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Forms of grease ice ridges on the south coast of the Baltic Sea

by

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Abstract

The paper presents the forms of grounded grease ice ridges as well as hydrological, meteorological and physiographic conditions of their occurrence on the south coast of the Baltic Sea. The author used results of observations and measurements performed during hiking expeditions and analyzed profiles and photographs showing the morphology of grease ice ridges which occur along the coast and are usually several meters wide and 1-3 m high. Their windward slopes are very steep, usually concave, with abrasion niches and ice cornices formed by waves. The leeward slopes are gentle (20-30°) and coincident with the angle of the natural slip (angle of slide) of the grease ice, slush and shuga tossed by waves. The major factor leading to grease piling is the movement of waves generated by a strong onshore (NW, N, NE) wind. Such wind conditions occur mainly when a low-pressure area extends to the E, SE and/or S of the southern Baltic, and a high-pressure area – to the W, NW and/or N.

Key words: forms of grease ice ridges, grease ice ridge profiles, hydrological-meteorological conditions, south coast of the Baltic Sea

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Introduction

The Baltic Sea is a marginal, relatively shallow and tideless sea, situated in the temperate climate zone. The southern Baltic is located in the west-wind drift zone, which is characterized by frequent passages of low-pressure systems. The cyclones generally transport warm air masses in winter. The climate in the southern Baltic is relatively mild and the sea is only occasionally covered with ice (cf. Preobraženskij 1960; Palosuo 1966; Janērus & Jansson 1982). Various ice phenomena may occur in the southern Baltic Sea during moderate and, in particular, severe winters. The average frequency of ice occurrence in the Baltic Sea in 1961-2010 ranged from 30-50% in Pomeranian Bay to 10-20% in the area of Władysławowo (Schmelzer & Holford 2012). Such a large range of ice occurrence frequency results mainly from the bathymetric conditions in the southern Baltic Sea. Solid ice cover, which may be formed during a severe winter, is very rare there. The floating ice – grease ice, slush, shuga, pancake ice or floe – is the dominant ice form (Majewski 1987; Girjatowicz 1990).

The following definitions of ice terms were applied (WMO Sea Ice Nomenclature): frazil ice – fine spicules or plates of ice, suspended in water; grease ice – a later stage of freezing than frazil ice when the crystals have coagulated to form a soupy layer on the surface; grease ice reflects little light, giving the sea a matt appearance; slush – snow which is saturated and mixed with water on land or ice surfaces, or as a viscous floating mass in water after a heavy snowfall; shuga – an accumulation of spongy white ice lumps, a few centimeters across, formed from grease ice or slush and sometimes from anchor ice rising to the surface; ridge – a line or wall of broken ice forced up by pressure; it may be fresh or weathered. The submerged volume of broken ice under a ridge, forced downward by pressure, is referred to as ice keel. As regards the term "grease ice ridge", the author defines it as a wall of new ice (frazil ice, grease ice, slush, shuga) dumped along the coast as a result of wave motion. The windward slope is very steep, mostly concave, while the leeward slope is more gentle, coincident with the angle of slide.

Ice phenomena on the south coast of the Baltic Sea do not cause serious sailing difficulties. The accumulated ice, however, and a grease ice ridge along the coast in particular, may be an obstacle to the fishing boats moored on the beach. For that reason, fishing in winter is very limited. They are not only an obstacle to the fishing boats, but they also block the inflow of small rivers and canals into the sea. Pulling these boats off the beach into the water requires a passage cut through a ridge. A ridge on the shore may also obstruct a beach landing. In order to overcome this problem, it is necessary to first make a profile of these piled-up ice forms (Kocur 1978).

Grease ice ridges protect the coast, and hence have a positive effect on its stability. A ridge protects the coast against abrasion caused by waves and acts as a specific breakwater for the shore situated in its shade (Giżejewski & Rudowski 1995). It is important to bear in mind, however, that these ice phenomena may have a destructive effect on the buildings erected on the coast. Moreover, grease ice ridges, especially those consolidated by the freezing water, are quite durable and last for a long time.

So far, there have been no studies devoted exclusively to grease ice ridges. Some information on such phenomena on the southern shores of the Baltic Sea can be found in publications devoted mainly to the dynamic effect of ice on the shore (Reinhard 1959; Jaworski 1967).

Given the limited knowledge of grease ice ridges, the purpose of this article is to present the forms of grounded grease ice ridges, as well as the hydrological, meteorological and physiographic conditions in which they are formed on the south coast of the Baltic Sea.

Materials and methods

The author used materials collected during observations of new ice (frazil ice, grease ice, slush, shuga) accumulated on the south coast of the Baltic Sea. The observations and morphometric measurements were conducted during repeated ice reconnaissance. Detailed observations have been carried out from the plane, ship and during hiking expeditions since the early 1970s. However, measurements of grease ice ridges during hiking have been rare so far and taken mainly in recent years in the areas of Świnoujście, Lubiewo, Międzyzdroje, Dziwnówek, Rewal, Władysławowo, Hel, Świbno and Krynica Morska (Fig. 1).

