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ANALYSIS OF ICE CONDITIONS IN THE BALTIC SEA AND IN THE PUCK BAY

ABSTRACT

The paper presents results of research based on analysis of ice conditions in the Baltic Sea and in the Puck Bay. Analyses are concerned on the last century the maximum ice extents in the Baltic Sea (1915–2015) and ice conditions in the Puck Bay (1986–2005). Ice conditions in the Baltic Sea are generally of average intensity and depend mainly on the type of winters (mild, average/ normal and severe), however, the Baltic bays and gulfs cover the sea ice almost every year. The average ice extent in the Baltic Sea during typical winters, the ice extent in the Baltic Sea during winters in years from 1915 to 2015 and the average time limits the occurrence of the first ice, number of days with ice, ice thickness, terms the disappearance of the last ice in the Puck Bay together with examples of ice forms are presented in this paper. The phenomenon of ice has a significant impact on human activities in the sea, have an effect on weather and climate, plant and animal life, fishery and ports activities and the safety of navigation.

Key words:
sea ice, ice condition, Baltic Sea, Puck Bay.

INTRODUCTION

The issue of freezing seas, the formation of sea ice, the drift ice floe and the movement of the masses of ice are areas of interest in the physical oceanography. Sea ice poses a danger for the conduct of all forms of human activity on marine areas and affect the continuity of operation of the ports. According to K. Łomniewski the ice phenomena involves a wide range of climatic and oceanographic factors. Ice has an impact on the weather, the living conditions of plants and animals in the sea

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and on fisheries [7]. Sea ice is formed as a result of cooling water to the temperature of the freezing point. Process of the cooling water occurs when the thermal balance of the surface of the sea is negative, and so when the water has accumulated in a heat into the atmosphere. Meteorological elements which determine the balance values to include mainly air temperature and solar radiation, and hydrological elements the biggest role of the temperature of the water [13]. The existence of the phenomena of ice on areas of bays is dependent on the size, depth, the size of cover from the open sea, the configuration of the shoreline, the directions of the winds and the supply of river water.

The phenomenon of ice in the southern part of the Baltic Sea are generally small intensity, however, gulfs and inner bays cover by ice each year.

DATA AND METHODS

The article aim is to present the ice conditions of the Baltic Sea and the Puck Bay as a part of the Baltic Sea and while their time and physical characteristics that specify the size of this phenomenon. Moreover, a secondary purpose of the article is to collect in one aggregate study problems of ice conditions during winters in the Baltic Sea and the Puck Bay, considering the use of this information by marine students of academies during the study of oceanography.

Following methods were used to achieve the above objectives such analysis and inference. Implementation of the research was based on the historical material gathered by research institutes and in publications. It should be noted that issues of ice conditions in the Baltic Sea and the Puck Bay are not in literature too wide presented, however, systematic studies by the national research and scientific institutes in the Baltic maritime areas and publication of their results will give a pretty good view of the studied phenomenon. The primary sources of data for analysis were publications and the data of the Finish Meteorological Institute [1, 3], the Polish Institute of Meteorology and Water Management, Swedish Meteorological and Hydrological Institute, the Polish Maritime Institute [5] and Hydrographic Office of the Polish Navy [6], as well as K. Łomniewski [7, 8] and W. Zakrzewski [13] publications.

Annual extents of ice cover in the Baltic Sea since 1720 are provided by the Finish Meteorological Institute (FMI) in the publication *Ice winters in the Baltic Sea* [1]. For the purposes of this article uses the data of maximum annual ice extent from the last century (1915–2015). In figure 1 the ice extents in the Baltic Sea during winters in years from 1915 to 2015 based on the data from FMI are presented [1].

