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South Baltic rip currents detected by a field survey

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Abstract. The paper presents results of experimental investigations of currents in the nearshore region of the south Baltic Sea. The analysis is based on the field data collected near Lubiatowo (Poland) using the measuring equipment which was simultaneously operated both by the Polish and Russian research teams. The venture was aimed at detection of rip currents that are rare and insufficiently explored phenomena in the south Baltic coastal zone. The data include wind velocity and direction, deep-water wave buoy records and currents surveyed by means of drifters. The measurements were carried out in the area whose hydrodynamics, lithodynamics and morphodynamics are typical of the south Baltic sandy coast. It appears that the nearshore water flows are mostly represented by longshore wave-driven currents with mean velocities of 0.22–0.53 m/s, and the maximum velocity of 1.32 m/s. Water circulation patterns resembling rip currents with velocities of up to 0.34 m/s were identified only on one day, when specific wave conditions occurred at the study site. Contrary to strong longshore currents generated by storm waves, rip currents occur under mild or moderate wave conditions, when many beach users are willing to swim in nearshore waters. The present findings can therefore be useful for the improvement of swimmers' safety in the south Baltic Sea regions.

Keywords: *Baltic Sea; coastal currents; drifters; waves; wind*

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INTRODUCTION

Water flows in the coastal zone are complex processes generated by a number of interacting phenomena varying in time and space. In non-tidal regions such as the Baltic Sea, wind is the major driving force of coastal hydrodynamics. Currents can be induced either directly by wind or by waves. Wave transformation, particularly wave energy dissipation due to breaking, is a major cause of wave-driven currents. Parameters of wind- and wave-driven currents strongly depend on instantaneous local conditions: wind speed and direction, wave characteristics (height, period and direction of propagation), and morphology of the coastal bottom (Ostrowski *et al*. 2018).

The nearshore flow patterns can be dominated by longshore or cross-shore currents. Rip currents are specific seaward-directed cross-shore currents. The state-of-the-art and the theoretical model of longshore and cross-shore currents in a multi-bar coastal zone (for multiple wave breaking), as well as comparisons of model results with experimental data, are given by Szmytkiewicz (2002).

The longshore current, generated by the waves that obliquely approach the shore and break in the surf zone, is the dominant and most visible nearshore phenomenon. Part of the energy (and momentum) of breaking waves is converted to a steady flow. The longshore current is in general considerably stronger than the cross-shore current (conventionally named return flow or undertow). In severe storm conditions in the south Baltic surf zone, the longshore current velocity can reach 1.5 m/s, while the highest velocity of the return flow in the same extreme conditions attains 0.5 m/s (Ostrowski *et al*. 2016).

Based on the field data collected near Lubiatowo (south Baltic) and theoretical modelling with the commercial software MIKE 21, Sokolov and Chubarenko (2012) found the wind-induced component of currents in the surf zone to be quite significant under certain conditions. It appears that if wind blows parallel to the shoreline, its contribution to the generation of the longshore current can reach almost 50%, and more than 20% if it blows at an angle of 45° to the shoreline. In all cases, however, the wave-driven longshore current is the predominant flow in the surf zone.

The influence of the Coriolis effect may be neglected in coastal areas of the Baltic Sea. A wind-driven current occurring in shallow basins has almost the same direction in the water column as the wind blowing over the water surface. As the surface Ekman layer and the bottom Ekman layer overlap, the development of the Ekman spiral is hindered, and the wind-induced flow takes place in the wind direction (Krauss 2001; Trzeciak 2000; Valle-Levinson 2016). The present paper deals with currents occurring temporarily and locally. Hence, the possible wind-driven current velocity is vertically unidirectional, compatible with the wind direction.

Rip currents are a sub-type of compensative flows. Their character is similar to that of return currents, but they are not distributed uniformly along the sea shore. Rip currents occur locally in the form of narrow streams of water directed offshore, with almost uniform vertical velocity profile. The scheme of the typical situation, in which rip currents are generated, is shown in Fig. 1.

As indicated in Fig. 1, rip currents appear at locations of the convergence of longshore currents (feeding currents), which depend mainly on the configuration of the shoreline, and the nearshore bottom. Most

