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INFLUENCE OF METEOROLOGICAL CONDITIONS IN AUTUMN/WINTER 2021–2022 ON THE DEVELOPMENT OF STORM SURGES AND THE DUNE EROSION ON THE POLISH BALTIC COAST AS A RESULT OF CLIMATE CHANGES

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Abstract:
This paper presents details of 37 storm surges that occurred on the Polish southern Baltic Sea coast in the autumn/winter 2021–2022 season. They emerged during the passage of a larger number of low-pressure systems than usual from the SW-W direction over the Baltic Sea. Based on an assessment of meteorological and hydrological conditions during the storms, the relationship between the wind parameters, the sea level increase, and its maximum elevation was ascertained. The relationship between the sea level and the run-up elevation was ascertained. The elevation of the sea level and run-up on the onshore were compared with the beach height. Sections with a lower beach were affected by dune erosion already at a lower sea level. The dependence of dune erosion on the sea level elevation was presented. The value of the dune base retreat depended on the beach elevation and the sea level expressed by the onshore flow called run-up. The most significant erosion occurred during the storm Nadine with a sea level of 1.0–1.28 m AMSL. The average erosion varied between 1.0 and 4.5 m. The maximum erosion values reached 8–13 m.

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Key words: storm surges, run-up, wind force, low-pressure systems, dune retreat.

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INTRODUCTION

The South Baltic coast is a non-tidal zone, its shores are mainly affected by annual sea level growth and sea level rise, wave and wind action during storm surge (Sztobryn et al., 2005; Kowalewska-Kalkowska, 2021). With the observed climate change, the South Baltic Sea average level rises and the number of smaller surges grow (Zeidler *et al*., 1995; Samuelsson and Stigebrandt, 1996; Johansson *et al*., 2001; Suursaar *et al*., 2003; Sztobryn *et al*., 2005; Richter *et al*., 2007; Gräwe and Burchard 2012; Jaagus, Suursaar 2013; Hünicke *et al*., 2015; Weisse and Weidemann, 2017; MacPherson *et al*., 2019; Wolski and Wisniewski 2020; Kowalewska-Kalkowska, 2021). This causes an increased risk of erosion, the potential scale of which should be measured concerning the size of storm surges.

The southern Baltic Sea, including the Polish coast, is haunted by frequent SW and W winds occurring during an eastward passage of low-pressure systems (Trzeciak, 2001; Andersson, 2002; Leckebusch and Ulbrich, 2004; Miętus *et al*., 2004; Kowalewska-Kalkowska and Kowalewski, 2005; Sztorbyn *et al*., 2005; Wolski *et al*. 2014). The largest surges are related to very active and large low-pressure baric systems (Sztorbyn *et al*., 2005; Kowalewska-Kalkowska, 2018, 2021). Winds, particularly the heavy ones, result from pressure differences during system shifts over Scandinavia and the Baltic Sea. They are responsible for meteorological forcing resulting in short-term sea-level variations. High speed winds (>10 m/s), named the storm surge winds (Trzeciak, 2001; Sztobryn *et al*., 2005; Stont *et al*., 2012), are observed mostly during colder season and most frequently arrive from SW, W and NW directions. Such winds account for about 50% of annual winds in the Polish southern Baltic coast. In the cold season (October-March), 17–20% of storm winds come from SW and W, 15–26% from NW and 6–12% from NE (Trzeciak, 2001). The annual probability of the heaviest winds (>15 m/s) is about 6% (Zeidler *et al*., 1995; Trzeciak 2001; Sztobryn *et al*., 2005) and in 1976–2000 about half of all storm surge events on the southern Baltic coast were caused by a strong northerly airflow over the Baltic, with high atmospheric pressure over Scandinavia and a depression shifting southwards (Sztobryn *et al*., 2005).

The storm surge on the Baltic coast is understood as a strong wind action producing high waves accompanied by an increase in the sea level over a short period (Trzeciak, 2001; Sztobryn *et al*., 2005; Dailidienė *et al*., 2006; Hünicke *et al*., 2015; Kowalewska-Kalkowska, 2021). The length of this phenomenon is ranged from 1 to 3 days. The factor most important for rising the water level is the water inflow from the North Sea which occurs when the wind changes its direction from SW to NW. Surges at the southern Baltic coast are most frequent during the autumn-winter period, November to February (Zeidler *et al*., 1995; Sztobryn *et al*., 2005; Dailidienė *et al*., 2006; Surkova *et al*., 2015; Kowalewska-Kalkowska, 2018, 2021).

During the autumn/winter season 2021–2022, a great number of smaller and larger storm surges were observed, which resulted from lows passing over the Scandinavian Peninsula and the Baltic Sea from the southwest to the east. It was the largest number of surges in the 21st century. The aim of the study was the analysis of: (a) meteorological conditions of the autumn-winter 2021/2022, (b) hydrological fluctuations and sea level changes during surges, (c) a comparison of sea level to observed erosion during selected surges, and (d) explanation of sea level during the surge to dune erosion.

GENERAL CHARACTERISTICS OF THE POLISH BALTIC COAST MORPHOLOGY

The Polish coast is over 500 km long and is mainly exposed to the north; including 464 km of the open coast (Fig. 1A). Over 80% of this coast consists of dune systems developed on sandbars composed of loose sand (Zawadzka-Kahlau, 1999; Pruszak and Zawadzka, 2008; Łabuz, 2013) of different sandbar width and coastal dune height (Fig. 1B). The rest is a cliff coast that is not under this research. Only 15% of coastal dunes are more or less currently accumuled and 35% are eroded after every higher storm surge with sea level (SL) >1 m above mean sea level (AMSL) (Łabuz, 2013).

The South Baltic coast is mainly exposed to the north, from which storm surges are frequent. The Polish coast is under constant threat from autumn/winter storm surges (Zawadzka-Kahlau, 1999; Pruszak and Zawadzka, 2008). The coastline is mostly aligned and mainly exposed to the north (Fig. 1A). The middle part of the coast in Koszalin and Ustka Bays forms a concave coastline oriented to the west and exposed to W-NW surges. On the two sandbars located in large bays, Świna in the west and Vistula in the east, the shoreline is concave and both have different orientation. One part of both sandbars is exposed to NW and the other to NE. For this reason, the greatest erosion in both bays occurs during storms perpendicular to the shore, from the NW or NE sector. In the Gulf of Gdańsk, a part of the coast is exposed to the east, where erosion is usually smaller due to the absence of strong surges from that direction. On the narrow Hel Peninsula (Hel Spit), exposed to the northeast, the erosion occurs mainly during NW to NE storm surges. The rest of the coast is aligned but with several northerly shifting sand promontories, where coast orientation is changing from more or less WNW to N exposition. That is why it has a different exposition for wind and waves impact at every few kilometers (Łabuz, 2013). The analysis of long-term coast retreat stated that the coastline is divided into numerous accumulative and erosive circulation systems (Zawadzka-Kahlau, 1999). The erosive tendencies prevail, especially on the middle coast, exposed to the west and northwest (Fig. 1C).

MATERIAL AND METHODS

Information on the occurrence of storm surges in the autumn-winter 2021–2022 and their characteristics were collected from gauge stations of the Polish Maritime Bureau and the Harbour Master's Offices located along the coast (Fig. 1C). The meteorological and hydrological data were based on materials obtained from the Institute of Meteorology and Water Management in Poland (www.imgw.pl) and Federal Office for Maritime Navigation and Hydrography (Bundesamt für Seeschifffahrt und Hydrographie BSH, Germany, www.bsh.de). The names of storm surges were used, based on names of low-pressure systems given by the Institute of Meteorology of the Free University of Berlin (http://www.met.fu-berlin.de/wetterpate/).

The main descriptors of the storm magnitude included the highest storm sea level (HSL), the duration of surge (hours, TSL) and sea level higher than 1 m (TSL with HSL >1 m). The run-up on the shore (SLr), resulting in the sea level rise (SL) observed during or after the main surges was also taken into account. The assessment presented below considers the sea level changes read from the water gauges located in Świnoujście (SW code, Fig. 1) on the western coast, and in Władysławowo (WA code) on the eastern coast. For the central coast, the sea levels in Kołobrzeg (code KG) and Ustka (code US) were assessed.

The wind information (speed, direction and its changes) was extracted from hourly readings at the Institute of Meteorology and Water Management (IMGW) from selected coastal weather stations (https://www.imgw.pl). The wind speed and directions as well as the changes in the sea level were assessed. The dependences between them were determined. Table 1 contains elaborated characteristics of all storm surges with hydro-meteorological indicators that are average for the Polish Baltic coast.

Field research was carried out to measure the extent of erosion caused by selected storm surges, including the largest ones. Changes in the relief of the coastal forms were determined based on the analysis of the cross-shore profiles from the waterline to the stable dune. The field measurements involved the use of geodesic tools, including cross-shore linear levelling using the optical and laser leveller. The presence of a storm surge impact on the shore morphology involved the measurement of due to retreat, beach levelling and the highest surge range on the beach called the run-up or swash (SLr). Based on this, the extent of storm surges was compared with dune location and beach height before the surges. The main variable of the coast erosion is dune or cliff toe retreat. This study is focused

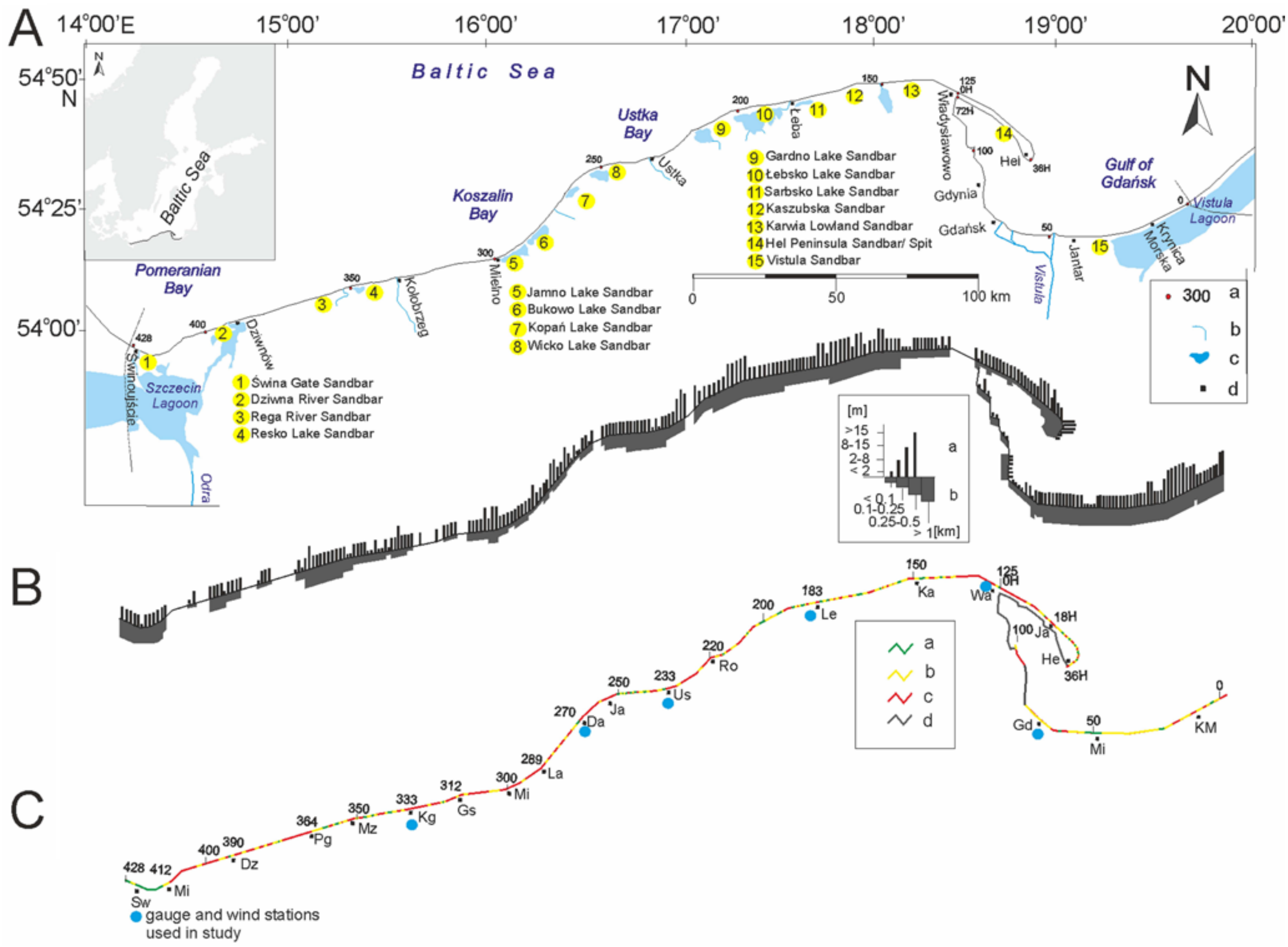

Fig. 1. Location and shoreline of the Polish Baltic coast. A – coastline extends with sandbars location, a – coast kilometrage 0–428, b – rivers, c – lakes and lagoons, d – main towns. B – sandbars parameters, a – height, b – width. C – coast dynamics for the period 2010–2013, a – accumulation, b – fluctuation, c – erosion, d – no data.

only on examination of beach height and dune toe changes caused by storm surges. Values were achieved from the cross-shore profiles and compared to the observed run-up and closed gauge station water level.

