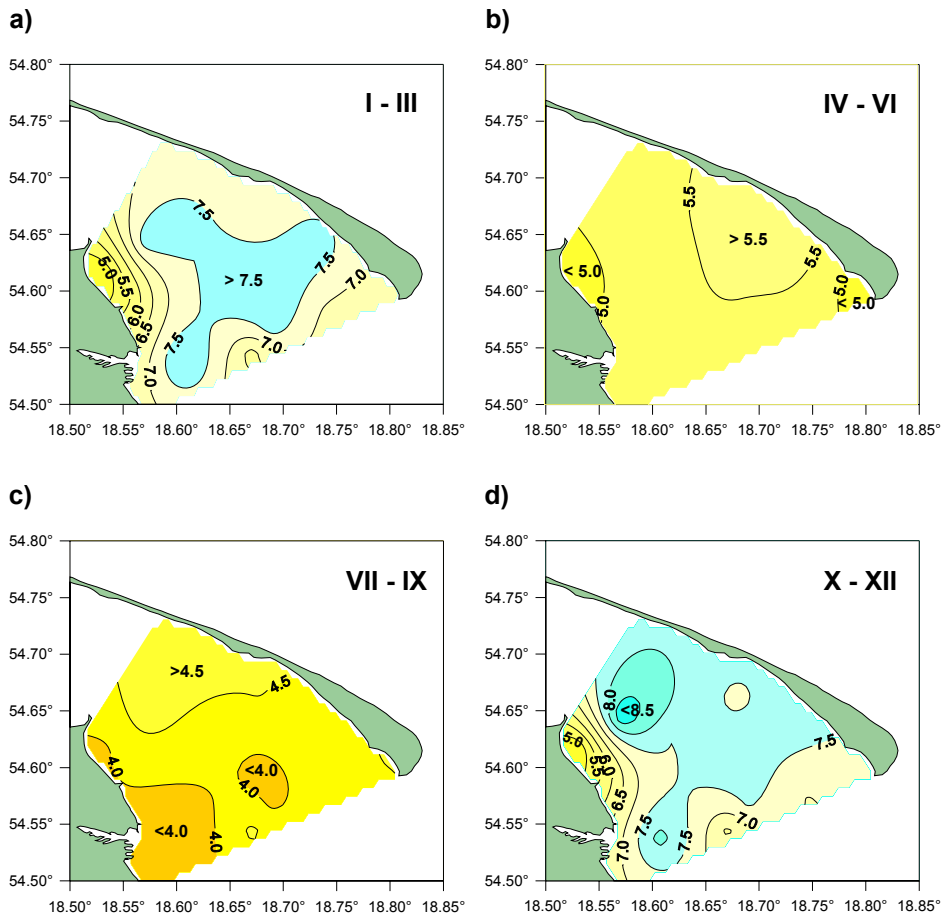


Fig. 7. Spatial distribution of mean Secchi depth values [m] (1981-1997) in different seasons of year in Outer Puck Bay (Matciak 1998).

was more frequent (ca. 18%) than the outflow (ca. 9.6%). The most intensive inflows were noted with northeast and west winds with the highest value of water volume of 0.026 km^3 which flowed into Puck Lagoon during twenty four hours. It was a significant part of the total water volume in this shallow part of Puck Bay (c.a. 8%). Unfortunately, there is a lack of current data on the physical properties of the water in Puck Lagoon since systematic research has not recently been carried out in this area. Therefore we do not know whether it is still characterized by higher water transparency as compared to the Outer Puck Bay. Generally, the upwelling influence on the optical conditions of the

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Puck Bay waters can be dependent on the long-term changes that occur in this area. During the last four decades a permanent decrease in surface water transparency has been observed in the Gulf of Gdańsk, accompanied by a decrease in Secchi depth variability (Trzosińska 1992, Łysiak-Pastuszak, Piątkowska 2004). It is commonly explained by strong eutrophication of the water environment. A growing amount of suspended marine organic particles in the surface layer is eventually transported downward and the deeper waters are becoming less transparent too. As a result, there are reduced differences in water optical state during upwelling.

ACKNOWLEDGEMENTS

Editing assistance of the article was provided by BALTDER (EVK3-CT-2002-80005), founded by the European Commission under the 5th Framework Programme.

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