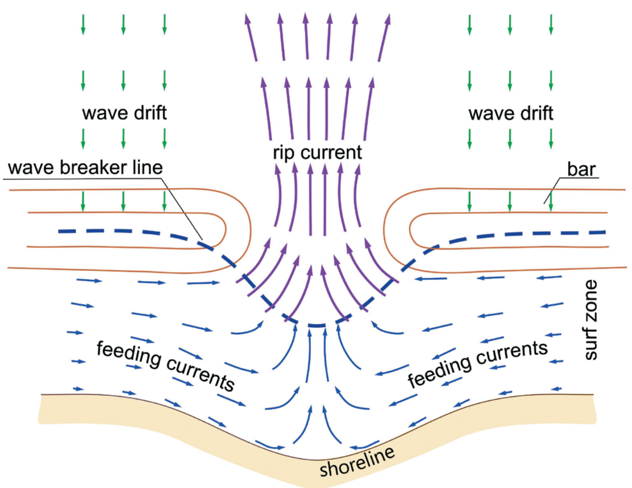

Fig. 1 Scheme of rip current generation

often, such a convergence can take place approximately in the middle of the shoreline concavity and in the vicinity of the gap between underwater bars. A perpendicular wave approach to the shore creates favourable conditions for the occurrence of distinct rip currents. When waves approach the shore obliquely, these currents are insignificant, and cause just meandering of the longshore water flow.

Although complicated mechanisms generating rip currents make their theoretical description and modelling extremely difficult, publications on this topic (see review by Castelle *et al*. 2016) are numerous. They are mostly devoted to steeply inclined nearshore zones and none of them deals with the Baltic Sea, particularly the mildly sloped south Baltic sandy coast. The rapidly changing location of rip currents, which prevents their identification by means of permanently installed current meters, makes field investigations troublesome. Employment of radar techniques for flow measurements in the surf zone also proves difficult, because the sea surface is disturbed by breaking waves. One of the few successful field surveys of rip currents was carried out using a marine radar by Haller *et al*. (2014).

There are very few documented investigations of rip currents in the south Baltic coastal zone. The first investigations of these currents in Poland were carried out by Rudowski (1970), who identified traces of rip currents at many locations of the Polish coast in the layout and shapes of small bed forms. Similarly, Furmańczyk (1994) interpreted gaps in the nearshore bars of the Hel Peninsula, visible in aerial photographs, as effects of rip currents. Finally, in historical aerial photos, Furmańczyk and Szakowski (2001) identified traces of rip currents as discontinuities in the first nearshore bar. In the photographs taken under storm conditions, they also found seaward-directed streams of turbid water, resembling rip currents.

Considerable progress in this field was made by Schönhofer (2014), who managed to identify nearshore water flows resembling rip currents and to determine their velocities, as well as the offshore range. The hypothesis, which was formulated based on the data obtained from the field surveys in Lubiatowo using GPS-GSM drifters coupled with theoretical considerations, suggests that such circulation patterns can occur in the multi-bar nearshore zone when a storm calms down and surface waves are dominated by swell. Rip currents occurred when storms were calming down, with steepness (H/L) of swell waves ranging from 0.02 to 0.03. During such events, the deep-water significant wave height amounted to about 1 m, and the corresponding wave period was approximately 5 s. The wave approach angle with respect to the cross-shore profile did not exceed 20°. The average velocity of the identified rip currents was estimated at 0.17 m/s, and the maximum at about 0.4 m/s. The influence of local wind conditions on nearshore water circulation patterns, including rip currents, was not analysed within those investigations.

In recent years, rip currents in the south Baltic, particularly on the Polish coast, have attracted interest not only from researchers, but also from entire coastal communities and their guests. During each summer season, several cases of drowning in the sea are claimed by media (radio, TV) to have been caused by cross-shore currents, especially rip currents. Strong cross-shore currents, such as undertow, develop generally under storm conditions, when there are few people on the beach and no one enters the water. Rip currents occur during good weather, under mild or moderate wave conditions, when many beach users are willing to swim in nearshore waters. To improve swimmers' safety, it is therefore important to continue investigations of rip currents.

To verify previous findings on features of rip currents, in the autumn of 2017, the Polish-Russian research team performed intensive short-term field measurements. The main objective of this survey was detection of this rare and insufficiently explored phenomenon. The drifters that were used in 2017 were equipped with large fins and, thus, differed from those employed by Schönhofer (2014) distinctly. Such a construction allowed more reliable measurements of currents representative of a relatively thick surface water layer. In addition, this survey studied the influence of local wind conditions on nearshore water circulation patterns, including rip currents. Taking into account the above-mentioned peculiarities of the 2017 survey, the data obtained can be viewed as new, original and independent experimental material that is not related to the previously obtained field data. The present paper describes the survey of 2017 and discusses its results.

MATERIALS AND METHODS

The present study is based on wind, wave and current data collected in the period from October 24, 2017 to November 4, 2017, as well as on some other archival information and data.

The measurements were carried out by the Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN) and the Atlantic Branch of the Institute of Oceanology of the Russian Academy of Sciences (AB IO RAS) using scientific instruments located at the IBW PAN Coastal Research Station (CRS) in Lubiatowo and its vicinity. The study area of CRS Lubiatowo is situated about 70 km NW of Gdańsk (see Fig. 2). The hydrodynamics, lithodynamics and morphodynamics in the region of Lubiatowo are typical of the south Baltic sandy coast (see Ostrowski *et al*. 2016). For purposes of the present study, we used offshore wave buoy data, current data, as well as wind data collected on land at CRS Lubiatowo.