Fifteen profiles of grease ice ridges perpendicular to the coast line were made in the area of Świnoujście, Lubiewo, Międzyzdroje and Dziwnówek in the period of 1995/1996-2011/2012. The study used seven of these profiles, showing the morphology of ice ridges formed on the beach, their variability in time and space, as well as the remnants of melting ridges. During the ice reconnaissance, photographic documentation of these ice forms was also made, including several dozen photographs of grease ice ridges. The author selected and analyzed 12 photographs in order to present the structure of ridges, especially the shape

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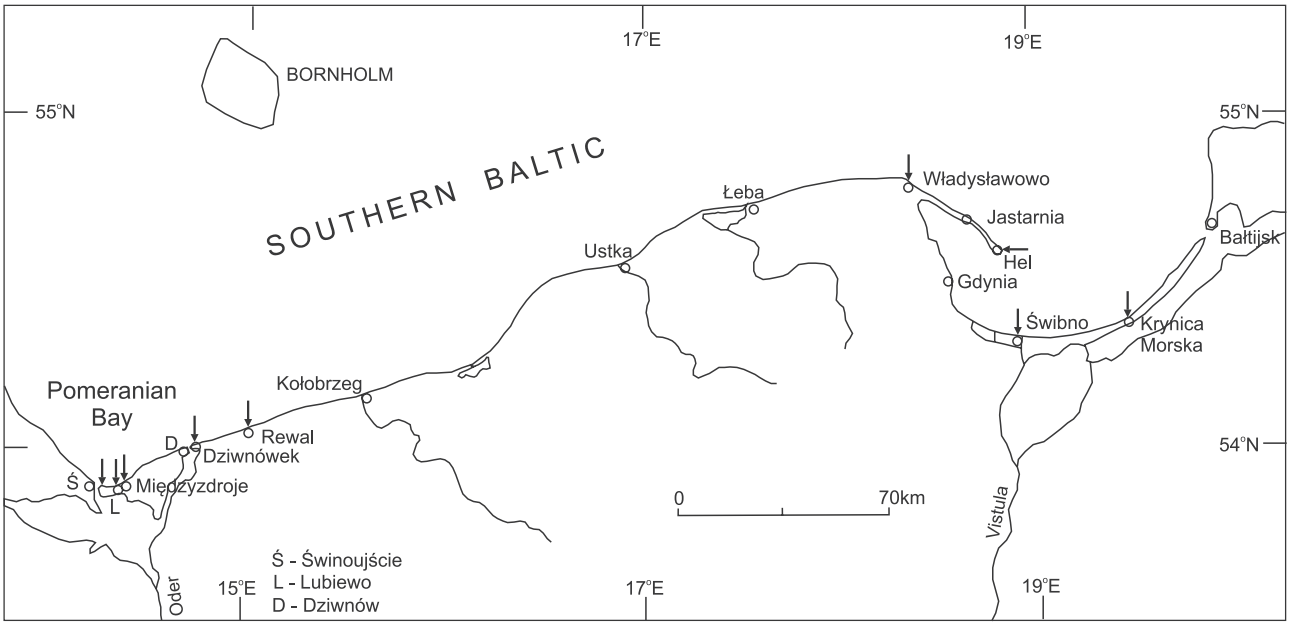


Figure 1

Location of hydro-meteorological stations and the study areas on the south coast of the Baltic Sea. The observational spots are marked with arrows.

of their windward (facing the sea) and leeward (facing the land) slopes.

A measuring tape was used as a tool to measure grease ice ridges (their length, width, height and the ice thickness) and their location. The other tools included an ice drill, an ice leveling rod, a compass and, recently, the Global Positioning System (GPS).

Data on hydrological and meteorological conditions such as air temperature, wind direction and state of the sea, as well as the water level come from Świnoujście and Dziwnów harbor masters' offices. For the purpose of describing the meteorological situation when grease ice ridges were being formed, meteorological charts were also used (Analysis chart, 25 January 2010). Other helpful materials included two meteorological charts from 3 January 1980 and 10 January 1987 – the days when grease ice ridges were being formed (Synoptic chart…). Typical weather conditions conducive to the formation of ridges are presented in Fig. 2.

Hydrological and meteorological conditions of grease ice ridges

The first forms of ice formed *in situ* on the south coast of the Baltic Sea at the beginning of the ice season are frazil ice, grease ice, slush and shuga. This kind of floating ice remains on the undulating sea surface for a relatively long time because waves hinder the solidification of ice. On the other hand, ice rind appears on the smooth surface of the dead-calm sea and disintegrates rapidly. In estuarine areas, pancake ice and floe drift into the sea and may disintegrate due to wave movements. Depending on the wave motion