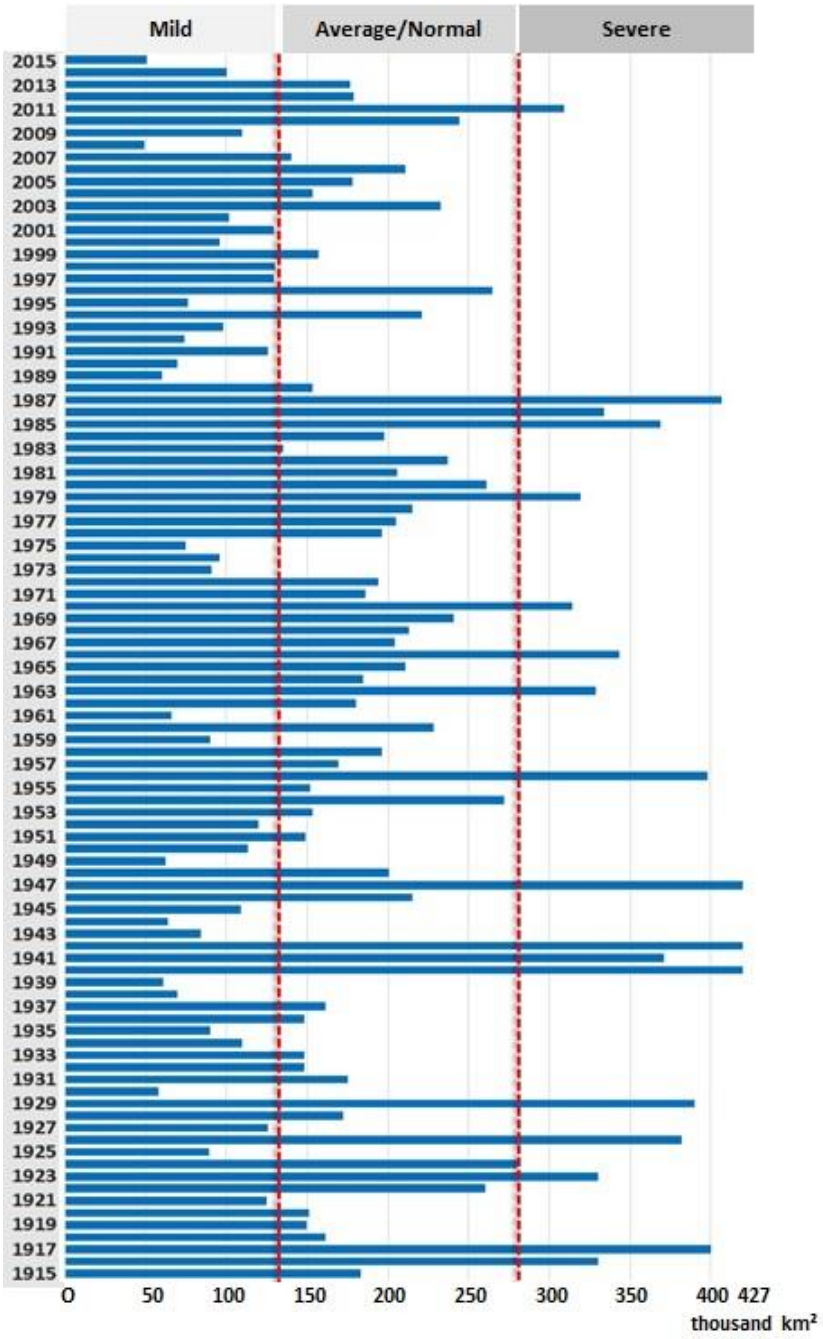


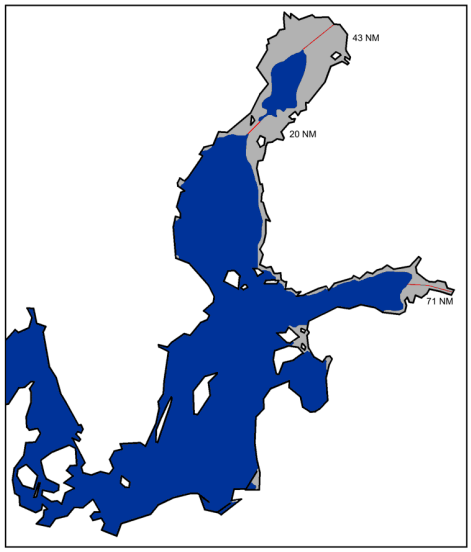
Fig. 1. Ice extents in the Baltic Sea during winters in years from 1915 to 2015
[own study based on the data from the Finish Meteorological Institute]

The total area of the Baltic Sea (including the area of Baltic States) is 427 362 km^2, and without Baltic States is 384 703 km^2 [8]. The distribution of winter intensity in the Baltic Sea was determined based on the area of ice extent in the following limits:

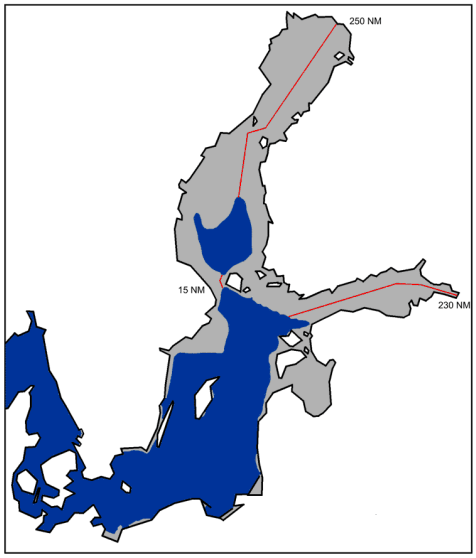
- mild winters — not more then 135 000 km^2;
- average/normal winters — from 135 000 km^2 to 280 000 km^2;
- severe winters — more then 280 000 km^2.

By making data analysis presented in figure 1, it is concluded that the intensity of the winters in the end of the twentieth century and the beginning of the twenty-first century, in comparison with previous years is much lower. From 1987 to the present day, only once did the severe winter in 2011, and we only deal with average/normal and mild winters.

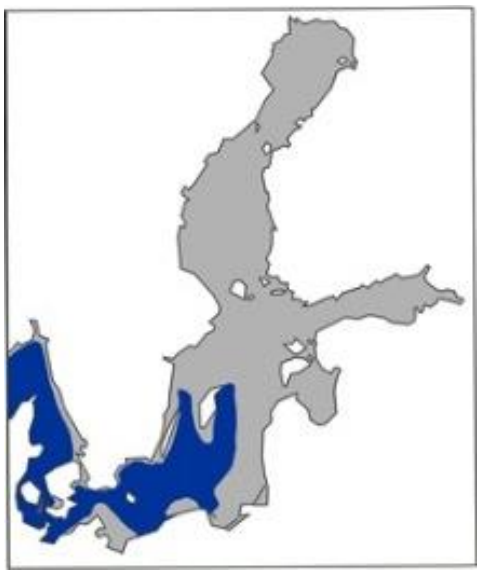
Examples of typical maximum ice extents on the Baltic Sea during winters in the twenty-first century are shown in figure 2.



The maximum ice extent in winter 2014/2015 was 51 000 km^2 on 23nd January, 2015 (mild winter)



The maximum ice extent in winter 2012/2013 was 177 000 km^2 on the 15th March, 2013 (normal winter)



The maximum ice extent in winter 2010/2011 was 309 000 km^2 on 25th February, 2011 (severe winter)

The maximum ice extent in winter 2007/2008 was 49,000 km^2 on 24th March, 2008 (mild winter)

The maximum ice extent in winter 2004/2005 was 178 000 km^2 on 16th March, 2005 (normal winter)

The maximum ice extent in winter 1999/2000 was 95 000 km^2 on 24th February, 2000 (mild winter)

Fig. 2. Examples of typical maximum ice extents on the Baltic Sea during winters in the twenty-first century [1]

In the last thirty years (since 1987) the maximum ice extent in the Baltic Sea observed on 25th February, 2011 (fig. 3). An example of the range of ice on the water of the Baltic Sea during the winter. The ice condition at this day in the western part of the Baltic Sea and Baltic Straits do not count as ice conditions during severe winter, however, but rest areas of the Baltic Sea definitely have these conditions.