This study used data collected in June and September before the storms season. It consists of 195 separate profiles, selected from 328 measured ones. The profiles are located mostly 1 km apart from each other along the examined sandbars (Fig. 1) and are a part of a larger study along the coast. The field study was repeated after minor storms in autumn 2021 and after the largest storms in January and February 2022. Due to the high frequency of surges, only a part of the coast was selected for a field study after the lower surges in 2021. Coast changes after the Henrik and Rudolf storms cover the entire western and central dune coast from Świnoujście to Ustka and Hel Spit with Vistula Sandbar. Changes of the coast after the Gerhild and Ida storms in January 2022 cover only a part of the western coast from Świnoujście to Kołobrzeg and selected, mostly erosive fragments of the eastern coast (selected based on own data). It was not possible to finish them due to successive storms in January and February. That is why some data are not presented when two or more surges could cause the observed dune erosion. Changes of the coast after the Marie and Nadine surges were carried out separately, just after their completion at the beginning of February 2022 on the eastern coast: on the Vistula Sandbar and the Hel Spit, and then on the whole eastern and central coast. During the research, other average surges, such as the Ylenia and Antonia were formed. All observed dune toe erosion processed were terminated before these events. The western coast after the Nadine surge in January was checked in March, but due to low SL erosion it was not expected and not observed at all.

RESULTS

Influence of meteorological conditions on storms in the autumn/winter 2021–2022

The autumn and winter of 2021–2022 were another warmer seasons in the 21st century. The air temperature rise in the cold season resulted from an often inflow of

Table 1. List of low-pressure systems causing storm surges in autumn-winter-spring of 2021–22 on the southern Baltic coast (SW – Świnoujście, US – Ustka, WA – Władysławowo).

No.	No. in month	Period, days	Name of low-pressure sytem	Wind direction	Wind speed average range, V (m/s)	Max. SL (m AMSL)				Max. growth of SL (cm)	
						West (SW)	Middle (US)	East (WA)	Average of 7 stations	West (SW)	East (WA)
1	1 Sep	23-25	Tim	SW-WNW	9-16	0.15	0.29	0.31	0.28	70	50
2	1 Oct	15-17	Gerold	SW-WNW	10-12	0.38	0.48	0.43	0.43	32	38
3	2 Oct	20-23	Hendrik	WSW-NW	11-15	0.57	0.63	0.70	0.64	85	74
4	1 Nov	04-05	Rudolf I (Peter)	WNW	10-12	0.93	0.53	0.52	0.58	76	31
5	2 Nov	07-08	Rudolf II	WSW-W	10-13	0.64	0.63	0.64	0.63	42	37
6	3 Nov	18-21	Volker	WSW-W	10-16	0.62	0.45	0.56	0.52	73	28
7	4 Nov	28-30	Andreas I	NNW-N	6-12	0.61	0.60	0.61	0.57	50	23
8	5 Nov	30-01	Christian	SW-NW	8-13	0.78	0.46	0.50	0.56	74	24
9	1 Dec	02-03	Daniel	W-NW-W-SW	9-18	0.75	0.80	0.74	0.74	100	59
10	2 Dec	05-06	Edi	ENE-E	6-9	0.58	0.44	0.44	0.46	36	25
11	3 Dec	19-20	Neo	W-NNW-NNE	7-12	0.71	0.61	0.67	0.64	70	60
12	4 Dec	24-25	Quintinus	W-NW	6-11	0.72	0.48	0.50	0.52	74	44
13	1 Jan	05-06	nn	WSW-NW	7-11	0.66	059	0.62	0.62	73	40
14	2 Jan	14-15	nn	W-NW	9-12	0.41	045	0.62	0.53	51	44
15	3 Jan	17-19	Gerhild	WSW-NW	10-18	0.85	0.84	0.74	0.85	104	65
16	4 Jan	19-21	Ida I	WSW-NNE	11-15	1.00	1.01	1,07	1.03	127	86
17	5 Jan	21-22	Ida II	NNW-NNE	9-12	0.72	0.66	0.72	0.71	31	28
18	6 Jan	27-29	Marie	WSW-NW	10-15	0.78	0.78	0.87	0.79	96	64
19	7 Jan	29-31	Nadine	WSW-NNW	11-20	0.99	1.02	1.28	1.11	134	109
20	1 Feb	01-02	Philine	WSW-NW	9-12	0.73	0.67	0.70	0.69	53	25
21	2 Feb	05-06	Queena	WSW-W-WSW	10-12	0.41	0.47	0.51	0.48	26	25
22	3 Feb	07-08	Roxane	WSW-WNW	9-12	0.60	0.62	0.69	0.63	15	16
23	4 Feb	08-09	Tanyalak	WSW-W	9-10	0.44	0.50	0.57	0.51	21	11
24	5 Feb	11-12	Sarai I	W-NW-WSW	6-9	0.60	0.62	0.66	0.63	30	20
25	6 Feb	13-14	Vera	SSW-WSW	8-10	0.26	0.32	0.33	0.41	25	25
26	7 Feb	15-17	Xandra	WSW-W	8-14	0.38	0.50	0.67	0.56	36	48
27	8 Feb	17-19	Ylenia (Dudley)	SW-WNW	11-22	0.55	0.63	0.90	0.80	53	62
28	9 Feb	19-20	Zenyep (Eunice)	SSW-W	12-14	0.49	0.59	0.62	0.58	29	32
29	10 Feb	20-22	Antonia (Franklin)	WSW-NW	10-15	0.84	0.92	0.91	0.90	100	52
30	11 Feb	23-24	Bibi	SW-WNW	9-12	0.69	0.74	0.84	0.78	29	34
31	12 Feb	25-27	nn	WSW-NE	9-13	0.75	0.72	0.75	0.74	32	36
32	1 Mar	03-04	nn	N-NE	7-10	0.40	0.43	0.45	0.41	29	26
33	2 Mar	30-01	nn	ENE-N-N	9-12	0.60	0.48	0.46	0.53	54	42
34	1 Apr	04-05	Mirella	SW-WNW	10-13	0.45	0.42	0.44	0.55	35	41
35	2 Apr	08-10	Nasim	WSW-WNW	9-12	0.53	0.52	0.53	0.52	41	43
36	3 Apr	15-16	nn	NE	8-11	0.50	0.35	0.40	0.39	40	35
37	4 Apr	23-25	nn	NNE-ENE	7-13	0.48	0.43	0.42	0.45	32	28

Average – based on 7 gauge stations marked on fig. 1C, nn – no name of low-pressure system. Source: based on data from: IMGW-PIB: https://www.imgw.pl/, IM-FUB: http://www.met.fu-berlin.de/wetterpate, Polish Maritime Office.

warm air masses from the SW-W direction. From December to February, the air monthly mean temperature exceeded 2.5–4.5°C (SW, KG, US). Thus, it was almost 5°C higher than the mean values for winter ranging between -3.3 and 1.7°C (Miętus *et al.*, 2004). For example, the mean long-term air temperature in January or February in winter from 1960–1961 to 2019–2020 was close to 0°C (Girjatowicz *et al.*, 2022).

The warming was related to a large number of low-pressure systems that usually develop in the North Atlantic or Iceland. The low-pressure systems passing over the Baltic Sea induced changes in wind speed and direction and along the coast (Trzeciak, 2001; Andersson, 2002; Miętus *et al.*, 2004). This caused development of waves and changes in the sea level. Such air circulation usually prevails from November to March with few storm surges (Trzeciak, 2001; Sztobryn *et al.*, 2005). During the analysed period, 47 such phenomena passed over northern Europe from October to December 2021 and 38 between January and March 2022 (BSH, www.bsh.de). Atmospheric pressure in the lows over the Baltic Sea ranged from 985 to 1010 hPa. These were responsible for sea level changes, including recognised and

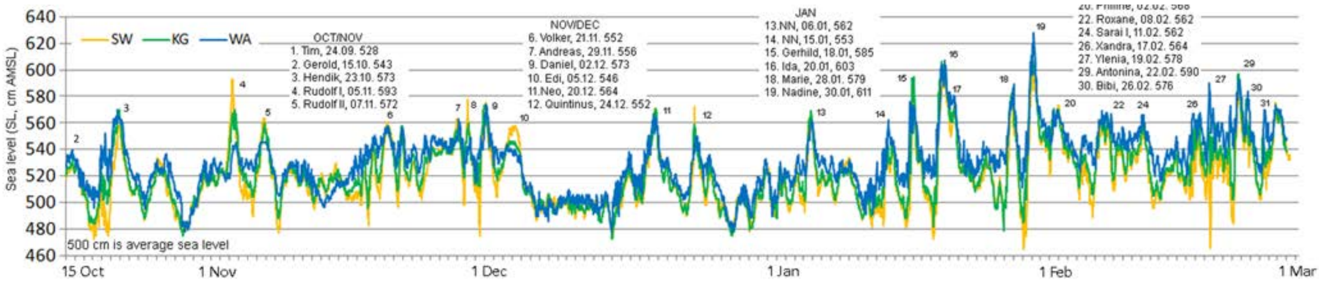

Fig. 2. Hourly sea level changes for period 15.10.2021 to 1.03.2022 with names of main low-pressure systems (numbers as listed in table 1). Gauge station: SW – Świnoujście, KG – Kołobrzeg, WA – Władysławowo, average sea level = 500 cm. Data source of own graph: Maritime Office, IMGW.

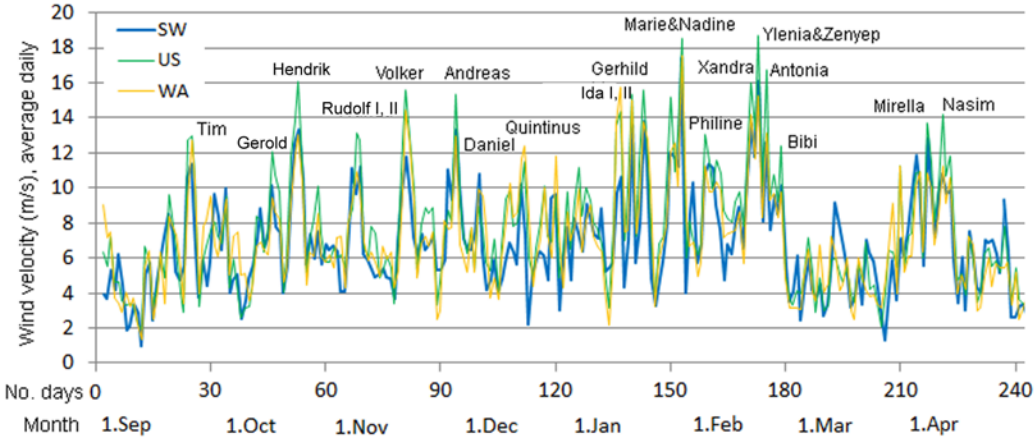

Fig. 3. Average daily wind velocity for the period 09.2021 to 04.2022 with names of main low-pressure systems. Wind station: SW – Świnoujście, US – Ustka, WA – Władysławowo. Data source of own graph: IMGW.

observed storm surges during the autumn/winter period (Fig. 2).

The mean wind speed in the autumn/winter season exceeds 5–7 m/s, whereby the highest values occur at the central coast between Ustka and Rozewie (Trzeciak, 2001; Miętus *et al*., 2004). In the assessed period (September 2021 – March 2022), stronger winds than usually prevailed, reaching monthly average 7.0–8.1 m/s (Table 2). Storm winds on the Polish Baltic coast were defined as winds with a speed exceeding 10 m/s (Trzeciak, 2001; Sztobryn *et al*., 2005). During the study period, a wind with V >10 m/s occurred more frequently from the SW than from the NW direction. High wind speeds were observed in Świnoujście (SW), Ustka (US) and Władysławowo (WA) from the end of August 2021 until the end of February 2022, and then in the first half of April (Fig. 3). It was frequently higher by approx. 2 m/s at

Table 2. Characteristic of surges along the southern Baltic coast during season 2021–2022.

Harbour, gauge station	Świnoujście (SW)	Kołobrzeg (KG)	Darłowo (DA)	Ustka (US)	Łeba (LE)	Władysławowo (WA)	Gdańsk (GD)
Location of harbour	53º55N 14º16E	54º11N 15º33E	54º26N 16º22E	54º45N 16º51E	54º46N 17º33E	54º47N 18º25E	54º21N 18º39E
Distance of harbours (km)	0	92	63	35	51	59	56
Warning SL (m)	0.60	0.70	0.70	0.70	0.70	0.50	0.50
Alarm SL (m)	0.80	1.10	1.10	1.00	1.10	0.70	0.70
Average wind IX-III (m/s)	7.2	7.0	7.4	8.1	7.9	7.5	7.3
No. of SL > 0.5 m	25	24	27	22	22	26	25
No. of SL > 0.8 m	5	5	7	4	4	5	7
No. of SL > 1.0 m	2	2	3	2	0*	2	2
Average storm SL (m)	0.65	0.68	0.68	0.63	0.60*	0.69	0.66
Max. SL (m AMSL)	1.00	1.20	1.18	1.02	0.96*	1.28	1.21
Max. SL in 21st century (m AMSL), year	1.48, 2006	1.50, 2017	1.65, 2017	1.45, 2017	1.23*, 2017	1.45, 2004	1.44, 2004

* – the gauge station in Łeba usually shows a lower sea level than in others. It could be related to elevation change due to uplift observed just on this coast or with device assembly. Source: based on data from: IMGW-PIB: https://www.imgw.pl/, Polish Maritime Office, own investigation.