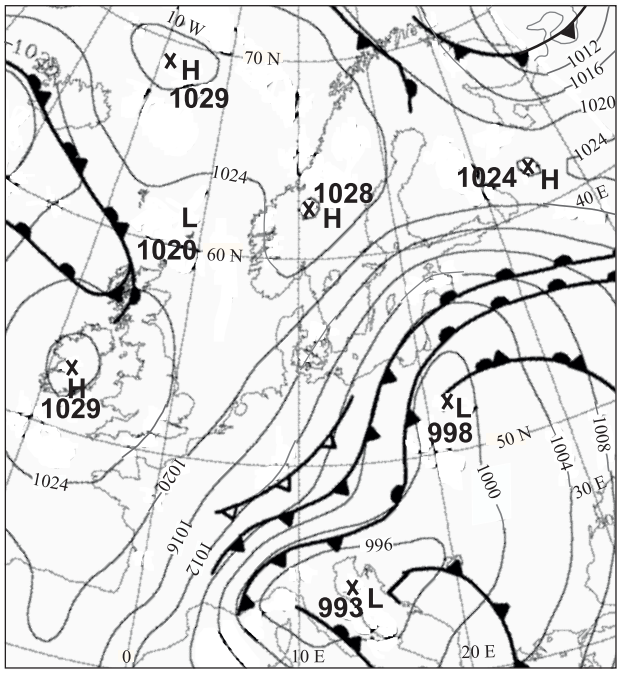


Figure 2

Weather over Europe at 00 UTC on 25th December 2010

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intensity, new ice (grease ice, slush, shuga) and disintegrated brash ice may be solidified, piled up, or even washed up on the shore. The small ice which is washed up on the shore, mainly grease ice, slush and shuga form grease ice ridges along the coast.

At the beginning of the grease ice ridge formation, the windward side is steeper than the leeward side. The steepness of the windward slopes increases with increasing height of a ridge. The leaching activity of the waves results in the concave form of this slope. In the warmer period (AT > 0°C) and with lower water levels, the grease ice ridge may be undercut at the base and gradually start to crumble.

The process of grease ice ridge formation requires strong, northern onshore wind (NW, N, NE) with a long wave fetch, especially from NE. Such winds are generated mainly when the low-pressure area spreads to the E, SE and/or S of the southern Baltic and the high-pressure area – to the W, NW and/or N. An example of a typical pressure system in which grease ice ridges are formed is presented in the meteorological chart for Europe, dated the 25th December 2010 (Fig. 2). The chart shows a vast, nearly meridional area of high pressure with several centers, extending from Spain across Great Britain, Norway and further eastward. At the same time, a trough with its center over the North Adriatic Sea can be observed in the south-eastern part of the southern Baltic. A concentration of isobars (a high pressure gradient) of SW-NE orientation occurs over the central and southern Baltic. Such an arrangement of isobars generated a strong wind (15 m s^{-1}) from the north and a high sea state (7°, Table 1). On the 23-26th December 2010, very cold, polar-continental air was moving from north-western Russia. The air temperature decreased to -8°C, which was conducive to the formation and persistence of initial forms of ice.

In such anemobaric conditions (strong onshore wind), the water level significantly increased (86 cm above the average level). In that period, with high water levels and strong sea waves, two grease ice ridges were formed on the beach and on a submerged bar. They were separated by a field of compressed grease ice, resembling a freshly plowed field (furrows, Fig. 3a). Figure 3 a-c shows the transformation of the grease ice ridge profile over a relatively short period (several days), i.e. between the 28th December 2010 and the 15th January 2011.

Figure 3a shows a typical grease ice ridge located on the land side, about 3 m high above sea level, with a gentle leeward side (22°) and a very steep, concave windward side with an ice cornice. When viewed from the sea, three moderately high (2 m above sea level) and irregular grease ice ridges can be observed next to the first ridge. A 1-1.5 m thick pressure grease ice field is located in a hollow, in front of the above-mentioned ridges, at a distance of about 15 m. Further toward the sea, another grease ice ridge with very gentle leeward slopes was formed on the submerged bar. These very gentle slopes (slightly inclined toward the land and resembling terraces) were formed mainly by wave water. On the side facing the sea, a ridge rose up to 1.5 m above sea level like a staircase, with steps every 0.5 m. Its windward slopes were very steep, with an ice cornice (Fig. 3a).

Figure 3b shows a low (1 m above sea level), undulating, domed hummock facing the sea, which developed on the 29th December 2010. On that day, the southern Baltic was on the edge of a shallow low-pressure area with its center over Latvia. This hummock was formed as a result of 3-cm-thick ice rind thrusting generated by the NW onshore wind blowing at a speed of 6-8 m s^{-1}. Sheets of the ice rind pushed from the windward side were breaking off under their own weight on the leeward side of the hummock. The piling-up brash ice built the leeward slope, whose inclination was similar to that of the windward side (Fig. 3b). This ice rind was formed on the 28/29th December 2010 in a high pressure wedge, in the presence of a weak baffling wind and a significant drop in the air temperature to -9°C.

Fig. 3c shows a clear change in the ice profile viewed from the sea. On the 1st January 2011, during the period of slight warming (2°C), a storm occurred (up to 20 m s^{-1}) with the wind blowing from the land (SW). As a result of sea waves, a hummock formed

Table 1

Hydrological and meteorological conditions in Świnoujście during the formation of grease ice ridges along the shore of the southern Baltic Sea

Date	Mean diurnal air temperature (°C, in Szczecin)	Direction and maximum wind velocity (m s^{-1})	State of the sea (in degree)	Water level (cm)
January 3, 1980	-4.5	NW 11	5	42
January 10, 1987	-12.6	NE 12	6	50
December 25, 2010	-5.0	N 15	7	86