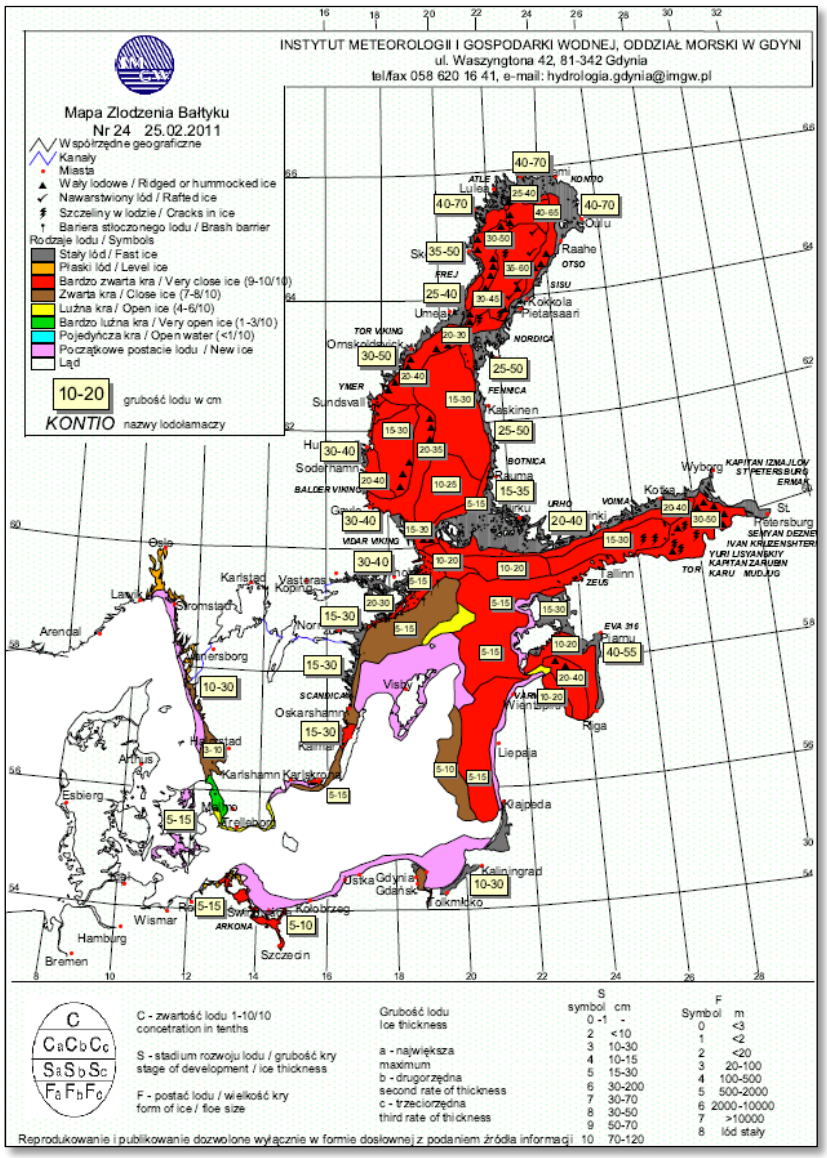


Fig. 3. Maximum ice extent in the Baltic Sea observed on 25th February, 2011 [the Institute of Meteorology and Water Management, Baltic Sea Ice Chart No 24 on 25th February, 2011]

According to the Finnish Ice Service of the Finnish Meteorological Institute the Baltic Sea ice season 2015–2016 was mild and clearly shorter than average winter. The peak of the ice winter was reached on 22nd January, 2016, when ice covered an area of 110 000 km^2. Maximum ice extent of the ice season 2015–2016 in the Baltic Sea on 22nd January, 2016 is presented in figure 4.