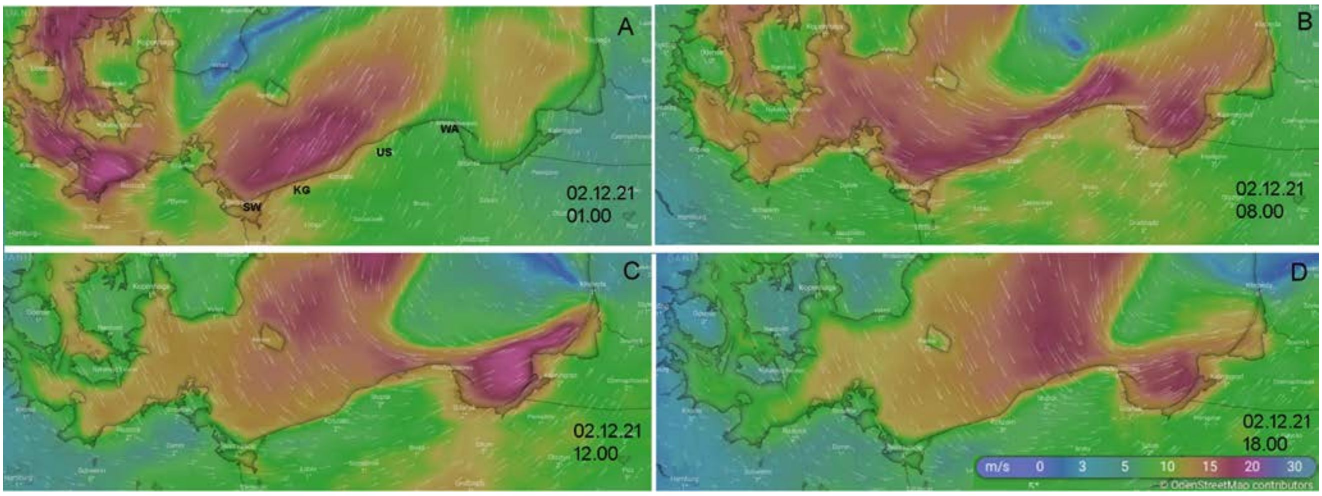

Fig. 4. Changes in wind velocity and direction during the shorter and smaller low-pressure system Daniel, 02–03.12.2021 along the South Baltic coast (based on: https://www.windy.com/pl/). Phases: A – SW wind caused water lowering but inflow by Baltic Straits. B – NW winds caused sea growth in the West and middle part of the South coast. C – shifting NW winds toward the East caused sea growth further East. D – the wind was slower and direction changed to N, sea level has decreased.

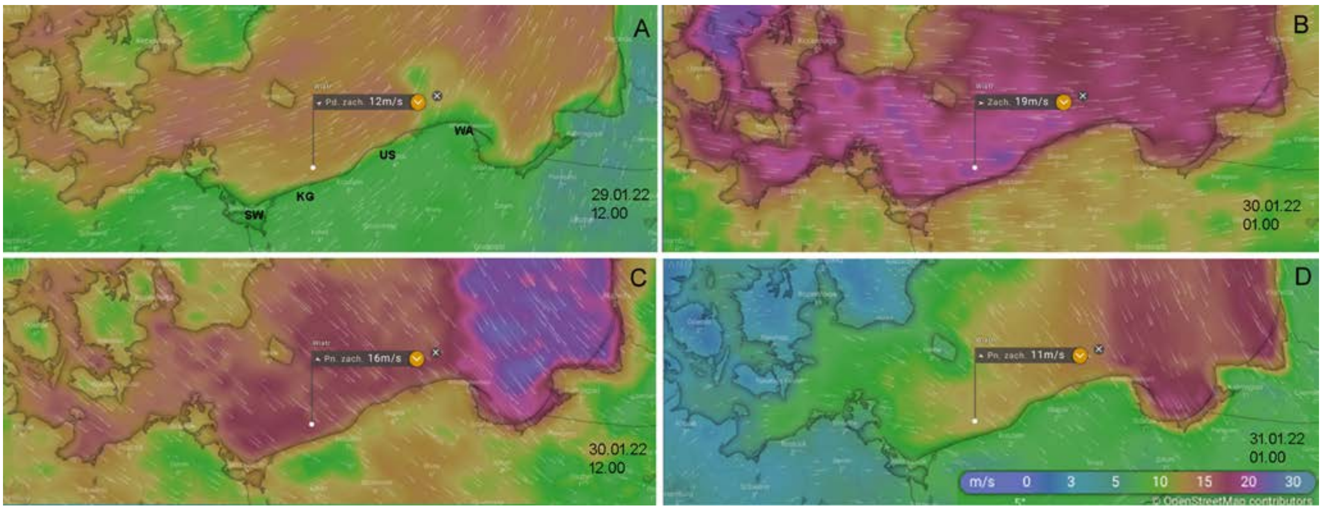

Fig. 5. Changes in wind speed and direction during the longer and deeper low-pressure system Nadine, 29–31.01.2022 along the South Baltic coast (based on: https://www.windy.com/pl/). Phases: A – SW wind lowered sea level after Marie surge. B – very strong W wind is causing sea level growth. C – stronger and longer NW wind caused higher sea level growth in the eastern part of the South Baltic coast. D – with the strong winds in the East part of the coast, storm surge was longer and higher.

the central coast (in Ustka, see Fig. 2). The mean daily wind speed exceeded 14 m/s a couple of times. However, the highest speed values occurred during the passage of low-pressure systems (the main ones recognised with names after Wetterzentale, http://www.met.fu-berlin.de/wetterpate). The mean wind speed values exceeded 9–14 m/s during storm surges. At maximum, they were 15–22 m/s.

On the southern Baltic Sea coast, the autumn and winter wind blows most frequently from the SW and W directions (Trzeciak, 2001), with the highest wind blows from SW, W and NW. The wind from these directions results from circulation of the air masses of low-pressure systems from west to east (Zeidler *et al.*, 1995; Trzeciak, 2001; Girjatowicz *et al.*, 2016). The air circulation is then directed towards the centre of the low-pressure system and changes its direction when the system passes over the southern Baltic Sea (Trzeciak 2001; Miętus *et al.*, 2004; Sztobryn *et al.*, 2005). During the autumn/winter 2021–2022, there were periods with WSW-WNW winds, only with W winds, and frequently with SW to W winds or W to NW winds (Table 1). Phenomena with the wind direction changing strictly from NW to NE or only with a NE wind were observed the least frequently. In the analysed period, during the passage of the low-pressure system over the Scandinavian Peninsula and the Baltic Sea, the wind blew at the beginning from the SW to the centre of the low. For the smaller and short storm Daniel (2–3 December 2021) and the longer and larger storm Nadine (29–31 January 2022), wind field maps can be used as an example (Figs 4, 5). In the first phase of a surge with the SW wind, the sea level dropped (Figs 4A, 5A). In the next phase, the wind shifted its direction to W and then to NW (Figs 4B–C, 5B–C). At the western coast, at the end of the low-pressure system passage, the wind speed was already lower and the sea level started to drop. Usually, the faster lowering of sea level at the western coast than in the east was related to the ongoing new low with the next episode of wind from SW. That is why the sea level at the western coast was lower between surges than in the east (Fig. 3, yellow line). At the same time, a higher wind speed still occurred in the eastern part of the southern Baltic Sea coast and the sea level had no chance of returning to a lower state. Over there, the sea level remained higher (Fig. 3, blue line) and the wind of high speed was blowing from NW to N (or NE) (Figs 4D, 5D).

A fraction of the shorter low-pressure systems in 2021–2022 featured SW to W winds (Table 1). The onshore high-speed wind lasted shorter and caused a lower water surge. In the case of short but deep low-pressure systems, the wind usually was blowing from SSW to NNW. These were winds blowing with a high to a very high speed of 10–16 m/s. Their offshore direction (SSW-WSW) usually led to a sea level lowering at the southern Baltic Sea shore, especially at the western coast in the Pomeranian Bay. Their longshore direction (W or WSW-WNW) caused surges on shores exposed to the western wind, as in Koszalin and Ustka Bays. Similarly, a higher sea surge at a wind blowing from the W emerged in the eastern part of the Vistula Spit and further on the Sambian Peninsula. This coast section located in the Gulf of Gdańsk is also exposed to the western winds (Fig. 1).

During the passage of longer and deeper low-pressure systems (pressure 985 hPa), high wind speeds and the largest water level growth from minimum to the maximum are observed. During such phenomena, the wind direction shifts from SW to NE along the entire coast (Trzeciak, 2001; Miętus *et al*., 2004). A long-lasting and high wind from W to NW affects a water inflow through the Danish straits, which influences development of the highest sea level rise at the southern Baltic coast (Zeidler *et al*., 1995; Trzeciak, 2001; Sztorbyn *et al*., 2005; Wolski and Wiśniewski, 2020). In the study period, onshore winds caused the largest surges in January and February 2022 (Fig. 3, Table 1). The longest-lasting surges with the highest sea level occurred when the wind shifted from WNW through NW to NE. Then, the highest sea level arose on the entire Polish coast and was observed several times in the assessed period (Figs 2, 3). At that time, the wind speeds exceeded 10–15 m/s on average, and the maximum was 17–22 m/s (Figs 2, 6, 8). When the high-speed wind blew onshore, the sea level rose. Such bigger surges occurred with Gerhild and Ida, Marie and Nadine or Ylenia, Zenyep and Antonia lows (Figs 2, 3, 7, 8, Table 1).

Storm surges caused by the NE wind occurred less frequently. In 2021–2022, four smaller surges emerged at this wind direction, with a lower sea level, up to 0.4–0.5 m AMSL. In the last 22 years, surges from this direction with the sea level H >1 m occurred only 6 times at the Polish Baltic coast (Łabuz, 2022).

When the low-pressure systems were passing by, the wind blowing along the coast changed its speed and direction (storms Tim and Nadine) or only the speed (storm Volker) and slightly the direction (storm Rudolf). Figure 6 presents the difference in wind parameters during selected surges along the Polish Baltic coast (Świnoujście, Kołobrzeg, Ustka and Władysławowo). This contributed to the observed variations in sea level over time and along the shore. Due to varying directions of wind passing over the southern Baltic Sea, surge phases were distinguished for each storm lasting over 2 days. They corresponded with the time of sea level rise and its fluctuations due to the wind direction and speed changes. Figure 8 shows the relationship between the changes in wind speed and sea level. In the T0 phase, the wind usually had an offshore SW to SSW direction. In the T1 phase, a W to NW (NNW) wind led to a quick sea level rise to its maximum. This phase usually lasted from 10 to 24 hours. The maximum sea level was reached faster at the western coast (Świnoujście) than in the east (Władysławowo). In the T1 to T2 phase, NW to NNW (N) winds resulted in a persisting high sea level. During that time, the wind speed increased or decreased, resulting in a further sea level rise or drop. The T3 phase was related to a drop in sea level. In many cases, the wind direction change was related to its higher speed, resulting in the sea level rising again. For this reason, the storm surge was doubled. The water level rose on one occasion with a W to NW wind, and then with an NNW to N or NNE wind.

When the cold season is warmer than usual, it is related to a bigger number of low-pressure systems that are shifted further towards the north, than in the average winter (ca. 85 in autumn/winter 2021–2022). Their passage is often over northern Scandinavia, then the Bothnia Bay and then Estonia/ Finland to the east. Among them there were Hendrik, Queena, Zenyep and Roxana which caused lower surges and much more in winter 2022 that not caused a surge at the southern Baltic coast. In such conditions, at the southern Baltic coast the offshore SW wind prevails, which blows to the centre of the lows. On the other hand, when the low-pressure system shifts in the lower latitude, through the northern German and Polish coast to the east as Tim, Volker, Tanylak, and Sarai, the surge is small due to more alongshore wind (SSW-WNW). However, if such a shifting low is directed over Scandinavia to the Baltic Sea or is redirected from Scandinavia through the Baltic toward Belarus like during Ida, Marie, Nadine and Antonia, the wind is more often from W to NW and NE. Such meteorological model produces the highest and longest storm surges at the southern Baltic coast. The conclusion is that a climate warming is accompanied by lower surges during a single season with wind direction likely offshore than onshore.