Fig. 2 Location of CRS Lubiatowo on the Baltic coast

The seashore near Lubiatowo is mildly sloped (with an inclination of 1–2%) and composed of fine quartz sand. Cross-shore bathymetric profiles display 3–4 stable bars and an ephemeral one close to the shoreline. Such a multi-bar profile of the sea bottom is favourable for gradual wave energy dissipation through multiple wave breaking, see Pruszak *et al.* (2008). The cross-shore bottom profile at CRS Lubiatowo is shown in Fig. 3. This cross-shore transect is typical of the south Baltic coast. Similar shapes of the nearshore bottom relief can be encountered near Łeba, westwards of Lubiatowo, while the number of bars occurring along the Hel Peninsula, eastwards of Lubiatowo, is smaller (see Fig. 2 for locations).

Within the framework of the joint Polish-Russian field experiments, IBW PAN carried out measurements of wind velocity and direction at CRS Lubiatowo, and also deep-water wave measurements, while the AB IO RAS team conducted measurements of currents.

The wind data were collected using the cup anemometer SW-48 (produced by MORS, Poland) installed on a 22 m mast. The mast was located on land close to CRS Lubiatowo (54°48.70' N, 17°50.43' E),

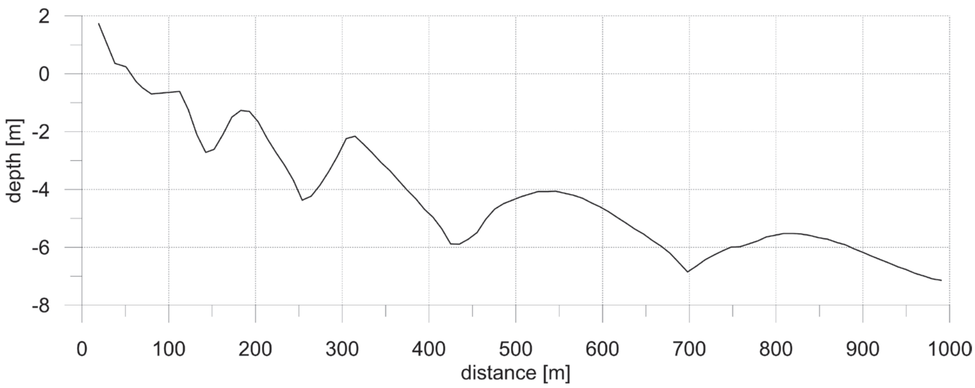

Fig. 3 Cross-shore bottom profile at CRS Lubiatowo (see Fig. 2 for the location)

at a distance of about 150 m from the shoreline. The anemometer was installed a few metres above the upper branches of nearby trees.

The measurements of wind parameters (particularly velocity) were biased because of the anemometer location and, therefore, these inland data were not suitable for direct use. Although the mast, on which the anemometer was installed, was 12 m higher than stipulated by the relevant standards (10 m), the recorded wind speed was smaller than that measured over a flat ground (without trees or other obstacles as required at state meteorological stations in Poland), which can be explained by the increased terrain roughness due to the presence of trees. Secondly, wind parameters at sea, where waves and currents were measured, differ from wind parameters on land. This problem was already faced by Ostrowski *et al*. (2018), who investigated differences between the wind speed measured at CRS Lubiatowo and the wind speed over the sea in the nearshore region. To do so, they compared the measured data with the values obtained from the ICM operating model (UM model) provided by SatBaltyk System (*http://satbaltyk.iopan.gda.pl*). These data were deemed reliable due to constant data assimilation and calibration of the model with the data measured at various meteorological stations. The statistical analysis of long-term time series showed a strong positive correlation between the "land" wind velocity and its "sea" counterpart. The joint analysis of the wind parameters measured at CRS Lubiatowo and those determined over the sea by the model yielded the following regression equation, representing the relationship between the "sea" wind velocity W_{sea} and the "land" wind velocity W_{land} (Ostrowski *et al*. 2018):

$$W_{sea} = 1.76W_{land} + 1.92 \quad (1)$$

The offshore wave measurements were carried out at water depth of 18 m by the Directional Waverider buoy DWR-7 Mk. III moored at 54°50.34' N and 17°50.33' E, at a distance of about 1.5 Nm (i.e. about 2.8 km) from the shoreline, see Fig. 2. The measurements of water surface elevations by the device are accurate to 0.01 m, and they are carried out continuously with a frequency of 2.56 Hz. The statistical and stochastic wave parameters are determined once per hour on the basis of time series not shorter than 20 minutes. These results, together with raw data, are stored in the buoy logger, and are also transmitted by radio to a receiver and a computer located in the CRS Lubiatowo building. Some basic data are periodically transmitted as SMSs to a receiving computer at the IBW PAN headquarters in Gdańsk.