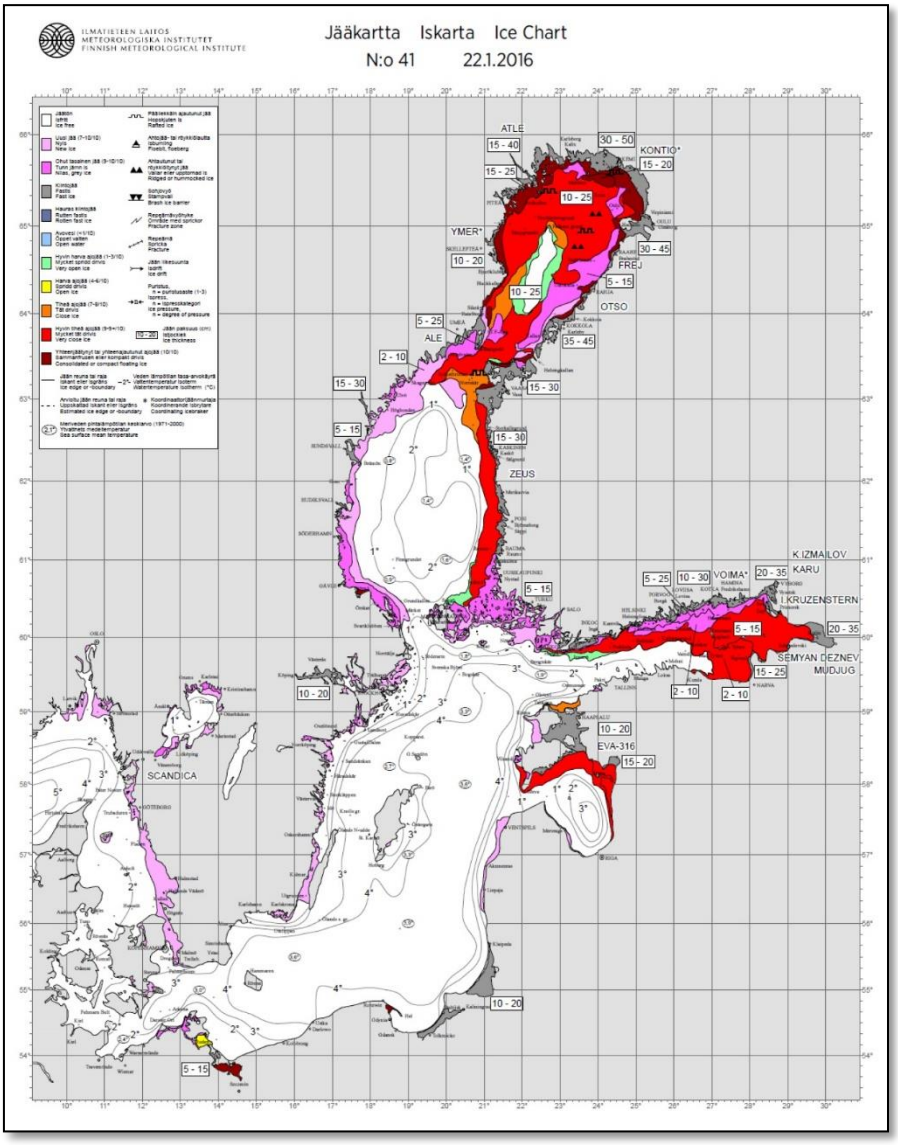


Fig. 4. Maximum ice extent of the ice season 2015–2016 in the Baltic Sea reached on 22nd January, 2016 [the Finish Meteorological Institute, Ice Chart No 41 from 22nd January, 2016]

CHARACTERISTICS OF ICE CONDITIONS IN THE BALTIC SEA

The Baltic Sea is the interior sea of the Atlantic Ocean, which is its transcontinental leg in northeastern Europe. The Baltic Sea extends longitudinal almost in a straight line over about 1300 km, and its latitudinal extent is approximately 700 km [8]. The length of the shipping line through the Baltic Sea is approximately 920 nautical miles from Luleå and Kemi ports in the northern part of the Gulf of Bothnia to the Skagerrak. Much of this route in winter is covered by ice, and the intensity of ice is dependent on the type of winter in the Baltic Sea.

The process of ice formation in the Baltic Sea starts along the coasts of the northern Bay of Bothnia and the inner Gulf of Finland. This occurs usually in October – November. Thereafter the freezing spreads to the Quark, the open Bay of Bothnia and the coasts of the Sea of Bothnia. In normal winters the ice gets to cover also the rest of the Sea of Bothnia, the Archipelago Sea, the whole Gulf of Finland and parts of the Northern and the Central Baltic. In mild winters the Sea of Bothnia doesn't freeze at all and the Gulf of Finland only gets a partial ice cover. In severe winters the ice reaches the Danish Sounds (the Baltic Sounds) and the Central Baltic. The last area that freezes up is an area north-east of the Bornholm Island in the Southern Baltic Sea. The melting season starts in April and proceeds from the south to the north. In the Central and the North Baltic, the ice disappears in early April. By the beginning of May there is only ice left in the northern Bay of Bothnia, where also the last ice pieces melt away by the beginning of June. The ice in the Baltic Sea exists as fast ice and drift ice. Fast ice is situated in coastal and archipelago areas, where the depth is less than 15 meters. It develops during early ice season and remains stationary to the melting period [3].

The FMI publication show that drift ice movements are large: in stormy conditions the drift of the ice field can move 20–30 km in a single day. The motion results in uneven and broken ice field with distinct floes up to several kilometers in diameter, leads, and cracks, slush and brash ice barriers, rafted ice and ridged ice. The ridges and brash ice barriers are the most significant obstructions to navigation in the Baltic Sea. Powerful, ice-strengthened vessels can break through ice up to almost one meter thick, but they are not capable of navigate through ridges without icebreaker assistance. Ice dynamics affects navigation considerably — high pressure in the ice fields can be dangerous to the vessels, and it may at least cause time delays from hours up to days [3].

The ice formation process in the Baltic Sea is a constant phenomenon occurring each year, however, its intensity, most often characterized by distribution of ice, is variable. Depending on the severity of winters range of an ice on the water of the Baltic Sea can be divided into the following three groups:

- ice extent in **mild winters** (includes the northern part of the Gulf of Bothnia, the eastern part of the Gulf of Finland, the northern part of the Gulf of Riga and parts of inner bays);
- ice extent in **average/normal winters** (all areas of the Gulfs: Bothnia, Finnish, Ryska, most coastal and Baltic waters);
- ice extent in **severe winters** (the entire Baltic Sea excluding its central part south of the Gotland Island).

The average ice extent in the Baltic Sea during typical winters is presented in figure 5. This work is based on data from Institute of Meteorology and Water Management — Maritime Branch in Gdynia, the Finish Meteorological Institute and Swedish Meteorological and Hydrological Institute.

The phenomenon of the ice formation process in the southern part of the Baltic Sea is described in *Pilot of the Baltic Sea* [6]. Fragments of this description were used to characterize the ice formation process of the Baltic Sea. The intensity of the phenomena of the ice on the Baltic Sea, and hence, on the Polish marine areas and the Polish coast, generally is small. Hence the conclusion that winter in the Baltic Sea most often have mainly characterize mild and normal. During severe winters first drift ice appears at the end of November and the first half of December at harbors, shallow and sheltered bays, as well as in brine the eastern part of the South coast. At the end of December and in the first half of January bodies of these overlap with ice edge, and drift ice spreads to larger areas of the sea. The second half of January is characterized by intensive development of ice cover. Along the banks the developing costal ice, reaching the maximum range. The ice is covered with almost the whole western part of the area of the sea with proximity to the island of Bornholm. In March starts crushing ice; most often in the vicinity and along the Swedish coast, where fading away in the second half of March. The average length of the period of ice during the winters harsh and very strict ranges off the coast from 45 to 110 days [6].