Storm surges in the autumn/winter 2021–2022

In the autumn/winter 2021–2022, between the second half of September and the middle of April, a prevailing western circulation with SW to NW winds was observed (Fig. 6). During that period, 37 storms emerged on the Polish coast, including 32 caused by low-pressure systems passing from the SW to NW (Fig. 8, Table 1). They were

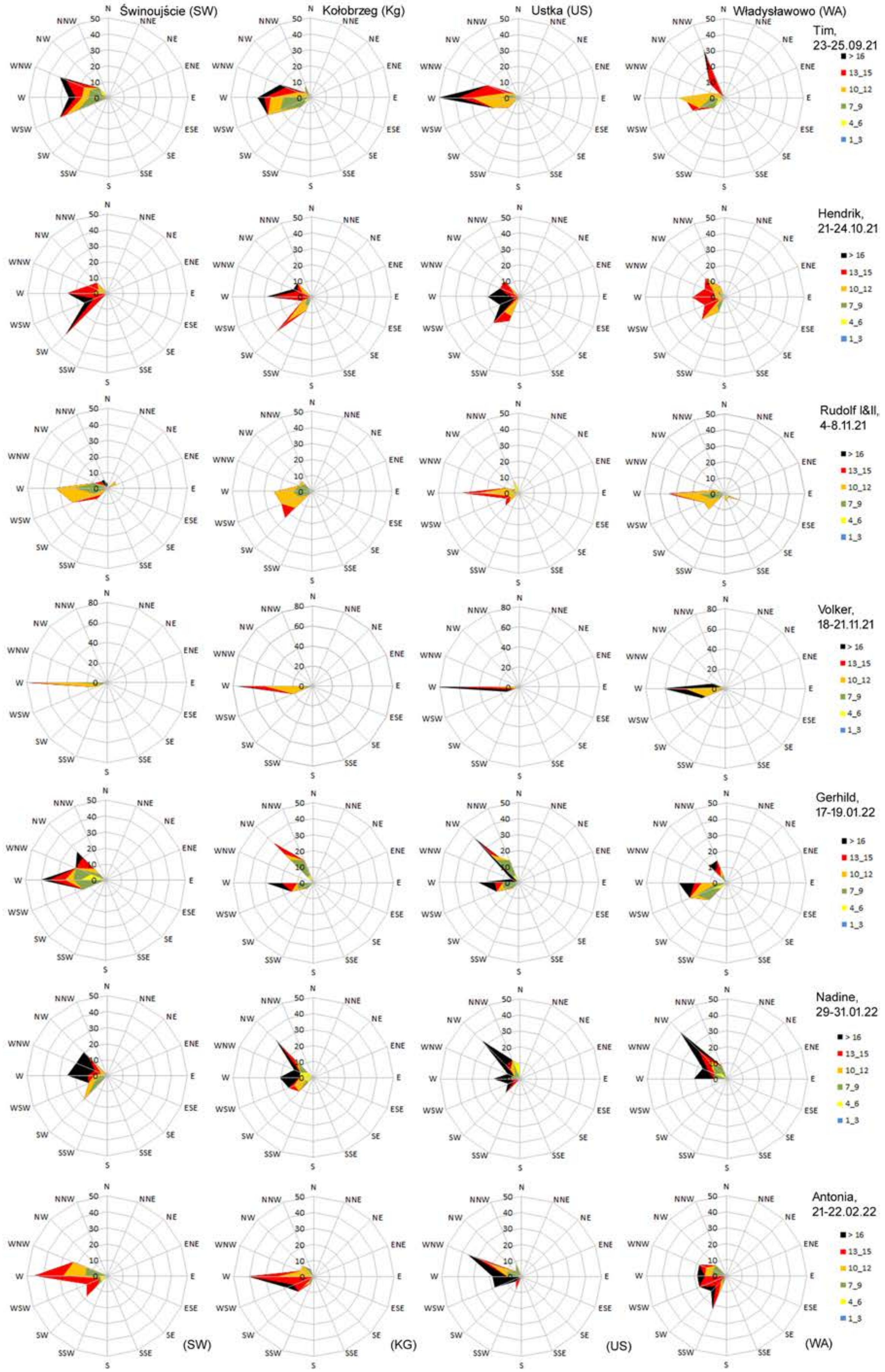

Fig. 6. Comparison of wind roses for storm surges with prevailing SW, W or NW winds (see table 1). Data source of own graphs: IMGW.

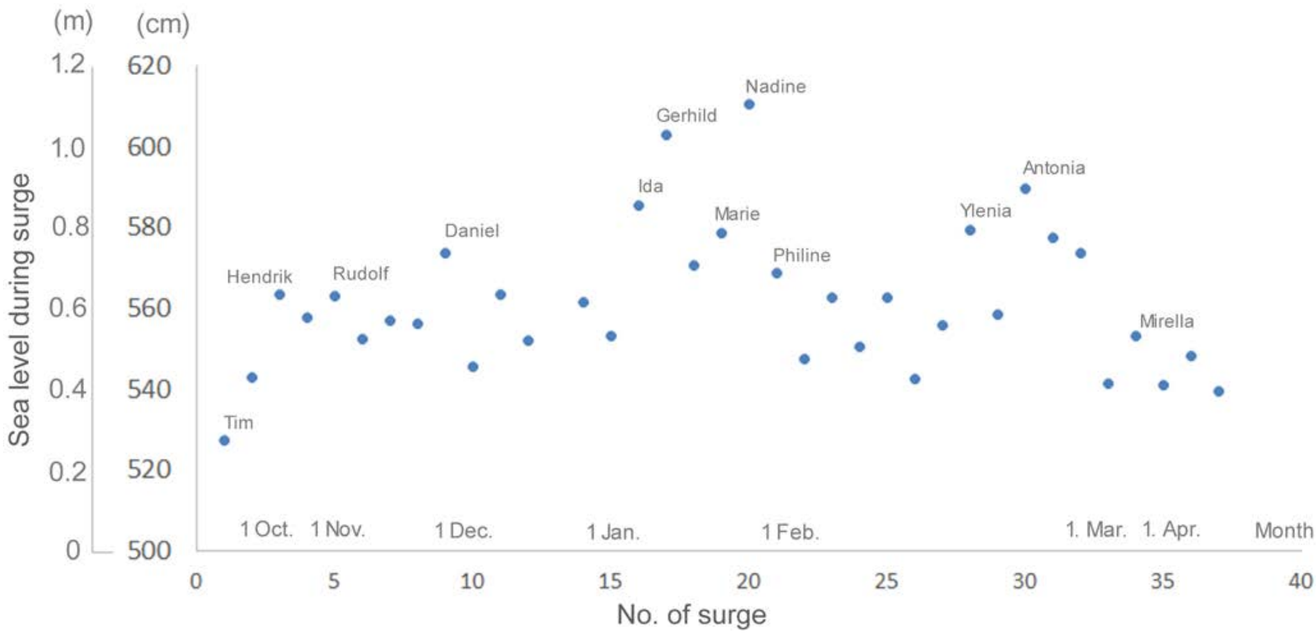

Fig. 7. Average max. sea level during storm surges in season 2021–2022 (average from 7 gauge stations, fig. 1). Main surges with names, data source: Maritime Office, IMGW, Wetterzentrale.

highlighted based on sea level change and parameters of wind, related to atmospheric pressure. Some of them were easy to separate, but some developed one after another or even were almost together. For example, when the previous storm was still at the eastern coast, a new one arose at the western coast. During their passage, the sea level rose significantly above the minimum values (Fig. 3, Table 1). Among them, the sea level exceeded the warning level during 15 storms and during 10, it surpassed the alarm level c.a. 580 cm above the mean level in the harbours (Table 2). Five surges were an exception, including four at the end of March and in April 2022, which emerged at an NNE wind. In addition, throughout the period, between storms, the sea level has changed greatly between the lowest 466 cm to 628 cm (with 500 cm as the average sea level).

The first remarkable storm emerged on September 24 as a result of a high SW-WNW wind, with an average daily speed of up to 13 m/s (storm Tim) (Figs 2, 6). On September 23, a high-speed wind of phase T0 lowered the sea level and then, in the phase T1–T2, a WNW wind caused it to rise. The highest sea level reached 528 cm on average, which was 0.28 m above the mean level (Table 1). This was not a large value, if not taking into account the absolute increase in the water level during this low. The sea level rose from a very low level by 70 cm at the western coast and 50 cm at the eastern coast.

In October, the first storm surge was Gerold and just after, another one emerged during the low Hendrik (985 hPa). It caused the sea level rise up to 563 cm on average (Figs 2, 3, 8A). On October 20–23, an SW wind with a speed of 11–14 m/s changed the direction to NW with a speed of 14–16 m/s. It caused the sea level rise and onshore waves to develop, resulting in a beach erosion at the Polish sand-bar-dune coast, up to 1 m AMSL (Fig. 12).

At the beginning of November 2021, another smaller but double surge associated with low-pressure Rudolf with an SSW-W wind and a sea level of up to 563 cm occurred (4–8 November 2021) (Figs 2, 3, 6, 7, 8B). Its effect was a lowering of the beaches of the Koszalin Bay coast. The wind waves were perpendicular to the coast exposition. On November 18–21, a low-pressure system named Volker induced a high wind from the W direction, which blew for 3 days at a speed of up to 14–16 m/s (Figs 2, 3, 6, Table 1). Its diversion changed to WNW and caused the sea level rise to 555 cm. No erosion of the beaches that had been lowered by the preceding storm Rudolf was observed. On November 28–30, two low-pressure systems, Andreas and Christian, were observed which caused an SW to NW wind with a speed of 6–13 m/s and a sea level rise to 550 cm.

During December two low-pressure systems induced a short-lasting increase in the onshore wind speed and a water surge of up to 580 cm (Daniel and Edi; Table 1). These both events were short and they could erode the beach up to 1.6 m AMSL (Fig. 10). Two further low-pressure systems emerged at the end of December, causing a wind speed increase up to 8–12 m/s. The wind direction was initially SW and then changed to NW. This caused the sea level rise to 563 cm on average (Neo, Quintinus, Table 1). No dune erosion was observed due to a low sea level.

Two further storm surges emerged in the first half of January 2022 due to NW winds. At the beginning of the first of them, an SW wind with a speed of up to 12 m/s changed its direction to NNW. Due to this, the sea level rose on average to approx. 559 cm. The subsequent storm had a similar course. These surges did not cause any erosion of the dunes.

They were followed by a larger surge associated with the low-pressure system Gerhild (980 hPa) (Figs 3, 6, 8C, Table 1). On January16–17, a WNW to NW wind blowing

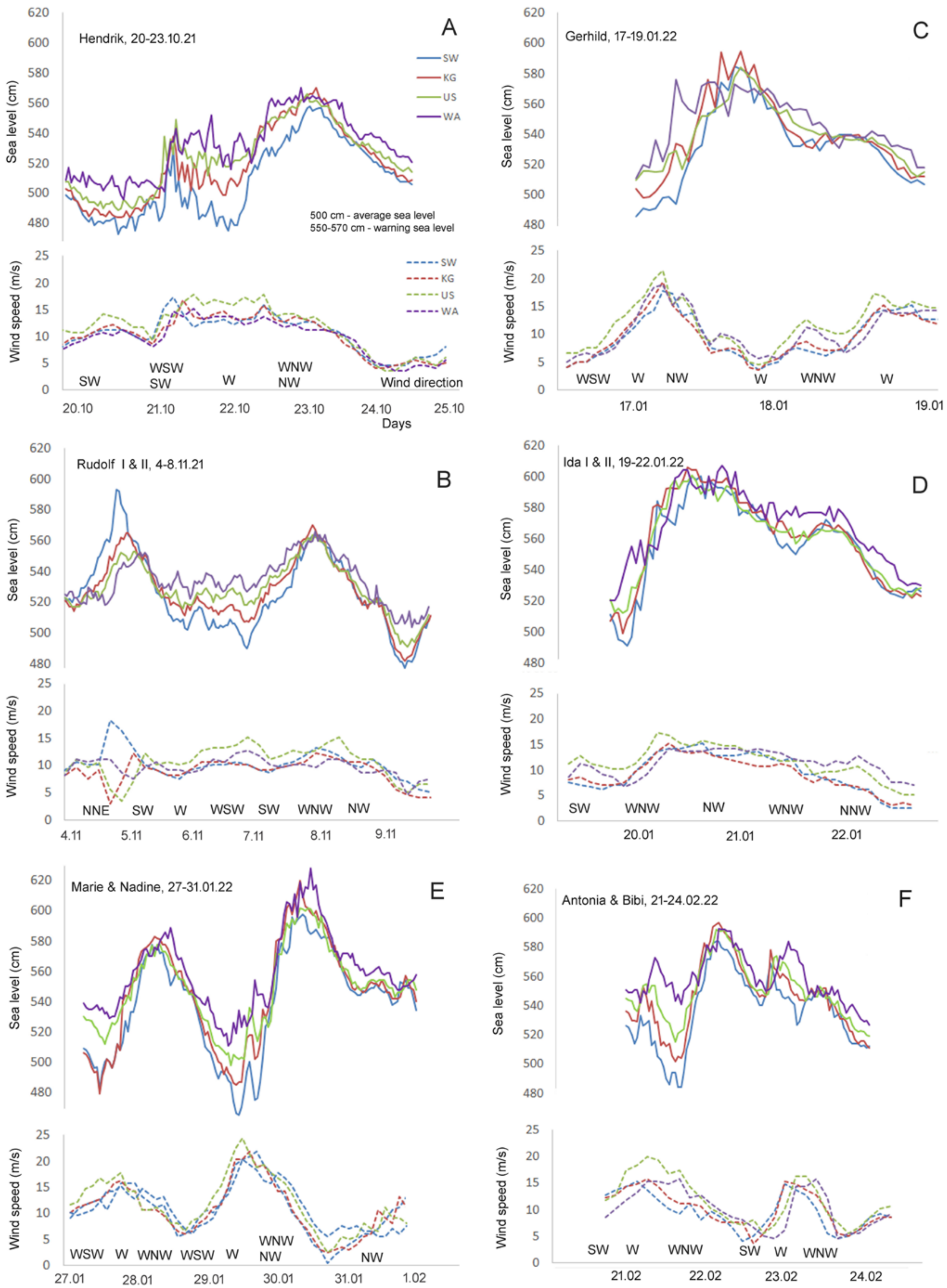

Fig. 8. Comparison of wind parameters to sea level growth of selected surges in season 2021–2022. A – Hendrik, B – Rudolf, C – Gerhild, D – Ida, E – Marie&Nadine, F – Antonia&Bibi. Data source of own graphs: Maritime Office, IMGW, Wetterzentrale.

at a speed of 11–18 m/s caused the sea level to rise rapidly (T0–T1 phase). This rise, reaching from 0.7 to 1.1 m AMSL, was observed along the entire coastline at the end of 17 January (T2). A higher rise was observed at the western coast, where beaches of up to 2 m were flooded by sea waves. This was the first storm during the 2021–2022 winter with the sea level exceeding 600 cm (1 m AMSL).