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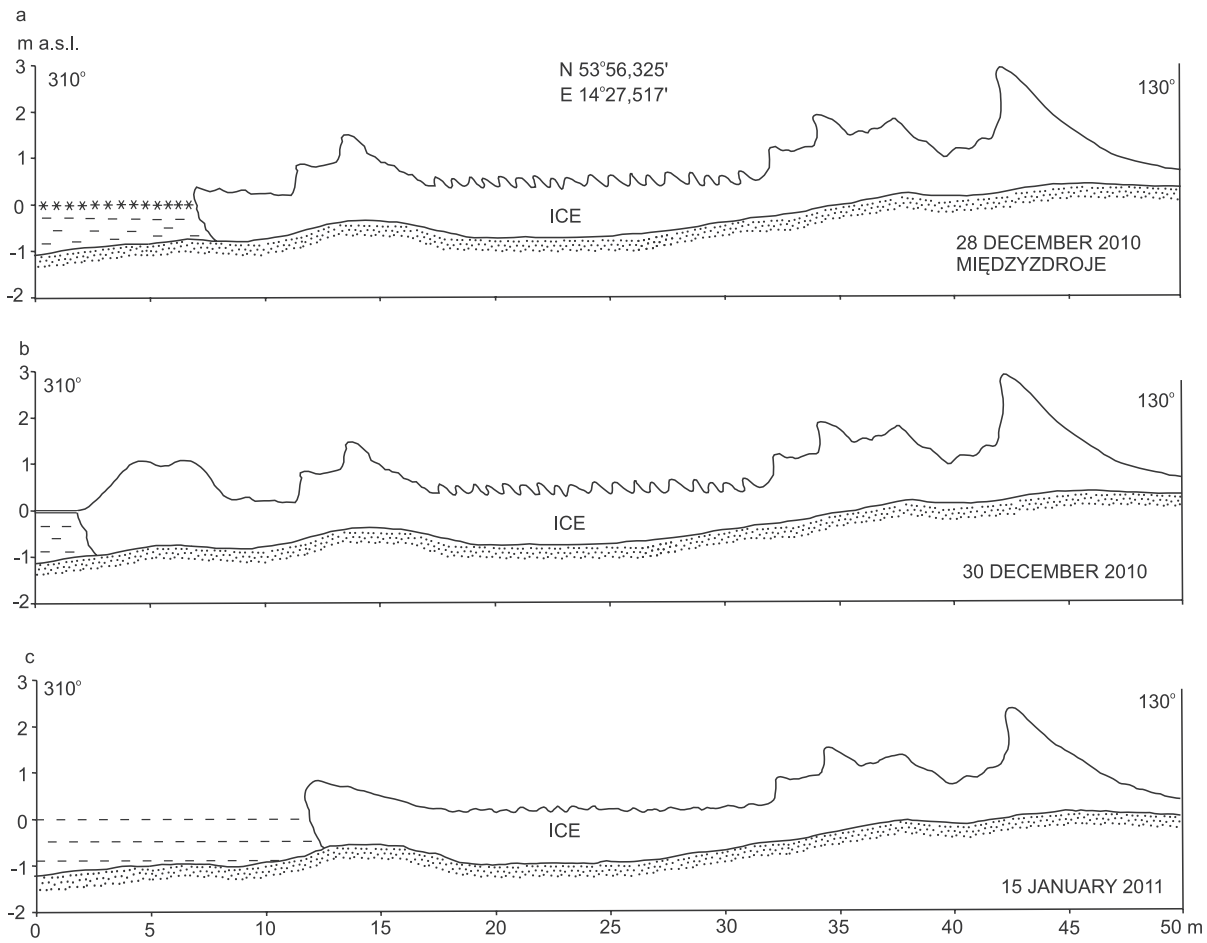


Figure 3

Changes in cross sections of grease ice ridges, 28th December 2010 – 15th January 2011 (a-c), the shore in Międzyzdroje area. The vertical zero reference level with regard to Figure 3 was respectively: 507 (+7 cm, a), 503 (+3 cm, b) and 519 (+19 cm, c) in Świnoujście. This information is given in the caption of Figure 3.

from ice rind was broken into pieces and a grease ice ridge was partly washed up on the shore. The brash ice which came from the broken hummock drifted eastward. On that day, the southern Baltic Sea was under the influence of a deep low with its center over Stockholm. In the following days, especially in the warmer periods (AT > 0°C), the grease ice ridge underwent further washing off and melting. Between the 30th December 2010 and the 15th January 2011, the height of those ridges only slightly decreased and the width was reduced by about 10 m (Fig. 3b and c). The remains of the grease ice ridge formed on the beach lasted until March.

During long and severe winters, grease ice ridges may last even till April (Fig. 4). Figure 4 shows four separate fragments of melting grease ice ridges on the shore in Lubiewo, observed on the 9th April 1996. They were located at coastal elevations, on their windward slopes and on the beach.

Forms of grease ice ridges

A grease ice ridge is a distinctive type of piled up, grounded ice, occurring on the south coast of the Baltic Sea. It is usually observed at the beginning of winter, after the formation of new ice (frazil ice, grease ice, slush, shuga). Its thickness does not prevent the wave motion of sea water. Such a ridge usually extends over many kilometers along the coast, parallel to the coastline. Local, short grease ice ridges may be formed in small and shallow bays where initial ice forms occur sooner.