During normal winters ice first ice appears in the second half of December in the inner bays on the south coast and western shores of the Rügen Island. In the first half of January freezes the Szczecin Lagoon and the Port of Stralsund. In the second half of January ice edge includes the Rügen Island and further extends to the shores of Sweden. Almost everywhere in the vicinity of the banks observed drift ice. The breakdown of ice usually starts in the first half of February. The release of the ice is the end of March. During the mild winters solid ice does not occur. At the beginning of January, it freezes the Szczecin Lagoon and the approach to the Port of Stralsund, that ice often crumble. At the beginning of February, the development of ice extent reaches its maximum, then quickly decreasing and at the end of February disappears [6].

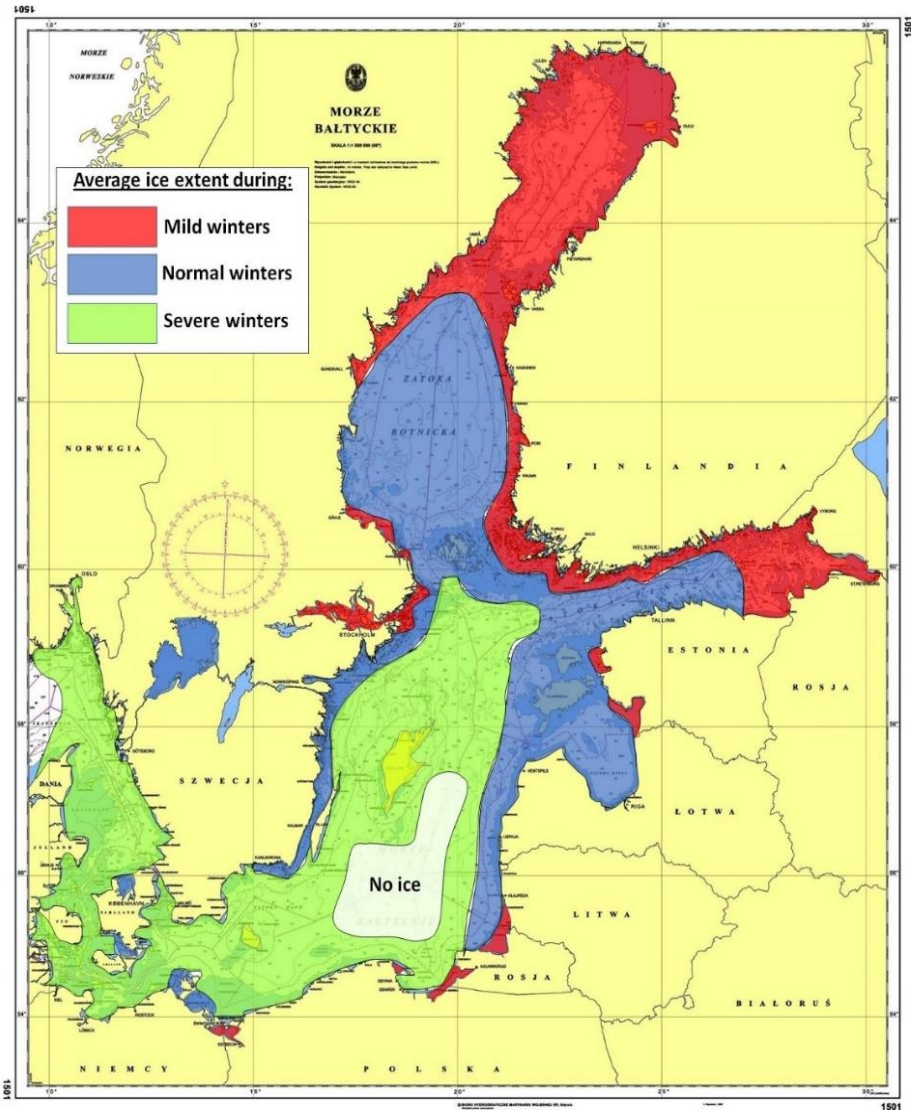


Fig. 5. The average ice extent in the Baltic Sea during typical winters [own study based on the chart No. 1501 of the Hydrographic Office of the Polish Navy; data from the Institute of Meteorology and Water Management — Maritime Branch in Gdynia, the Finish Meteorological Institute and the Swedish Meteorological and Hydrological Institute]

The last winter 2016/2017 in Poland and the Baltic Sea belonged to the mild winters. The ice phenomena occurring in the coastal zone observed were mainly in the area of lakes and partly the Gulf of Gdańsk. Examples are this year's ice charts of the Baltic Sea showing the location of ice on the Polish coast in the days of the 17th January, 2017 (fig. 6) and 20th February, 2017 (fig. 7).