The subsequent surge was the low Ida (995 hPa), causing the sea level to rise again on January 19–22 along the entire coastline (Figs 3, 7, 8D, Table 1). In the T0 phase, prior to the sea level rise, the wind blew from the SW direction at a speed of up to 13 m/s (January19). Subsequently, the wind blowing from the W direction, up to 16 m/s (January 20) transitioned to WNW (January 21) and caused the sea level to rise to over 1 m AMSL (T1–T2 phases). As a result of another onshore wind speed increase during the same low-pressure system (January 22), it came to another surge with an elevation of up to 0.7 m AMSL (Ida II). During these both surges, the mean sea level along the Polish coast was up to 1.02 m. During this occurrence, the wind changed the direction from SW to NNE, causing a water surge along the entire southern Baltic Sea coastline. The storm resulted in the erosion of dunes in sections where the beach elevation was higher than the average, i.e. 2 m AMSL.

Five days after the storms Gerhild and Ida, other large surges emerged, leading to significant coastal erosion. Two subsequent low-pressure systems passing over Scandinavia at the end of January 2021, Marie (995 hPa) and Nadine (980 hPa), caused the highest sea level rise in the assessed period (Figs 3, 7, 8E). They also resulted in the greatest shore erosion of the Polish coast in the autumn/winter 2021–2022 (Fig. 15). On January 26, in the T0 phase, a wind blowing from the W-SSW direction at a speed of 11–13 m/s accompanied the passage of the low Marie in the eastern direction. In the T1 phase, on 28 January, a wind with a speed of up to 14 m/s changed the direction to WNW and NW. This caused the sea level to rise at the southern Baltic Sea coast by 0.6 to 0.8 m AMSL. The mean sea level at the Polish coast was 578 cm. In the T2 phase, the sea level dropped to 548 cm along with the wind speed decreasing to 12 m/s.

The low-pressure system called Marie was immediately followed by another low named Nadine. The wind speed drop at the end of the low Marie was immediately followed by an SW wind speed increase to 14 m/s at the end of the day of 29 January (Fig. 8E). It was the beginning of another storm induced by the low Nadine (T0 phase). At a strong SW wind, the sea level dropped briefly below the average. During the next few hours, it rose by more than 1–1.3 m AMSL (T1 phase). This resulted from a wind direction change from SW to W at a speed of up to 20 m/s (January 30). At the western coast of the Pomeranian Bay, the sea level rose 1.3 m but was only almost 1.0 m AMSL. It was due to a drop in the water level at the western coast just after the Marie low-passage system (Fig. 8E). At the Eastern coast SL growth was similar but reached maximum due to still high water level after the Marie storm. A large surge emerged between the western and central coast, reaching up to 1.2 m AMSL (Kołobrzeg, Darłowo). At the eastern coast, where the sea level was still higher after the preceding storm, a high wind caused the sea level to rise even more, up to 1.28 m AMSL (Władysławowo). Due to a long-lasting impact of a W to NW wind (Fig. 5C–D), the sea level at the central and eastern coast exceeded 1.2 m AMSL on January 30 (Fig. 8E). On January 31, in the phase T2 of the storm, the wind direction changed from NNW to NNE and its speed dropped. This led to a sea level lowering to approx. 550 cm. The surges Marie and Nadine caused the greatest erosion of beaches and dunes in the entire 2021–2022 season. It resulted from a high sea level and the observed onshore flow. No dune erosion was observed at the western coast of the Pomeranian Bay, where the sea level did not exceed 1 m above average.

The entire period of February was to 4.0°C warmer than usually, with strong wind 9–16 m/s in average during surges (Fig. 2). Therefore, February was characterised by 12 separate events of low-pressure systems and a series of storm surges. Eight storms with SW-WNW winds emerged, causing the sea level rise to 560 cm. At the eastern coast, the sea level reached even 580 and 590 cm with wind V >15 m/s. This resulted from a permanently high sea level in this part of the coast, caused by a long-lasting high SW-W wind in January and February 2022 (and the whole winter).

The subsequent storm surge began on February 1 during another low, Philine, from SW to NW direction. During the storm Philine of February 1–2, the sea level reached 568 cm. The wind blew at a speed of up to 12 m/s in average. During the first half of February, five low surges emerged one after another with an average SL = 0.5 m (Figs 3, 8, Table 1), all with SSW to W wind.

In the period of February 15–27, six low-to-average surges were developed due to the fast passage of low-pressure systems. The sea level was changing rapidly from the lowest inducted by the SW wind to the highest caused by the WNW wind. Between February 17–19 surge Ylenia was characterised by an average SL up to 580 cm and absolute growth of 50–60 cm. This surge was accompanied by wind gusts up to 22 m/s. It was combined with low Zenyep, and another deeper Antonia (985 hPa). Within a few hours after Zenyep, the sea level dropped by 60 cm during the SW wind (T0). On February 20, a WSW to NW wind blowing at an average speed of 10–15 m/s caused the development of another higher surge associated with the low Antonina (Figs 3, 8F, Table 1). When the wind changed the direction to NW, the sea level rose by 50 cm at the eastern and 100 cm at the western coast (T1). The maximum sea level was 0.8–0.9 m AMSL (T2). The beaches were flooded again by the water at a high sea level and waves from the NW direction. In several locations with a very low and narrow beach, it came repeatedly to erosion of dunes (Fig. 12). Then, successive surges emerged within several hours, which was caused by development of a high-speed SW to WNW and then NE wind. During these surges, the sea level reached 570 cm on average (e.g. storm Bibi, Fig. 8F).

The lows were less active in March. Only two storm surges emerged then, featuring a maximum sea level of

560 cm with weaker wind from NE (Fig. 2). Four smaller surges emerged in April with a maximum sea level of 555 cm (storm Mirella). Two of them were caused by SW to NNW winds, and the last two resulted from NE winds.

During the storm surges developed by westerly winds, there was a delay in the sea level rise of two to three hours between the west and the east (SW and WA gauge stations). The absolute sea level rise above the minimum value was greater at the western coast. At the eastern coast, the sea level amplitude was lower during all surges. It was an effect of the permanently higher water level at the eastern coast throughout the entire period, attributable to SW-W winds (Fig. 3). At the eastern coast, the mean sea level during winter was 531 cm (WA) or 529 cm (US, LE). At the western coast, it was 520–523 cm. At the central coast, in the Koszalin Bay, the average sea level was 530 cm due to its exposure to the W direction.

Impact of the wind on the sea level

In the autumn/winter 2021–2022, a wind direction and speed varied along the coast due to passing of low-pressure systems (Fig. 2). The prevailing wind during the storm surges was usually SW to WNW, with the average speed exceeding 10–12 m/s. During the observed storm phenomena, the wind had a varied in speed and direction at each analysed meteorological station (Fig. 6). Thus, in gauge stations along the coast it caused different sea level rise and its maximum (Fig. 7). The highest wind speed and the largest number of surges were observed in January and February 2022.

There was a harmony between wind speed and direction with sea level elevation changes (Fig. 9, Table 3). Figure 9 presents the relationship between the mean wind speed and direction to the sea level elevation. Surges emerging at prevailing SW-W, WSW-NW and NW-NE winds and less frequently at an NNE-NE wind, were distinguished separately. The smaller surges emerged due to lower wind speed from SW to W (or shortly from WNW) as Hendrik, Rudolf, Daniel or Xandra. The larger ones developed at SW-W to NW wind of higher speed including Gerhild, Ida, Nadine, Ylenia or Antonia. In addition, during each surge a sea level rise was observed with increasing wind speed and change of its direction from offshore (SW) to onshore (NW).

At the wind speed of up to 10 m/s, a sea level reached 0.6 m AMSL, regardless of the wind direction. At a wind blowing with a speed above 14–15 m/s, the sea level at the mentioned wind directions differed significantly. The offshore or alongshore wind (SW-W) caused still maximum sea elevation up to 0.65 m AMSL. With the onshore wind (WNW-NW and probably NE), sea elevation was clearly larger, up to 1.1 m AMSL, depending on surge length and area. At a very high wind speed >16 m/s, the differences in the sea level rise were greater, ranging from 0.6 to 1.1 m AMSL (Fig. 9, Table 3). The higher speed of the onshore wind caused a higher sea level rise, up to 1.28 m AMSL. However, the high-speed offshore wind did not cause sea level rise, but rather its drop. The highest sea level during surges inducted by SW-W wind exceeded only 0.85 to 0.95 m AMSL.

The absolute water growth from the minimum up to the maximum prior to the surge was also greater during the high-speed wind (Table 3). Moreover, if a wind speed increase was observed after a decrease, the effect was again a sea surge: Rudolf I and II: 4–8th November 2021, Ida I and II: 20–22nd January 2022, Marie and Nadine: 27–31st January 2022 and further storms in February 2022 as Antonia. During storms with offshore SW to W winds it was 10–38 cm or 14 to 95 cm with an onshore W-NW wind. The highest increase exceeding 100 cm was observed during the strongest winds blowing onshore from the NNW to NNE sector.

As it was expected, strong winds up to 15 m/s from a land did not cause a sea level rise, as during the surge Hendrik with SW winds or while these blew along the coast (W) as the Volker storm. High SW winds caused the sea level to drop, which was evident in the hydrological data records. Such a situation took place at the beginning of several surges, as in: October 20 (Hendrik) by 20 cm, January 27 (Marie) by 20 cm, January 29 (Nadine) by 30 cm; January

Table 3. Relation of wind velocity and direction to max sea level (HSL) and its absolute growth (DHSL) during season 2021–2022.

Wind speed V (m/s)	Relation of wind azimuth to max. sea level (HSL) and its growth from min. to max. (ΔHSL), average values for the Polish South Baltic coast exposed to the North							
	SW-W		(SW) W-NW		NNW-NNE		NNE-ENE	
	HSL (m AMSL)	ΔHSL (cm)	HSL (m AMSL)	ΔHSL (cm)	HSL (m AMSL)	ΔHSL (cm)	HSL (m AMSL)	ΔHSL (cm)
(6–8]	0.35	10	0.45	14	0.46	15	0.25–0.30	20
(8–10]	0.35–0.45	15	0.51–0.77	38	0.50	20	0.38–0.42	30
(10–12]	0.48	26	0.57–0.69	40	0.60–0.70	33	0.50–0.60	35
(12–14]	0.52–0.63	38 max.73	0.58–0.78	69 max.75	0.72–0.75	65 max.74	0.72–0.74	60
(14–16]	0.55–0.64	45	0.66–0.96	54	1.05	106	–	–
(16–18]	0.56–0.71	56	0.74–1.10	95	1.14	nd	–	–
(18–20]	0.71–0.86	nd	0.94–1.09	nd	1.28	nd	–	–
(20–22)	–	–	1.00–1.20	nd	–	–	–	–

nd – no accurate data due to high sea level before or during ongoing surges. Source: based on data from: IMGW–PIB: https://www.imgw.pl/, Polish Maritime Office, own investigation.