One or several parallel ridges may be formed. They are usually situated several meters apart (Fig. 5 a-c). Figure 5 shows various forms of grease ice ridges extending over about 0.5 km along the beach in Dziwnówek, observed on the 23rd February 2012. It was a warmer period (AT=7°C), during which one

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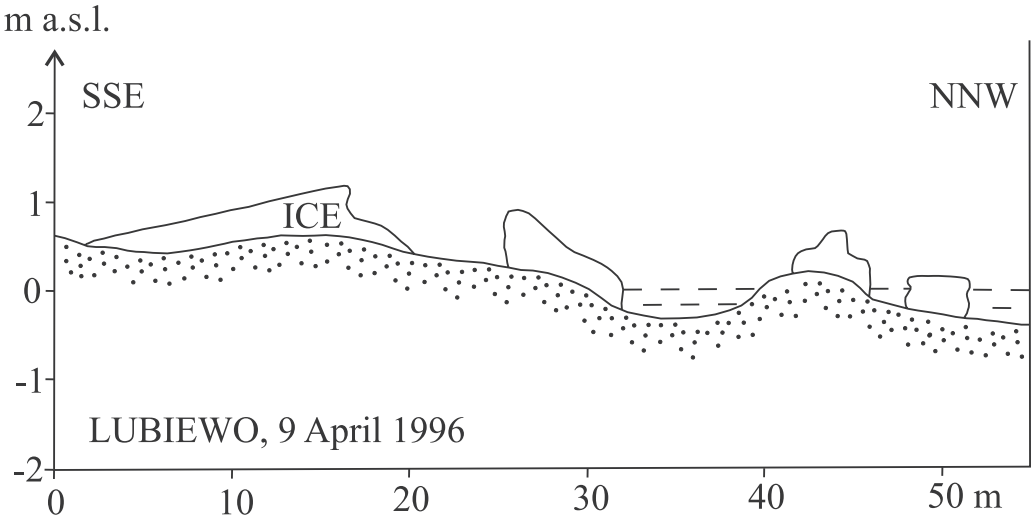


Figure 4

Cross-section of the coastal zone with fragments of melting grease ice ridges on the shore in Lubiewo area (9th April 1996)

could easily observe transformations of ridges at their fronts resulting from melting and wave movements. At the base of almost vertical slopes of these ridges, 1.5-2 m deep abrasion niches developed, threatening their stability (Fig. 5 a-c). Moving eastward from the west, the first profile featured two grease ice ridges parallel to the coast (Fig. 5a). Their height was about 2.5 m above sea level, and they were situated about 8 m apart from each other. Their total width was about 13 m, and the inclination of slopes was 15° and 20°.

Another profile located further east, about 0.4 km from the first one, featured four grease ice ridges (Fig. 5b). A small shelf/terrace (1.5 m wide and 1 m high above sea level) was located at the front. The highest ridge was formed about 1.5 m above the shelf, with a nearly vertical windward slope and a gentle (12°), undulating leeward slope. The next, slightly lower grease ice ridge, with the leeward slope inclination of 22°, was formed 8 m further toward the mainland. A miniature ridge (0.5 m above sea level), with a steep windward slope and a gentle leeward slope, was located on the beach, about 20 m from the front of these grease ice piles.

The third profile of grease ice ridges was made about 0.5 km east of the first one (Fig. 5c). The total width of these ridges was 26 m. A small grease ice ridge (resembling a terrace), with an almost vertical windward slope and a very gentle leeward side (7°), was found at the front (facing the sea). It was 5 m wide and 1.5 m high above sea level, and formed mainly by runoff wave water. There was also a higher grease ice ridge (2 m above sea level), with a steep windward slope and a gentle, slightly concave leeward slope (15°). The next, high grease ice ridge (2.2 m above sea level) was situated about 13 m from the sea. It had an undulating leeward side (20°). The last ridge occurred in a fragmentary form.

The width of the examined grease ice ridges varied over a relatively short (0.5 km) distance along the beach. It increased toward the east and was two times larger compared to the western part. On the other hand, the ridges did not differ significantly in their height (2.0-2.5 m above sea level). The location of tops and depressions of the ridges corresponded to the land relief, i.e. the tops roughly coincided with submerged bars and the concavities with hollows in the ground.

Grease ice ridges may reach considerable heights (up to several meters) due to strong onshore storms, raised water levels and high waves. Moreover, the formation of these high ridges is favored by the neighborhood of steep coasts, especially cliffs. At the base of cliffs, in places where beaches are narrower and steeper, grease ice, slush and shuga are tossed by waves at relatively great heights. Such a high grease ice ridge was observed at the cliff base in Rewal (Fig. 6). The ridge had the height of about 5 m and protected the cliff from further abrasion. It was formed at the beginning of January 1979 when the air temperature dropped below -10°C and the north wind gained the strength of a storm. The slope of this grease ice ridge gradually decreased toward the sea as a result of the weakening storm and waves. It was possible to see individual parts of the ridge, separated by terraces.