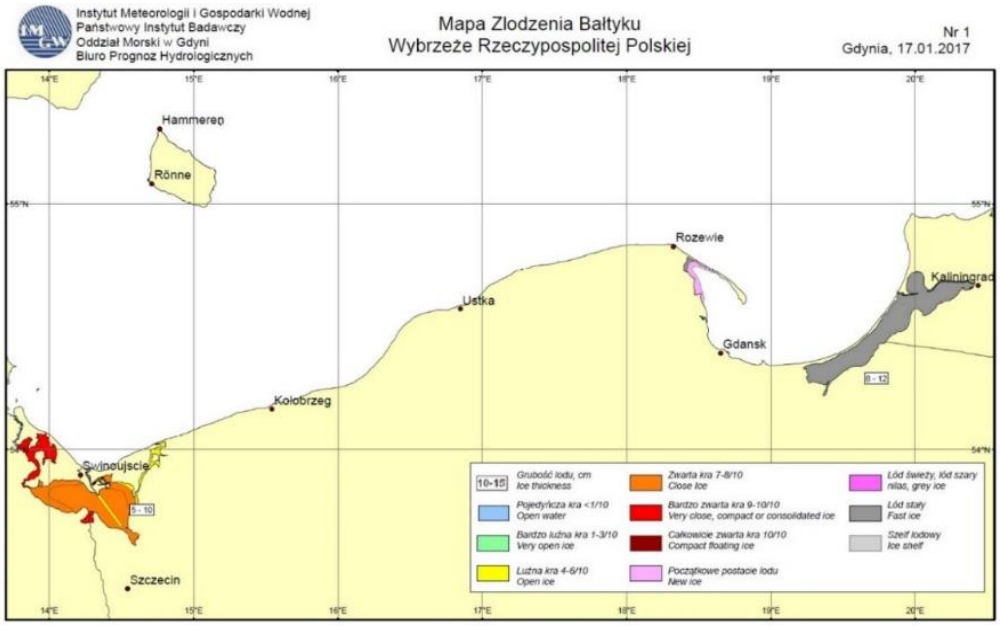


Fig. 6. Ice extent map of the Baltic Sea; the coast of the Republic of Poland on 17th January, 2017 [the Institute of Meteorology and Water Management, the map No. 1, 17th January, 2017]

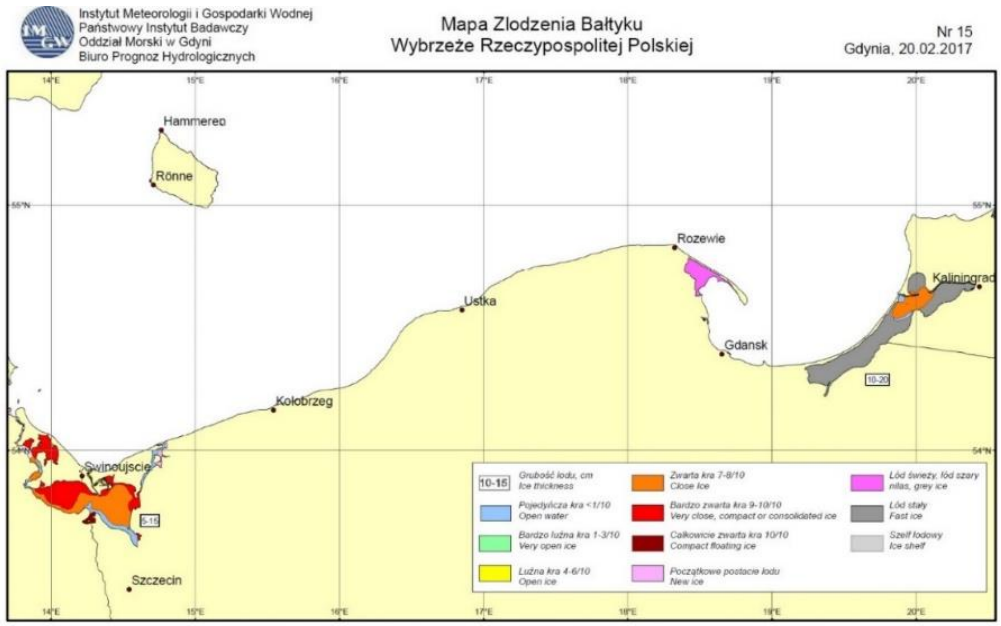


Fig. 7. Ice extent map of the Baltic Sea; the coast of the Republic of Poland on 20th February, 2017 [the Institute of Meteorology and Water Management, the map No. 15, 20th February, 2017]

CONDITIONS FOR THE FORMATION AND THE DISAPPEARANCE OF THE ICE ON THE PUCK BAY

The Puck Bay lies in the north-western part of the Gulf of Gdańsk between the mainland and the Hel Spit (Hel Peninsula). Its south-east boundary is a line connecting the Cape Hel (Cypel Helski — local name) with the Cape Oksywie (Cypel Oksywie — local name). The West Bank are three plates, quite high clumps (Oksywska, Pucka and Swarzewska) and on the banks with cliffs. Just to the North of the Port of Gdynia a cliff rises high of 42 m on the Cape Oksywie. The Cape Hel is low and consists with sounds.

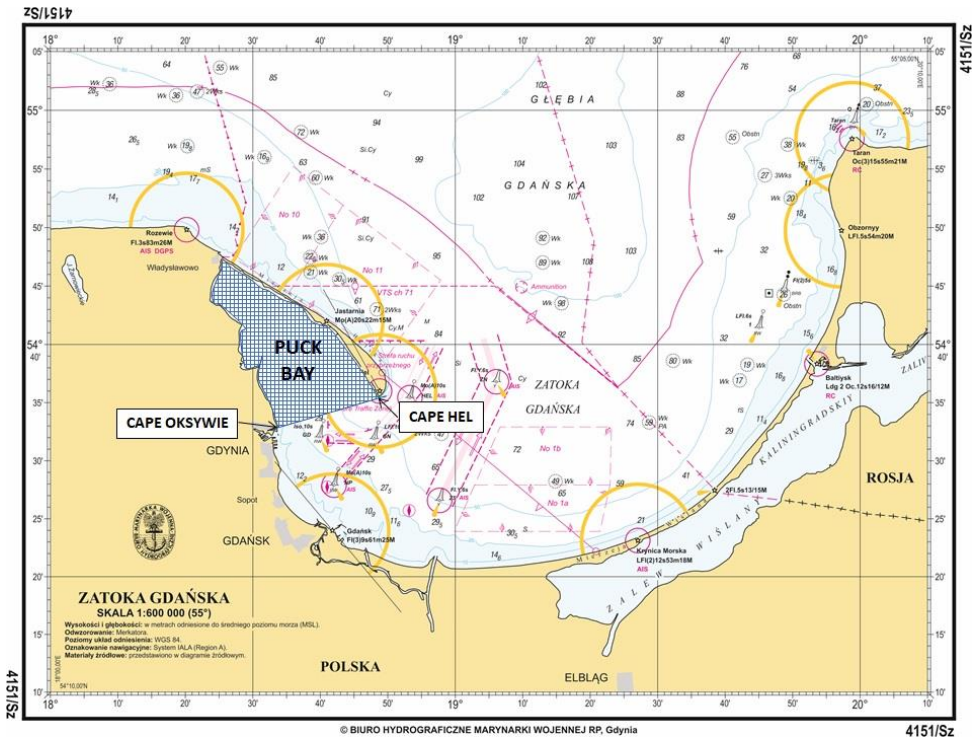


Fig. 8. The boundaries of the Puck Bay [own study based on the chart No. 14151/Sz of Hydrographic Office of the Polish Navy]