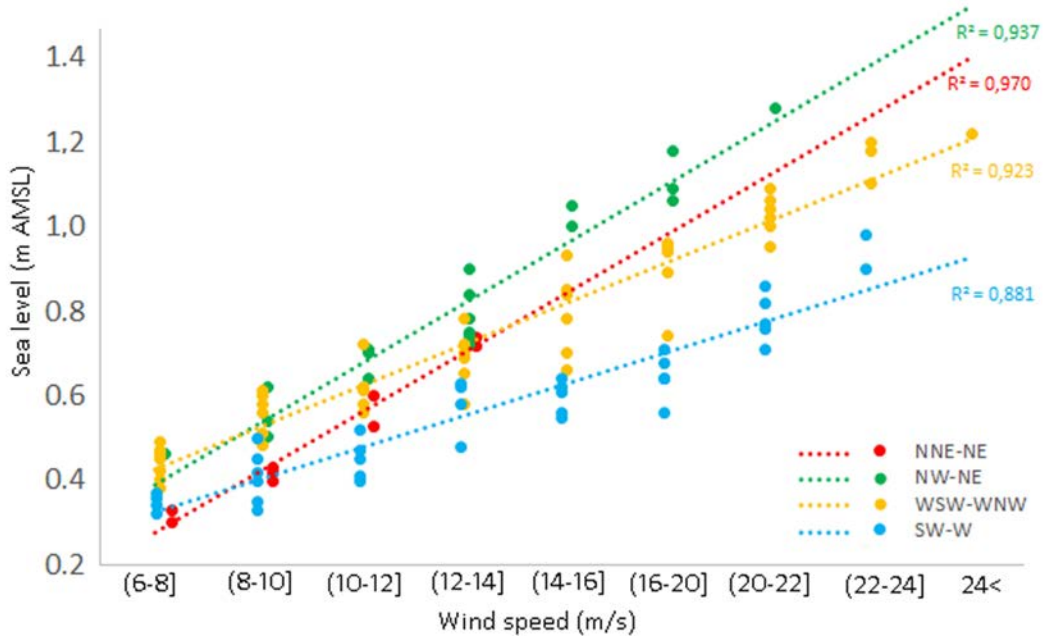

Fig. 9. Relation of maximum sea level to wind speed and direction. Data source of own research.

20 (Ida) by 20 cm, February 19 (Antonia) by 60 cm (Fig. 8). West winds dominated during smaller storm surges in November and February, which resulted in a sea level rise to maximum 0.6–0.7 m AMSL. With a wind from the W direction, the sea level rise was small, but evident at the central coast with western exposure as during the storm Volker (Darłowo, Ustka gauge station). During the long-lasting storm Volker (November 18–21) the wind blew at the coast for 60–80% of time from the W direction (Fig. 6). This one with so strong wind caused a sea level to rise only by 0.4 m AMSL at a speed of 12 m/s in Świnoujście, but up to 0.6 m AMSL at the central coast at a speed up to 16 m/s in Ustka, that is exposed to wind from the west.

Regardless of the initial sea level at the coast, its rise was clearly visible upon a wind direction change to NW (Fig. 9, Table 3). A high-speed wind changing its direction to NW, N (or NE) resulted in a higher water surge of up to 0.9 and 1.1 m AMSL along the entire coastline (Ida, Gerhild, Nadine, Antonia). During several storms, the water level rise was delayed towards the east, which was attributable to a gradual inflow of air masses and a shift of high wind from west to east. By comparing the exact time of the wind direction and speed change with a sea level rise, certain dependencies were determined. An increased wind speed or a shift of its direction to onshore resulted in a sea level rise at the Polish coast. A change in the sea level and a rise of waves usually ensued three to six hours after a wind direction change (Fig. 8). Moreover, if a wind speed increase was observed after a decrease, the effect was again a sea surge: Rudolf I and II on 4–8th November 2021, Ida I and II on 20–22nd January 2022, Marie and Nadine on 27–31st January 2022 and further storms in February 2022.

Moreover, during the ongoing surge, a similar course of changes in direction and speed and their impact on development of smaller and larger surges were observed. These relations were named phases of surge (explained above). In the first phase of each typical surge, the wind blew from SW or W (T0). At this time, the sea level at the Polish coast did not rise, but rather dropped by 0.2 to 0.4 m below the mean value or even more (Fig. 8). In the next phase, upon the wind direction change to W, the water surge increased at the western coast between Kołobrzeg and Darłowo and later on, at the central coast in Ustka and Łeba (T1). The rise amplitude was 30–90 cm depending on the wind speed and direction (Table 3). In the next phase (T2), the wind changed its direction from NNW to NW (or NE), causing the largest water elevation and waves at the western coast and gradually, at the central and eastern coast. At this time, the low-pressure system was moving towards the east, leading to a wind speed increase in the eastern part of the Polish coast between Ustka and Władysławowo (Figs 4, 5, phases). This resulted in a sea level rise in this coast section, which was recorded at water gauges between Ustka and Władysławowo. The wind blowing for a long time from the west caused the water to surge gradually from west to east. The delay in a sea level rise between the west and east coast was one to four hours. With wind and waves from the W to NW direction, a high water level emerged first at the western coast between Świnoujście and Kołobrzeg, then at the central (Darłowo-Ustka-Łeba) and the eastern coast (Władysławowo), and then in the Gulf of Gdańsk (Gdańsk, where it was usually lower by a few cm). During several surges, smaller sea level differences were observed at the eastern coast (Władysławowo, WA). This was an effect of a significant and long-lasting water surge in the eastern part due to frequent SW-NW winds. In the western part of the coast, after each sea level drop of 30–50 cm a surge was observed with ongoing SW wind.

Regularly, the end of one surge was the beginning of another (Fig. 3). Therefore, a high wind (8–10 m/s) blew at the beginning and end of a surge from the SW direction. Brief sea level drops of 20–35 cm occurred at a high WSW wind. For example, the SW wind blowing after the small storm of January 14–15 and before the storm Gerhild (January 17–19, 2022) lowered the sea level (January 16). Right after the end of the storm Gerhild and prior to the storm Ida (January 20–21), the SW wind lowered the sea level again (Fig. 7). A similar situation occurred after the storm Marie (January 27–29) followed by Nadine (January 29–31). Between them, the sea level at the western coast fell significantly at the SW wind. After Nadine, another storm from the SW direction developed (Philine, February 1–2). Such situation occurred repeatedly during the subsequent surges from February 5 to 28 (Fig. 3, Table 1).

During one storm, a different prevailing wind direction had an impact on the varying/different sea level rise along the coastline. During the storm Rudolf with a WSW to NNW wind with a speed of 11–13 m/s, the surge reached 0.7 m AMSL at the western coast (SW, KG). On the other hand, a brief episode of high wind from NNW with a speed of up to 17 m/s caused the water level rise to 0.9 m AMSL within four hours. At this time, a wind of up to 12 m/s from the W direction prevailed at the eastern coast, leading only to 0.5 m AMSL (WA) (Figs 6, 8B). On November 4, the short episode with strong NNE wind on the west coast caused fast sea level growth there (in Świnoujście, SW) by another 35 cm, up to 0.93 m AMSL.

During the storm Gerhild (January 17–19), the western coast was dominated by a W to NW wind (80% of the time) with a speed of up to 17 m/s, causing the water surge by 90 cm, i.e. to 0.85 m (SW). In Kołobrzeg and Ustka, W and NW winds dominated (70% of the time), causing the water growth along coast by ca. 80 cm to 0.84–0.9 m AMSL (Fig. 8C). At that time, a long-lasting high wind blowing from W with a speed of up to 17 m/s caused a water surge to 1.04 m AMSL at the shore exposed to the west (Darłowo). At the eastern coast, a high wind blew for 30% of the time from W and, for 15% of time, from the NW direction. A shorter NW wind period caused the sea level rise in Władysławowo only by 60 cm, i.e. from 510 to 574 cm (ca. 0.74 m AMSL).

During the strong storm surge Nadine, the NW wind blew at the western coast for 20% and at the east coast for up to 40% of time. For this reason, the maximum surge on the western coast reached only 0.99 m AMSL in Świnoujście and 1.28 m in Władysławowo (Figs 7, 9). During this storm, the actual sea level rise was greater at the western coast and amounted to 134 cm in Świnoujście and only to 109 cm in Władysławowo. At the western coast, a sea level was lower before the Nadine surge due to its larger drop after the Marie surge by 20–30 cm. This resulted from a SW wind with a speed of 10–12 m/s, which was a beginning of the wind action due to the ongoing low pressure named Nadine.

The main statement is that during the assessed surges, changes of the wind speed and direction had a significant impact on the sea level elevation, its diversity in time and along the coast.

Impact of the sea level on the run-up elevation vs beach elevation

During a storm, the sea level elevation has an impact on the water run-up range on the beach (shore). Based on observations in the autumn/winter 2021–2022 and in the preceding years, a relation was found between a sea level and a maximum water run-up to the shore. The run-up is a sum of sea level and wind-inducted waves that makes water uprush onto the shore. This parameter is giving the potential threat of the flooding when a sea level is known.

The maximum uprush can be observed during a storm surge and is always higher than the sea level observed at the gauge station, which is related to rushing waves from the open sea. On the shore (beach) the structures of sea accumulation can be defined as washover fans, organic or artificial debris found on the upper beach, low-lying land or between dune ridges and on banks of coastal river mouths. After the surge, it can be recognised, based on the different material than local, left by the highest wave run-up.

Figure 10 presents a relation of selected storm surge sea elevation to observed run-up compared to an average of previous studies. The surges, with water elevation up to 0.6 m AMSL did not threaten the shore due to low run-up, not exceeding 1 m. Usually, beaches of the southern Baltic coast are higher than 1.5 m, but excluding erosive coast sections with a permanent low-lying beach. During surges with a sea level of 0.6 to 0.8 m AMSL, the water run-up reached in average an elevation of 1.0–1.6 m AMSL. In the 2021–2022 storm season, the most frequent surge run-up reached 1 to 2 m AMSL. This means that water was threatening the shore up to 2.0 m AMSL. During surges of up to 1–1.1 m, the run-up reached 2.5 m AMSL (Gerhild, Ida). While the surge Nadine with the highest sea level of 1.28 m, the run-up reached 3.1–3.4 m at the eastern coast.

Figure 11 presents different values of the run-up elevation and range on the beach during several sea levels on the Kashubian Sandbar (Dębki village, km 147 of the coast kilometrage classification, Fig. 1C). The photographs show a large difference in the uprush elevation during surges with a sea level (SL) ranging from 540 to 607 cm AMSL (0.4–1.07 m). At the sea level of 0.7 m AMSL, the run-up reached a middle part of the beach. At a sea level of 1.07 m AMSL, the run-up reached the dune toe. The elevation of this beach during the observation period was 2.4 m AMSL. In the adjacent shore sections with a beach up to 1.2 m AMSL, the dunes were eroded already at a sea level of 0.7 m AMSL.

Storm height and beach elevation as factors of the dune erosion

The extent of dune erosion during the storms in the autumn/winter 2021–2022 depended on the initial shore morphology (prior to the storm) and the hydro-meteorological parameters of the surges. Depending on the beach elevation, the same surge caused erosion of just the beach or also the dune. Moreover, the subsequent surges, caused

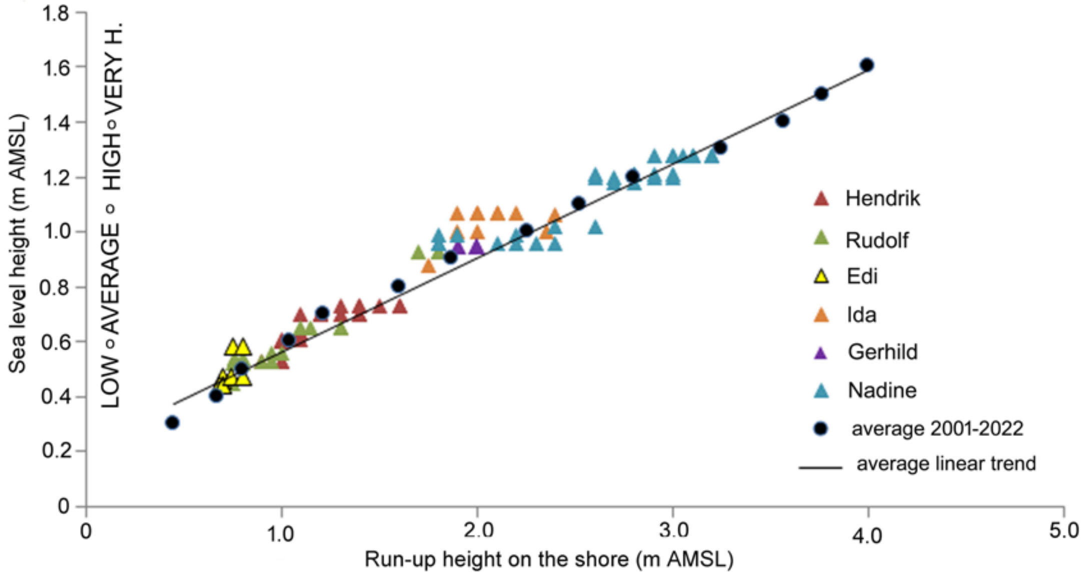

Fig. 10. Relation of the sea level (HSL) to the measured max. run-up (HSLr) to the shore during selected surges against the average relation trend. Data source of own graph: Maritime Office, field investigation.

Fig. 11. Short-term sea level change vs run-up range on the beach (photos from the camera: https://nadmorski24.pl/kamery/). A – situation after surge Gerhild with max. SL = 575 cm. B – a situation during surge Ida II, after Ida I with max. SL = 607 cm.

a cumulative increase in the dune erosion (Fig. 12). Firstly smaller surge lowered the entire beach and the next one, usually caused a dune toe to retreat.