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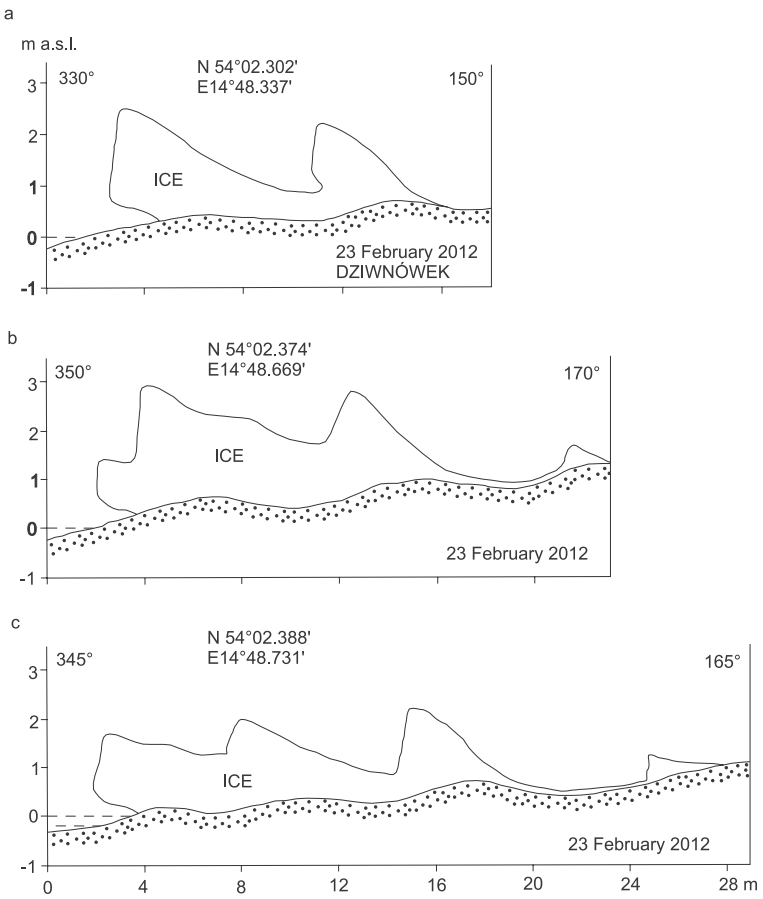


Figure 5

Changes in cross sections of grease ice ridges over the distance of 0.5 km (a-c) on the shore in Dziwnówek area (23rd February 2012)

Some parts of the windward slope were irregular and undulating. A thick snow cover was found on the beach in front of the ridge (Fig. 6).



Figure 6

High grease ice ridge descending toward the sea in Rewal area (11th January 1979)

Grease ice ridges usually have concave windward slopes with ice cornices formed in the process of ridge formation and washing out by waves. Occasionally, as viewed from the sea, the slope takes the form of a shell with a hollow every several meters (Figs 7 and 8). At these places, the ice ridge reaches the maximum height. In the longitudinal section (along the coast), such a ridge undulates with lower locations between individual shell forms. Figure 7 shows three shell forms in the background, located in a row along the coast in the town of Hel and pressure grease ice, slush and shuga in the form of a staircase in front of the shell forms (when viewed from the sea). Fast ice had formed on the sea surface from frozen grease ice, slush, shuga and pancake ice. Figure 8 shows distinctive shell forms as abrasion niches at the base of the windward slope of the grease ice ridge on the coast in Świnoujście. A low zone of pressure grease ice, slush and shuga developed in from the ridge.

A grease ice ridge may consist of several steps rising on the side facing the sea. Some steps are not

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Figure 7

Grease ice ridge with three concave shell formations in Hel area (12th March 1987)



Figure 8

Grease ice ridge with well-developed shell formations in Świnoujście area (6th March 1987)

continuous and they wedge out at some places (Fig. 9). Figure 9 shows a three-level grease ice ridge (the left side of the figure) turning into a two-tier ridge on the shore in Krynica Morska (the right side of the figure). We can see small niches at the base of windward slopes in the concave parts and ice cornices in the topmost parts.



Figure 9

Three-tier grease ice ridge in Krynica Morska area (13th March 1987)

The windward slopes of some grease ice ridges may be icy as a result of strong wind and wave water splashes freezing in frosty conditions (Fig. 10). Figure 10 shows a vertical and in some places concave (ice cornices) icy windward slope and a gentle, slightly concave leeward slope of the grease ice ridge on the shore in Władysławowo. Pressure grease ice, slush and shuga are found in front of this ridge, and a fast ice cover is observed on the sea surface. An irregular grease ice ridge of varying heights is located in the background.



Figure 10

Grease ice ridge with vertical and in some places concave windward slopes in Władysławowo region (12th March 1987)

The leeward slope of the grease ice ridge is relatively gentle in comparison with the windward slope. The grease ice, slush and shuga slide off, accumulate and consequently form the leeward side with a nearly identical inclination, corresponding to the angle of natural slip of grease ice, slush and shuga. The grease ice floating on the water surface in front of the ridge forms rounded forms of slush and shuga tossed together with splashes on the leeward side of the ridge. Figure 11 shows a very gentle leeward slope of a grease ice ridge with rounded forms of shuga on the shore in Międzyzdroje. The diameter of these "ice balls" ranged from a few to several centimeters.

The oldest grease ice ridges formed in the deeper parts of the beach are more weathered and contain more residues than those formed later and closer to the sea (Fig. 12). Figure 12 shows three small jagged grease ice ridges of different hues on the coast in Władysławowo. The ridge is darker on the land side than on the sea side. The coastal waters are covered with white ice formed from grease ice, slush and shuga. Rounded forms of shuga can be observed on the very gentle leeward slope of the ridge.