In figure 8 shows the location of the Puck Bay, along with points, which are the Cape Hel and the Cape Oksywie. The following description of the Puck Bay is taken from L. Kattle [4]. The Bay of Puck, also called the Small Sea, is the most westward part of the Gdańsk Bay. The Puck Bay is separated about 12 kilometers underwater sand shaft, periodically submerged. This shallow water sometimes called as the Ryf

Mew Barrier (local name) partially insulating about 120 km^2 of the basin. The Ryf Mew Barrier forms the configuration of the bottom of the Puck Bay, a relatively large area, small depth affects the different development of relations of the physic-chemical and biological proportions. It should be noted that the above diversity affects the formation of ice conditions on the water.

In the Puck Bay ice occurs an average of 63–72 days, and during the severe winters by 120–125 days [4]. On the ice phenomena in the area of the Puck Bay and the Hel Peninsula crucial relations have got the profile of depth, and smaller the salinity of the waters [11]. The Puck Bay in its north-western part is characterized by small depths and therefore a small heat capacity, which causes rapid heat loss and promotes of the ice formation. On this process also affects small waves or these lacks due to the separation of the Small Sea from the rest of the deeper areas of the Puck Bay through the Ryf Mew Barrier.

The typical form of ice occurring in the Puck Bay are presented in photos below. The solid ice in the Port of Puck observed on 1st February, 2014 is shown in photo 1. Usually every year a large area of the Puck Bay is covered by this form of ice. Another form of ice that characterizes not only the Puck Bay is a ridge ice. This form of ice is presented in photo 2. The ridged ice observed on a shore of the Hel Spit near the Chłupy Village is presented in photo 2. Brash ice barriers in the Puck Bay can reach a height of several meters. They get up on the shallows and areas of low depths. In photo 3 is shown a barrier of ice that was observed on 25th February, 2012. During the last days of January 2014 near Jastarnia on the Hel Spit (between the pier and entrance to harbor) adjacent to Puck Bay there appeared interesting forms of sea ice — ice balls. This is a very rare oceanographic phenomenon connected with sea ice in the waters off the Polish coast [2]. Ice balls observed in the Puck Bay on 1st February, 2014 is illustrated on figure 4.

Phot. 1. The solid ice in the Port of Puck observed on 1th February, 2014 [photo C. Dyrcz]

Phot. 2. The ridged ice observed on a shore of the Hel Spit near the Chałupy Village on 25th February, 2012 [photo C. Dyrcz]

Phot. 3. Brash ice barriers on the Puck Bay observed on 25th February, 2012 [photo C. Dyrcz]

Phot. 4. Ice bells observed in the Puck Bay near the Port of Jastarnia on 1st February, 2014 [photo C. Dyrcz]

The result of the analyzes indicats that the formation of ice in the Puck Bay is varied due to local conditions, which are resulting from the depth of the water, the degree of cover from the effect of open sea, coastline, wind direction, air temperature and other factors. The time periods analyzed are limited because the study covered the years 1986–2005 [5, 11].

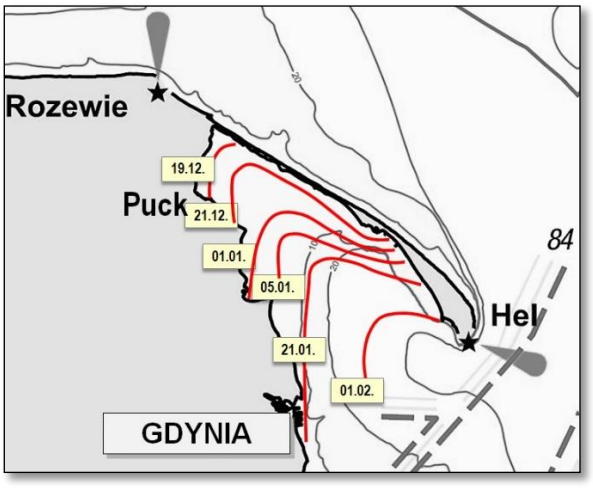


Fig. 9. The average time limits the occurrence of the first ice in the Puck Bay [based on K. Szefler, 1993]

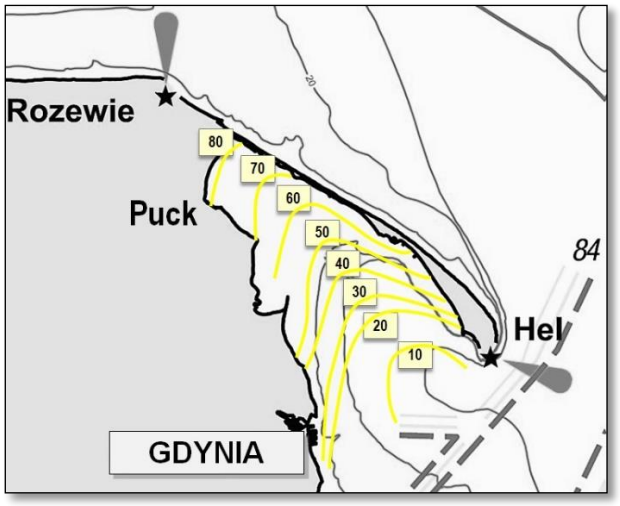


Fig. 10. The average number of days with ice in the Puck Bay
[based on K. Szefler, 1993]