Low storms in the autumn 2021 did not cause any erosion in sections with beaches elevated over 1.5 m (surge Hendrik or Rudolf). During these surges, mainly the beaches were washed out and cut off all embryo dunes (Fig. 12, October). Only in erosion-prone shore sections with a lower beach, the dunes were already eroded during surges with a sea level 0.65 to 0.75 m AMSL as Hendrik or Rudolf (Fig. 12, 13). At this sea level, the uprush water flooded the beaches up to of 1.8 m AMSL, causing all small dune structures to cut off and lowering the beach (Fig. 13, October 2021). During the storm surges with a sea level of 0.9 m < HSL < 1.0 m (Ida, Gerhild), dunes were eroded in the shore sections with beach elevated up to 2.0 m AMSL. The greatest dune toe retreat took place during the storm Nadine with a sea level HSL > 1.1 m. At that sea level, almost all shore sections with different shore dynamics and exposure were eroded. The erosion was greater at the eastern coast, where the sea level reached 1.28 m AMSL (Władysławowo, WA). Figures 12–14 show examples of dune and beach erosion mainly after the Nadine storm surge. The whole beach with embro dune forms tended to be eroded and a large frontal dune retreat was observed when the beach was significantly lower than run-up (Fig. 13). On the other hand, when run-up was lower as at the western coast, after lowering the beach only the frontal dune slightly retreated (Fig. 14).

The dune erosion was greater in the shore sections with W-NW exposure than in the ones with N or NE exposure. For this reason, the mean dune erosion at shores exposed to the western direction was 3.6 m in the Koszalin Bay and the Ustka Bay (central coast) or 3.1 m in the eastern part of the Vistula Spit. Greater dune erosion was found at the eastern coast between Łeba and Władysławowo, i.e. up to 3.5–4.3 m. In this section, the maximum sea level reached 1–1.28 m AMSL. The wind kept blowing longer from NW direction and a large portion of the measured sections had a beach well below 1.5 m (much lower than the uprush at this sea level).

The mean dune base retreat amounted to approx. 1 m at surges of up to 0.7 m AMSL. At that sea level, a beach was usually lowered (Fig. 12). The higher sea level and run-up

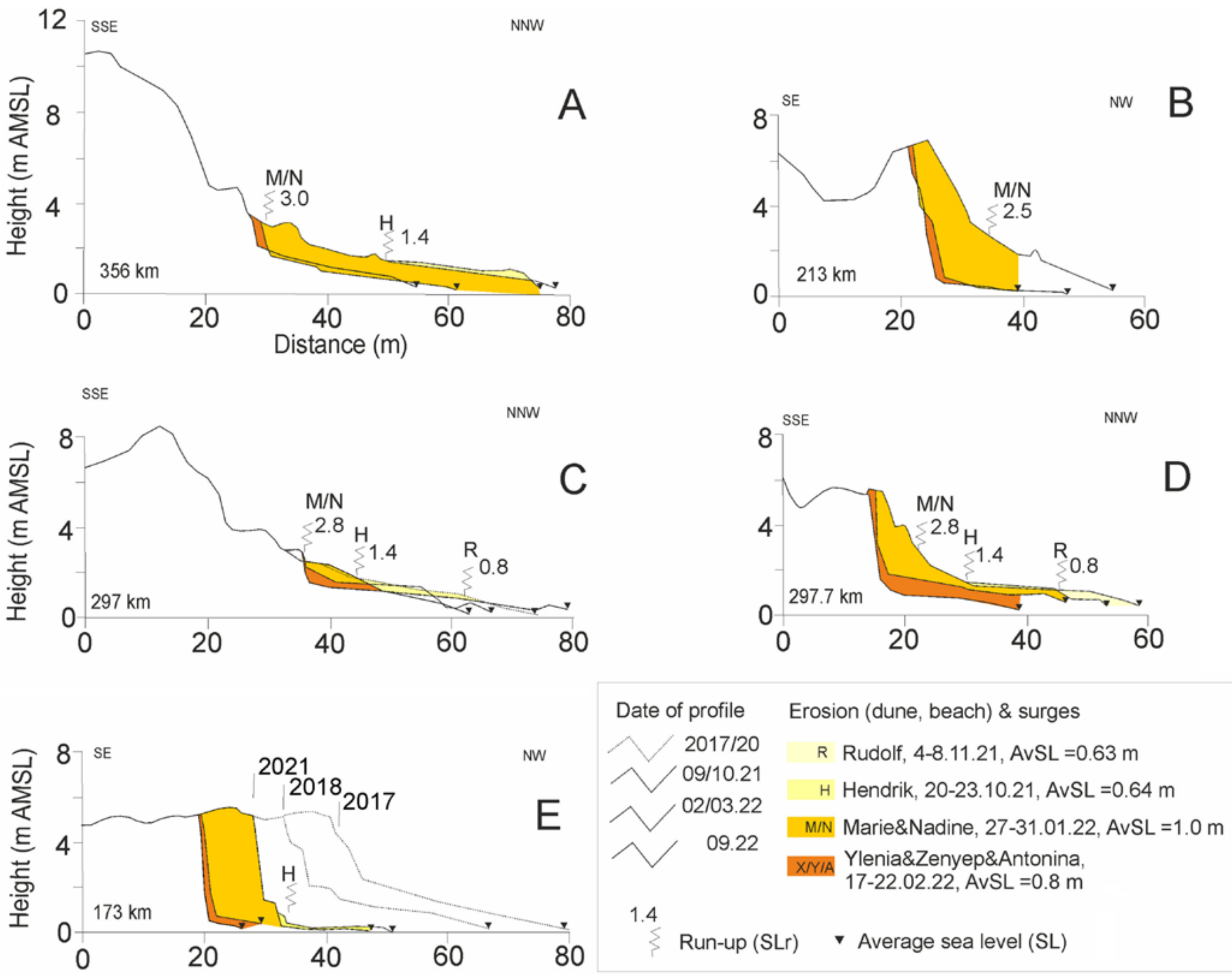

Fig. 12. Dune and beach erosion by 2021–2022 selected surges on the coast with different shapes and orientations (marked run-up during surges and volume of material erosion in colour). The previous smaller surges lowered the beach, then a higher easily eroded dune. A – high beach eroded by Marie&Nadine in Jan 2022, then by surges in mid of February. B – on the low beach large dune retreat, exposed to NW surges. C – higher beach, lowered in its lower part by smaller surges Hendrik and Rudolf and then erosion of the upper beach by higher surges Nadine and others. D – low beach was eroded by small surges, then eroded dune by higher ones, and significantly lowered beach after the next surges. E – retreat of the dune on the coast with a very low and narrow beach.

the larger erosion was observed (Fig. 15, Table 4). A limited dune erosion during the smaller surges (Hendrik and Rudolf) with a sea level of up to 0.8 m AMSL was observed where the beach was lower than the run-up. During the surges with a sea level of 0.9 to 1.0 m AMSL (Gerhild, Ida, Nadine at the western coast) the mean erosion was 1.5 to 2.5 m. There, the maximum dune erosion reached 6–8 m, which was the case in sections with a low beach. During surges with HSL >1.2 m AMSL, the mean erosion increased significantly up to 3 to 4 m at the central and eastern coast. The highest dune erosion values were 6–13 m (Fig. 15). They were observed in sections with low beaches and a shore exposure towards storms from the NW direction. During the largest storm in that period, Nadine (January 29–31), the beaches were lowered by 1–2 m. This led to the erosion of all embryonic dunes, entire foredune ridges or high hind dunes on shores with beach Hbe <2.8 m AMSL (Table 4). As a consequence of the storm, in sections with low beaches the foredunes were eroded completely or by half (Fig. 13B, C). The erosion was greater at the western shores of the north-protruding capes, where a beach height is usually low. There, erosion tendencies prevail due to coastline orientation against the common W-NW storm surges. Summarizing, the larger dune toe retreat was observed at the coast with low-lying beach, with elevation lower than 1 m, that was comparable with the run-up of an average surge.

DISCUSSION

Considering the conditions of climate change and the impact of storms at the southern Baltic Sea coast it must be underlined that the analysed 2021–2022 autumn/winter season was among the several unique ones in the 21st century. There was observed average strongest wind speed than usual, more strong winds from SW to NW, related to

Fig. 13. Comparison of coast retreat after smaller surges in Autumn 2021 and big Nadine in January 2022 on the West coast. Photos from 10.2021 show the coast after Hendrik & Rudolf surges in October 2021. A – lowered beach and then retreat of 3–5 m of a dune toe on the Rega River Sandbar, km 358, a – kilometrage sign. B – lowered beach with heavy minerals and then dune retreat of 6–8 m on the promontory on the Resko Lake Sandbar, km 349. C – embryo dune erosion after October surges, then dune retreat 2–3 m after Nadine surge, Jamno Lake Sandbar, km 290.

the larger number of passage low-pressure systems, higher temperature, more smaller surges, and higher seasonal average sea level and its big changes in a short time.

The passage of a low over the Baltic Sea in winter results in a storm surge (Trzeciak, 2001; Andersson, 2002; Miętus *et al*., 2004; Sztobryn *et al*., 2005; Kelpšaite and Dailidiené, 2011; Stont *et al*., 2012; Jaagus and Suursaar, 2013, Surkova *et al*., 2015; Girjatowicz *et al*., 2016; Kowalewska-Kalkowska, 2018, 2021, and others). The high atmospheric pressure over Scandinavia and a depression shifting south-eastwards is related with appearing strong northerly winds that cause surges at the southern Baltic coast (Sztobryn *et al*., 2005). The observed lows in autumn/winter 2021–2022 were shifted mainly from west to east over the Scandinavian Peninsula causing SW to WNW winds rather than NW ones.

A climate change observed in the Baltic Sea area results in a higher number of lows to pass and in an increasing pro-

Fig. 14. Examples of average dune retreat after Nadine surge in January 2022 on the East coast. A – the erosion of embryo dune, small foredune and 3–6 m retreat of a high dune, Vistula Sandbar, km 30. B – 6 m retreat of foredune on the Kashubian Sandbar, km 172, visible retreat in place of geological drilling for the future location of the nuclear power plant. C – washed out foredune of 8–10 m width on the Łebsko Lake Sandbar, km 206, a – the same dune peak.

portion of winds from the southwestern sector (Leckebusch and Ulbrich 2004; Jaagus and Suursaar, 2013; Hünicke *et al*., 2015; Girjatowicz *et al*., 2016). There was also an observed increase of storminess over the Baltic Sea in recent years (Surkova *et al.,* 2015). In the studied period, air temperature was higher by almost 5°C than the long-term mean values. The air temperature rise observed in autumn and winter results from the inflow of warmer air masses from over the Atlantic Ocean with the dominant southwest circulation (Trzeciak, 2001; Andersson, 2002; Miętus *et al*., 2004). These phenomena are linked to positive values of the NAO index (Andersson, 2002; Richter *et al*., 2007; Hünicke and Zorita, 2008; Girjatowicz *et al*., 2016; MacPherson *et al*., 2019). During a warmer winter more cyclones are observed, responsible for fast pressure changes and an increased wind speed (Sztorbyn *et al.,* 2005).

In the assessed autumn-winter period, winds with medium speed of 7.2–8.1 m/s prevailed, i.e. stronger by 3–4 m/s than usual (as presented by Trzeciak, 2001; Miętus *et al*., 2004). The often high-speed SW to NW wind resulted from the passage of numerous low-pressure systems over the Baltic Sea (85). They caused more than 35 storm surges. The sea level ranged from 0.6 to 1.3 m AMSL. During the greatest surges, the average wind speed ex-

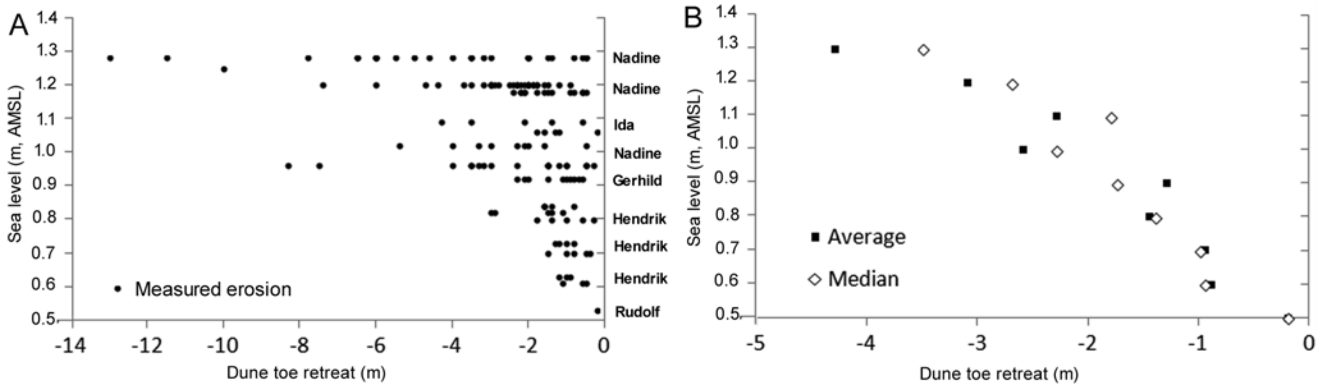

Fig. 15. Relationships between sea level and dune erosion (toe retreat) during 2021–2022 storm surges. A – single site erosion during surges. B – mean dune erosion for a given sea level. Data source of own graph: Maritime Office, field investigation.

ceeded 12–14 m/s. In the course of storm surges, high winds from SW to NW direction prevailed, with a speed of 9–12 m/s on daily average and 14–22 m/s at the maximum.