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Figure 11

Grease ice ridge with rounded slush forms on the leeward slope in Międzyzdroje area (5th February 1982)



Figure 12

Low grease ice ridges of a darker hue on the land side, in Władysławowo area (12th March 1987)

Sometimes, additional new ice may occur on grease ice ridges formed earlier in the season. It may be grease ice, slush, shuga, or flaking brash ice (Fig. 13). Figure 13 presents the coast in Międzyzdroje where a grease ice ridge (darker hue) with a layer of disintegrated ice (whiter hue), resembling grease ice, slush and shuga was observed. This ice is not consolidated and contains a large amount of air, hence the white color. Pressure grease ice, slush, shuga and disintegrated brash ice are situated in front of the ridge.

Some grease ice ridges may be built not only from grease ice, slush and shuga, but also from brash ice. Such ridges occur most often in estuaries, because the first ice on the sea is the ice brought by rivers. It is not only the grease ice, slush and shuga, but also pancake ice, floe and brash ice. A fragment of a grease ice ridge with some brash ice is presented in Figure 14, which shows concentrations of brash ice thawed into the grease ice, slush and shuga mass on the shore in Międzyzdroje. Small fragments of disintegrated brash ice occur at the base of the ridge, compressed as a result of wave activity and resembling grease ice, slush and shuga.



Figure 13

Grease ice ridge with a layer of small new ice in Międzyzdroje area (18th February 2012)



Figure 14

Fragment of a ridge formed from grease ice, slush, small brash ice and other small forms of ice in Międzyzdroje area (18th February 2012)

A heavily undermined grease ice ridge (a deeper abrasion niche) may break off over time under its own weight (Fig. 15). Figure 15 shows detached fragments in some parts of the ridge on the coast in Krynica Morska. After breaking off, the leeward surfaces of the ridge sloped toward the sea.

During storms in warm periods (AT > 0°C), the grease ice ridge is disintegrated by strong waves. The ridge closest to the sea disintegrates first and the one located nearest to the land – the last. Such a disintegrated ridge resembling boulders was observed on the coast in Świbno (Fig. 16). Figure 16 shows fragments of a ridge viewed from the sea, disintegrated by a storm. A fragment of an old, darker ridge can be seen on the land side.

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Figure 15

Ice slides at some sections of a grease ice ridge in Krynica Morska area (13th March 1987)



Figure 16

Fragments of a disintegrated grease ice ridge in Świbno area (9th February 1987)

The grease ice ridge formed along the coast is an obstacle for fishing boats moored on the beach, which have to be dragged into the sea on a rope. Figure 17 shows a melting and crumbling ridge in Międzyzdroje, blocking the beach fishing boats.



Figure 17

Melting and crumbling grease ice ridge in Międzyzdroje area (5th February 2011)

Conclusions

A grease ice ridge is a particular form of accumulated grounded ice, occurring mostly at the beginning of the ice season on the south coast of the Baltic Sea. It may occur along the whole coast, but mostly in the area of estuaries and in bays. The formation of grease ice ridges depends on meteorological and hydrological factors, mainly the wave movements generated by strong onshore wind and the wave fetch. The main factor generating high waves on the south coast of the Baltic Sea is a strong wind caused by clear low-pressure systems (Majewski et al. 1983; Paszkiewicz 1989). Low-pressure systems extending to the south-east of the southern Baltic often favor the formation of grease ice ridges when a low-pressure area extends to its E, SE and/or S side and a high-pressure area to its W, NW and/or N side. This is followed by the inflow of cold polar-continental or arctic air from the north (N, NE) and consequently a drop in air temperature below 0°C and formation of new ice. With strong sea level pressure gradients, strong onshore (north – NW, N, NE) winds cause high water levels and strong wave motion. These strong water movements are strengthened even further by the meridional distance of the Baltic Sea, which increases the wind fetch (cf. Jegorov 1974; Paszkiewicz 1989).

Nonetheless, significant cooling and ice phenomena in the southern Baltic Sea occur also when a high-pressure system moves east of the Baltic (cf. Betin 1962; Dziadziuszko & Majewski 1990) and frosty polar-continental air arrives from Russia. However, such a pressure system generates winds blowing from the land (E, SE, S), which are not favorable for the formation of grease ice ridges or other forms of ice accumulated on the south coast of the Baltic Sea.

In order for a grease ice ridge to be formed, a sufficient amount of new ice is needed. With small amounts of new ice, small bodies of pressure grease ice, slush and shuga, or partial forms of a grease ice ridge may develop on the shore. However, when grease ice, slush and shuga are thick and block wave movements, a grease ice ridge will not be formed. The thicker the new ice the stronger wind/waves are necessary to form a ridge. With weaker wind/smaller waves and thick grease ice, slush and shuga, the new ice floating in the coastal waters become compressed. Compressed and consolidated grease ice, slush and shuga form a characteristic, permanent ice cover on the sea with an uneven surface (Girjatowicz 2001).