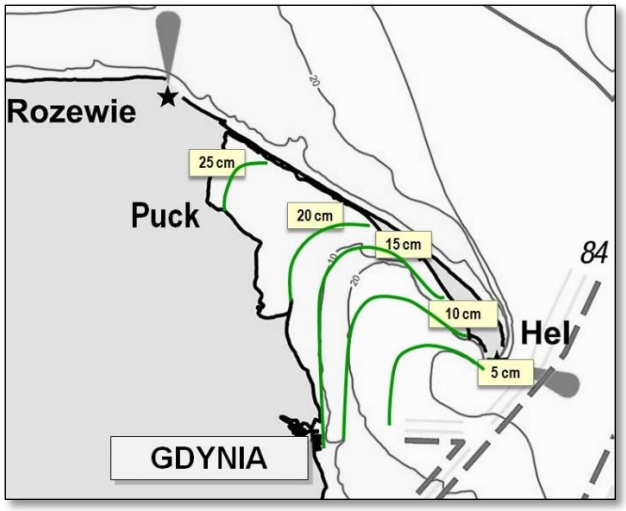


Fig. 11. The average ice thickness in the Puck Bay
[based on K. Szefler, 1993]

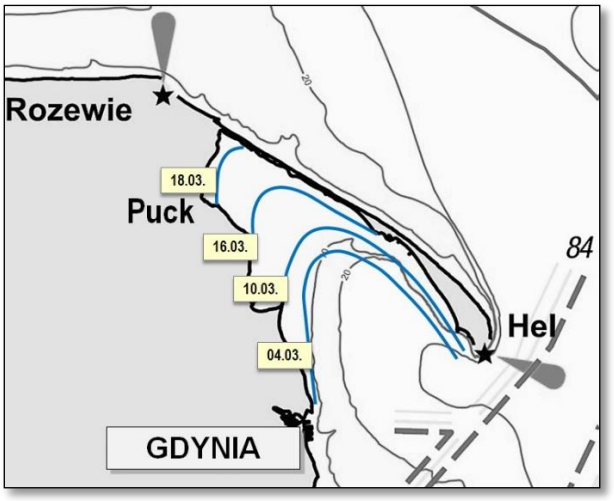


Fig. 12. Average terms the disappearance of the last ice in the Puck Bay [based on K. Szefler, 1993]

The first ice is formed on the Puck Bay in its northwestern part on 19th December, and during normal and severe winters it is observed at the southern border of the bay around on 1st February (fig. 9). The average number of days with ice in the Puck Bay is illustrated in figure 10. The longest, because on average over 80 days ice covers the northwestern part of the Puck Bay, compared to the southern border, where you can meet on average only for 10 days. The thickness of the ice cover is mainly the function of the air temperature, the water temperature and the duration of the conditions. The average maximum ice thickness values are shown in figure 11. The thickness of ice is estimated at an average of about 5 cm in the south of the water body to about 25 cm in its northwest. Failure of ice throughout the Puck Bay occurs in March (fig. 12). The central part of the Puck Bay gets rid of ice at the beginning of March about on 4th March, and in the north-west the ice disappears around on 18th March.

DISCUSSION AND CONCLUSIONS

In the conclusion of the analysis was made of the following generalizations:

1. The Baltic sea freezes every year, and the size of the ice extent depends on meteorological conditions (type of winter).
2. The ice phenomena in the southern part of the Baltic Sea are generally low in intensity and depend mainly on the type of winters, but the gulf and bays cover

the ice each year. An example is the Puck Bay and its northwestern part, where ice is actually observed each year.

3. In the Puck Bay, the ice occurs on average 63-72 days, and during severe winters 120–125 days. On the ice phenomena in the Puck Bay area depth relations are crucial decisive. The Puck Bay in its north-western part is characterized by low depths and therefore low heat capacity, which results in rapid cooling and promotes formation. The formation of ice on the Puck Bay is also affected by small ripple it due to the shaping of the sea bottom in the middle of the bay.
4. The thickness of the ice on the water of Puck Bay are estimated on average 25 cm in the north-western part to about 5 cm on the southern border of the Bay.
5. Ice on the Puck Bay has also an economic importance for the region, as with the occurrence of ice conditions the navigation floating marks of shoals and waterways to harbors are removed. Ports of Puck, Kuźnica and Jastarnia are closed for navigation throughout the duration of the ice age. Periodic closure of ports is also affected by the ice drift.

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ANALIZA WARUNKÓW ZLODZENIA MORZA BAŁTYCKIEGO I ZATOKI PUCKIEJ

STRESZCZENIE

W artykule przedstawiono wyniki badań opartych na analizie warunków występowania lodu na Morzu Bałtyckim i w Zatoce Puckiej. Analizy dotyczą maksymalnego zasięgu pokrywy lodowej w ostatnim stuleciu na Morzu Bałtyckim (1915–2015) i warunków występowania lodu na Zatoce Puckiej w latach 1986–2005. Zlodzenie Morza Bałtyckiego ma zazwyczaj umiarkowaną intensywność i zależy głównie od rodzaju zim (łagodna, średnia/normalna i surowa), jednakże prawie każdego roku lód morski pokrywa zatoki i zalewy bałtyckie. W artykule zobrazowano średni zasięg występowania lodu na Morzu Bałtyckim podczas typowych zim, wielkości obszarów zlodzenia w latach 1915–2015, średni czas początku i końca występowania lodu, liczbę dni z lodem oraz grubość lodu na Zatoce Puckiej wraz z przykładami rodzaju lodu. Zjawisko zlodzenia ma znaczący wpływ na działalność człowieka na morzu, wpływa na pogodę i klimat, życie roślinne i zwierzęce, rybołówstwo oraz funkcjonowanie portów i bezpieczeństwo nawigacji.

Słowa kluczowe:
lód morski, zlodzenie, Morze Bałtyckie, Zatoka Pucka.