A seasonal number of the storm surges with the highest sea level at the southern Baltic Sea coast has not changed in the recent years and they occur every few years (Samuelsson and Stigebrandt 1996; Sztobryn *et al*., 2005; Hünicke and Zorita, 2008; Gräwe and Burchard, 2012; Weisse and Widemann, 2017; Wolski and Wisniewski, 2020; Kowalewska-Kalkowska, 2018, and others). In the seasons from 1993/94 to 2018/19, storm surges at the western Polish coast were characterized by a high irregularity with a bigger number in 2001–2002, 2006–2007, 2011–2012 or 2018–2019 (Kowalewska-Kalkowska, 2021), all related to positive NAO years. During 2021–2022 stormy season was the highest number of storm surges in a single year observed in the southern Baltic Sea shore in the 21st century. The so far large number of storm surges in a single season was between 6 and 12 and even 16 surges during the winter season of 2019–2020, as confirmed by other research (Kowalewska-Kalkowska, 2018, 2021).

There are 3 different trajectories of low-pressure systems (cyclones) induced by westerly winds over the Baltic Sea area (Surkova *et al.,* 2015) passing: (a) far north over the Norwegian Sea, (b) through the Scandinavian Peninsula, and (c) directly over the Baltic Sea. In the observed period more lows passed the northern Scandinavia and the Bothnia Bay toward the East (Hendrik, Queena and more), which caused low or no surges at the southern Baltic coast. The lows shifted from Iceland through Scandinavia, the Baltic Sea toward the south-east and east, caused the largest surges (Ida, Marie, Nadine, Antonia). A sea level rose more significantly when the wind direction changed onshore from SW to NW. Some small to average surges developed with lows shifting through the southern part of Scandinavia and over the southern Baltic coast, from west to east (Tim, Volker, Tanylak). A climate warming is accompanied by an increase of lower surges during a single season, induced by the passage of lows further north, causing offshore wind over the southern Baltic.

Nevertheless, the growing average annual water level of the Baltic Sea and the Atlantic Ocean (Samuelsson and Stigebrandt, 1996; Cyberski and Wróblewski, 1999; Johansson *et al*., 2001; Dailidiené *et al*., 2006; Richter *et al*., 2007; Gräwe and Burchard, 2012) and increasing number of lower/smaller surges are creating a bigger threat for coast safety along the Baltic Sea. This was underlined in studies in the Baltic countries (Kont *et al*., 2008; Koltsova and

Table 4. Relation of sea level (SL) and run-up (SLr) to beach height (Hbe) and average dune erosion during season 2021–2022.

Se level, SL (m AMSL)	Average run-up, SLr (m AMSL)	Beach height threshold (m)	Average erosion (m)	Erosion, median (m)	Max. erosion (m)	Percentile 5	Percentile 25	Standard deviation (d)
0.4	0.66	<0.70	0	0	0	0	0	0
0.5	0.80	<0.80	-0.2	-0.2	-0.2	nn	nn	nn
0.6	1.04	<1.00	-0.6	-0.7	-1.1	-0.2	-1.0	0.30
0.7	1.22	<1.20	-0.9	-1.0	-1.5	-0.4	-1.2	0.36
0.8	1.52	<1.50	-1.5	-1.4	-3.0	-0.8	-1.6	0.76
0.9	1.87	<1.90	-1.4	-2.0	-2.3	-0.6	-2.1	0.67
1.0	2.26	<2.20	-2.6	-2.3	-8.3	-0.5	-3.3	1.55
1.1	2.53	<2.50	-2.8	-2.5	-12.5	-1.2	-3.9	1.33
1.2	2.80	<2.80	-3.1	-2.7	-7.4	-0.6*	-2.9	1.35
1.3	3.25	<3.20	-4.3	-3.5	-13.0	-0.5*	-6.0	3.24

*– value lower because a larger share of low erosion rate on the accumulative coast with high beach; nn – no data, too small data set. Source: based on own data.

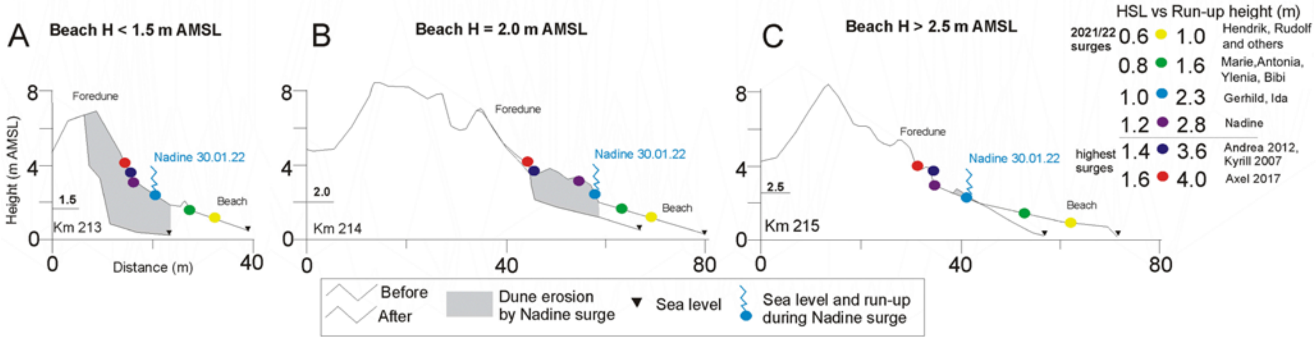

Fig. 16. Examples of coast dynamics with different beach heights on the Gardno Lake Sandbar (213–215 km) due to surge Nadine (HSL = 1.2 m) with a relation of different sea level heights (HSL) to the max. run-up on the shore. A – erosive coast with a beach lower than 1.5 m is strongly eroded by storm with HSL = 1.2 m and may be eroded by each lower surge with run-up higher than the beach. B – coast with average beach height H = 2.0 m has lowered beach and small erosion of dune toe and embryo dunes, but will be easily eroded by all higher surges with HSL >1.2 m. C – accumulative coast with a wide and higher than 2.5 m beach only has eroded part of the beach, but higher surges than HSL = 1.2 m may erode dune.

Belakova, 2009; Kelpšaite and Dailidiené, 2011; Ryabchuk *et al*., 2011; Bobykina and Stont, 2015, and others). Nowadays, the greatest erosion at the southern Baltic shore is observed during single large storm surges (Furmańczyk *et al*., 2011; Łabuz and Kowalewska-Kalkowska, 2011; Łabuz, 2014, 2022, 2023). Usually, the impact of smaller surges on the shore is not noticeable. However, several successive smaller surges are significant for the shore retreat process in erosion-prone sections.

On the other hand, successive surges, smaller to medium or larger, cause the extent of erosion to accumulate; to overlap single-coast retreat values. This was observed several times during 37 storm surges in 2021–2022 storm season. During warm winters, a change of the SW wind, into W and NW ones depends on the pace of the low-pressure system passage over the coast (Andersson, 2002; Leckebusch and Ulbrich, 2004; Miętus *et al*., 2004; Surkova *et al*., 2015). A change in the wind direction and speed during the passage of a low resulted in a varying sea level along the shore. During a great number of the observed lows of 2021–2022, SW to W winds prevailed and the sea level was not high. Many times, it was dropped 0.4–0.6 m below the average level. At the southern Baltic Sea coast, the sea level lowering is caused by offshore winds (Trzeciak, 2001; Miętus et al., 2004). The greatest sea level rise and the greatest storms emerge at a high NW to NE wind (Trzeciak, 2001; Miętus *et al*., 2004; Sztobryn *et al*., 2005; Wolski *et al*., 2014; Wolski and Wisniewski, 2020).

The run-up is an indicator of the water surge height during a storm (Nielsen and Hanslow, 1991). The run-up elevation depends on the sea level and the height of the wind waves. These parameters affect the extent of the beach and dune erosion. Additionally, the run-up elevation on the beach resulted from the highest sea level (Łabuz, 2014, 2022). The beach elevation prior to the storm is an indicator of a potential erosion hazard (Table 4).

At a sea level of up to 0.6 m AMSL, mostly erosion-prone shores were destroyed, with beaches being lower than the run-up Hbe < HSLr = 1.6 m (Fig. 16). During surges with a sea level of up to 1 m (Gerhild, Ida), the water flow onto the beaches reached 2.0–2.3 m. As a consequence, the erosion affected most beaches of the Polish Baltic Sea coast. Moreover, embryonic dunes were destroyed and the main dunes were eroded. At a sea level HSL ≤1.28 m AMSL, the dune erosion covered the longest stretches of the shore, including in accumulative sections. There, at an uprush of 2.8–3.4 m AMSL, the dune erosion was larger, dependent on the beach elevation.

In the 20th and 21st centuries the highest sea level, the average on the Polish coast exceeded 1.36 m AMSL in January 2017 during the Axel; with a total maximum 1.65 m AMSL at the central coast and run-up 4 m AMSL (gauge station DA, Figs 1, 16) and with average erosion 5.1 m and maximum 15–25 m (Łabuz 2023). The maximum dune erosion values at other Baltic Sea shores reached 6–21 m during the greatest storm surges (Eberhards *et al.,* 2006; Koltsova and Belakova, 2009; Kelpšaite and Dailidienė, 2011; Bobykina and Stont, 2015; Łabuz, 2015). During the surges in 2021–2022 at the Polish coast, the erosion was greater in places with beaches lower than the run-up. The average dune erosion during the Nadine surge in January 2022 reached 3.0–4.5 m and the maximum was 8–13 m. The greatest erosion took place with a sea level of 1.28 m AMSL, at the eastern coast. Moreover, the dune retreat was greater in sections exposed to the direction of the most frequent and high W-NW wind, causing the highest sea level rise: the Koszalin Bay, the Ustka Bay and the eastern part of the Vistula Sandbar. Due to the shore exposure, the erosion affected to a larger extent dunes on the western side of small capes forming the open sea coastline (the East coast between towns Rowy and Władysławowo and in a certain location at the western coast).

CONCLUSIONS

The autumn-winter season 2021–2022 at the Polish Baltic coast witnessed 37 surges of different sea level and wind speed. It was the largest number of surges in a single season in the 21st century. Each surge was produced by

SW-W to NW winds (among them only 4 from the NNE direction). The largest surge from the end of January, named the Nadine caused the biggest dune erosion. Subsequent minor surges that occurred before the Nadine have caused small erosion at the erosive part of the coast. These caused a lowering of beaches to 1.0–1.2 m AMSL. The highest surges including Gerhild, Ida, Antonia and Nadine caused a dune retreat. The largest surge Nadine caused a retreat of a dune toe to 4.5 m in average.

Meteorological and hydrological conditions during each major storm were ascertained. A numerical relationship between the wind speed, a wind direction and a sea level elevation was ascertained. During an average surge with prevailing offshore wind direction, a large rise in the sea level and its maximum elevation were noticeable. Frequent lows with an SW-W wind caused small surges and, at an SW wind, a sea level lowering at the southern Baltic Sea shore. NW winds caused a greater water surge at the southern Baltic Sea coast than SW-W winds. The wind speed impacts the sea level changes along the water gauges with a delay of one to four hours. During the assessed surges, the wind speed and changes in the wind direction had a significant impact on the sea level elevation.

A numerical relation between the sea level and its onshore flow was ascertained. A dependence of the observed erosion on the beach elevation was ascertained. An increase in dune erosion was observed on shores with beaches having a lower elevation than the run-up (uprush). The lower the beach, the greater the dune erosion, even during storms with a lower sea level. Medium storms with a sea level of 0.6 to 0.8 m AMSL caused erosion if the beaches were lower than 1.5 m. Large storms up to 1.2 m AMSL caused dune erosion in sections, where the beach elevation did not exceed 2.8 m ASML. Larger surges with HSL = 1.2 m AMSL exceeded the beach elevation in all accumulative sections. They cause erosion of dunes along the entire coast.

Lower surges occurring in autumn 2021 led only to a lowering of the beaches. A dune erosion was already observed at a sea level of 0.8 m above the average. It occurred where the beach elevation was 1.2–1.5 m AMSL. Depending on the beach elevation, the same surges caused erosion of just the beach or also the dunes. The beach elevation is an important morphological parameter when assessing the sea level and coastal erosion during a storm.

The extent of the coastal erosion (over the beach) depends on the sea level and the onshore flow at a given beach elevation. Overlapping, multiple storms cause greater erosion in a given period. The erosion was high due to an earlier backwash of beaches by lower storms, which emerged at the end of 2021 and at the beginning of January 2022.

Acknowledgement

Here, in memory of our colleague, I dedicate the work to Professor Halina Kowalewska-Kalkowska. She, for many years, has studied the conditions for development of storm surges in the southern Baltic Sea. She passed away in 2022.

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