With strong wind and onshore wave movements, the new ice is washed up on the shore, forming

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a characteristic ridge with a very steep, usually concave windward slope with ice cornices and abrasion niches, and with a much more gentle, usually slightly concave leeward slope. Such a ridge (in some places inclined toward the sea) was also observed along the coast of Pomeranian Bay in winter 1966 by Jaworski (1967), or in winter 1997 by Girjatowicz (1999). Shell (concave) formations occur in the highest places of a ridge on its windward slopes exposed to higher waves. Such shell forms are often observed every several meters on a ridge. Concave forms (niches) also occur along the whole grease ice ridge. Sometimes an overhang in the form of a shelf (cornice) may occur in the upper part of a ridge (Lutkovskij 1957). Occasionally, an opening through a ridge to the leeward side develops at these concave places. Small openings, usually ranging from a few to several tens of centimeters in diameter, but also much larger tunnels may occur.

A grease ice ridge often takes the form of a few steps descending toward the sea. Their width usually ranges from several tens of centimeters to several meters. Such a ridge is usually formed during a single subsiding storm.

The leeward slope of a grease ice ridge is usually inclined toward the land. The inclination is usually gentle – 20-30°. The formation of gentle slopes is favored by deposited rounded forms of shuga. They are formed on the windward side of a ridge as a result of wave movements. The whirling water compresses the grease ice, slush and shuga into spherical forms, even up to several centimeters in diameter. These "ice balls" are tossed by waves to the leeward slope of a ridge where they roll down and build this slope. That is why the leeward slope is gentle with an inclination corresponding to the angle of natural slip of these rounded forms of shuga. Slightly inclined leeward slopes resembling terraces are formed mostly by the wave water on the multi-tier ridges.

The location of grease ice ridges may depend on various factors, such as the morphology of the coast, the amount/thickness of new ice, the height of waves, or the water level. The main factors are the water level and the height of waves. With low levels and small wave motion, the ridges are usually formed on the shores, submerged bars and shoals near the shore. Along with the increasing water levels and wave motion, the ridges move further toward the beach. With the highest water levels and strong wave motion, the ridges develop at the back of the beach, at the base of dunes and cliffs; it is where the highest ridges are formed, usually several meters high. The height of ridges depends mainly on the water levels and the height of waves generated by strong wind. The higher the water levels and the waves, the higher the grease ice ridges.

In warm periods (AT > 0°C), deep niches are formed as a result of waves breaking at the base of grease ice ridges, causing their undercutting. Ridges lose stability and collapse. As a result of powerful storm waves, a ridge may break up into individual parts resembling boulders. Such "ice boulders" occur not only in the water, but also washed up on the beach. Far from the sea shore, they are quite durable and can last until late spring. Buried ice may stay on the beach even longer. Large pieces of buried ice (10 m long and 0.3 m thick) hidden under 1 m of sand were observed on the beach in Jastarnia even in late May (Giżejewski & Rudowski 1972).

Given the above, we may assume that a typical grease ice ridge has a very steep, concave windward slope with an ice cornice formed as a result of strong wind and wave movements (Fig. 18). An abrasion niche develops at the base of a ridge and its depth increases with time. The leeward slope is relatively gentle, slightly concave, with an inclination of usually 20-30°, formed in the process of rounded (spherical) forms

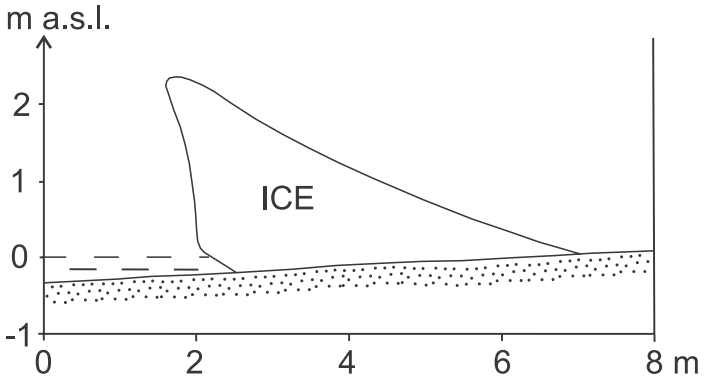


Figure 18

Grease ice ridge model

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of shuga rolling down together with seawater splashes. The height of grease ice ridges is usually 1-3 m and the width of a single ridge – 4-6 m.

Piled and grease ice ridges occurring on the coast of the Baltic Sea vary considerably. Piled ridges are built of brash ice produced in the process of breaking off of ice chunks during the collision and thrusting of ice floes (cf. Kovacs & Sodhi 1980; Leppäranta 2011). On the other hand, grease ice ridges are built of grease ice, shuga or/and fine brash ice. The piling factor for the piled ridges is mainly the effect of wind on the surface of a floe (cf. Kovacs & Sodhi 1980; Orviku et al. 2011; Leppäranta 2013), while the grease ice ridges are formed as a result of wave movements. Piled ridges also vary in terms of shape – their windward sides are usually less inclined than leeward sides (cf. Kovacs & Sodhi 1980; Christensen 1994), while the windward sides of grease ice ridges are very steep, usually concave, and their leeward sides are much gentler. Piled ridges are usually higher and wider than grease ice ridges. The height of piled ridges may reach several meters (cf. Leppäranta 2013; Christensen 1994; Orviku et al. 2011), while the height of grease ice ridges is usually 2-3 m. Piled ridges are usually formed after disintegration of solid ice in winter and spring (cf. Kovacs & Sodhi 1980; Alestalo & Häikiö 1976). Grease ice ridges normally occur at the beginning of the ice season.

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