The currents were measured by 10 drifters manufactured at AB IO RAS. The drifters, similarly to those used by Soomere *et al*. (2011), Davulienė *et al*. (2014) and Schönhofer (2014), use the technology of satellite positioning (GPS) and a cellular phone communication system (GSM). Each drifter is powered by a set of batteries lasting at least one week. Geographical coordinates of the drifter position are transmitted at time intervals ranging from several seconds to 2 minutes. A few types of drifters, slightly differing in structure and dimensions, were used in the autumn of 2017. In contradistinction to the drifters used by Schönhofer (2014), which were about 1 m in total height and were equipped with small dragging barrels (drogues) with a diameter of about 10 cm, the drifters used in 2017 had the total height of 1.5–2.5 m and were equipped with large fins immersed 0.3–0.6 m in water, without dragging barrels. Such a construction ensured more reliable measurements of currents representative of a relatively thick surface water layer.

Throughout the field campaign (Oct 24 – Nov 4, 2017), the GPS-GSM drifters were deployed in Lubiatowo and at coastal locations on shore segments adjacent to Lubiatowo, namely from Łeba to Władysławowo (see Fig. 2). Some drifters travelled along the shore of the Hel Peninsula and then over the deep waters far eastwards and south-eastwards, across the Gulf of Gdańsk. One of the drifters reached the Russian coast in the eastern part of the Gulf of Gdańsk about 20 km north of Baltiysk (see Fig. 2) on November 16, 2017, that is, long after the proper field survey completion. The present survey was aimed at identification of rip currents. Such currents can be detected in the shallow water, particularly in the surf zone. Therefore, only the currents occurring in the nearshore zone were investigated in the present study. Drifter tracks beyond 1–2 km from the shoreline were not taken into consideration. Open sea currents will be analysed within a separate study.

It should be noted that some drifter deployments were unsuccessful – the drifters were either immediately washed ashore (near CRS Lubiatowo) or trapped by groins (east of Łeba). Such cases were not interesting as the drifters stopped and did not move any more. Each drifter that was not moving was withdrawn from water and another attempt at its deployment was made. These situations were very common and occurred almost in all wind-wave conditions. Sometimes, GPS signals were too weak for sufficiently accurate positioning, or the GSM transmission system failed.

Each drifter had the number assigned. The cases subject to analysis involved 8 drifters (numbered 2, 4, 5, 7, 8, 9, 10 and 11). One qualified experiment means one successful deployment followed by a long-lasting track of the drifter (ca. half an hour or more). Double successful deployment/tracking of the same drifter denotes two separate experiments. In total, 15 experiments were qualified for the analysis.

In the period from Oct 24 to Nov 4, many attempts were made to detect rip currents, which were the major objective of the survey. On October 26, the wind blew from W, which was favourable for generating waves from W and the corresponding wave-driven longshore currents. Similar conditions occurred on November 1, with the wind blowing from the W-NW sector. This also resulted in distinct longshore currents. On November 3, the wind was initially blowing from N, then from NW-W, accompanied by waves coming from N. It was only on that day that rip currents were detected.

RESULTS AND DISCUSSION

The time series of the wind and wave data measured at CRS Lubiatowo from October 24, 2017 to November 4, 2017 are shown in Figs 4 and 5. Fig. 4 presents the wind velocity averaged over 10 minutes and recalculated by Eq. (1) so as to obtain the mean wind speed at sea (W_{sea}). Wind direction θ_{wind} is shown in Fig. 4 as measured. Records of the deep-water significant wave height H_s, wave period $T(H_s)$ and direction of wave propagation θ_{wave} are depicted in Fig. 5.

As can be seen in Fig. 4, the maximum mean wind velocity W_{sea} of 20 m/s was recorded on October 29. The wind was blowing from the N-NNW sector, almost perpendicularly to the shore, causing stormy deep-water waves with a significant wave height H_s of over 4 m and a wave period $T(H_s)$ of about 10 s to approach the coast from N. These extreme wave conditions were recorded during the night of October 29/30.

Although the plots of wind speed and wave height shown in Fig. 4 and Fig. 5 are slightly different, the extreme data were recorded at the same time, except for November 4, when a relatively strong wind was blowing in the seaward direction (from S to N) but high waves were not generated. Instead, a swell from W, which had been induced by a westerly wind previously in the afternoon on November 3, was observed. The correlation between wave height and the local wind is never very high, because waves are generated both close to the place of observation (wind waves) and in remote areas (swell). Wind conditions are rarely uniform over the entire Baltic. However, as found by Cerkowniak *et al*. (2015), extreme storm events in the south Baltic Sea are caused by waves generated by persistent wind fields, which are homogeneous over the entire basin. This presumably took place at night on October 29/30.

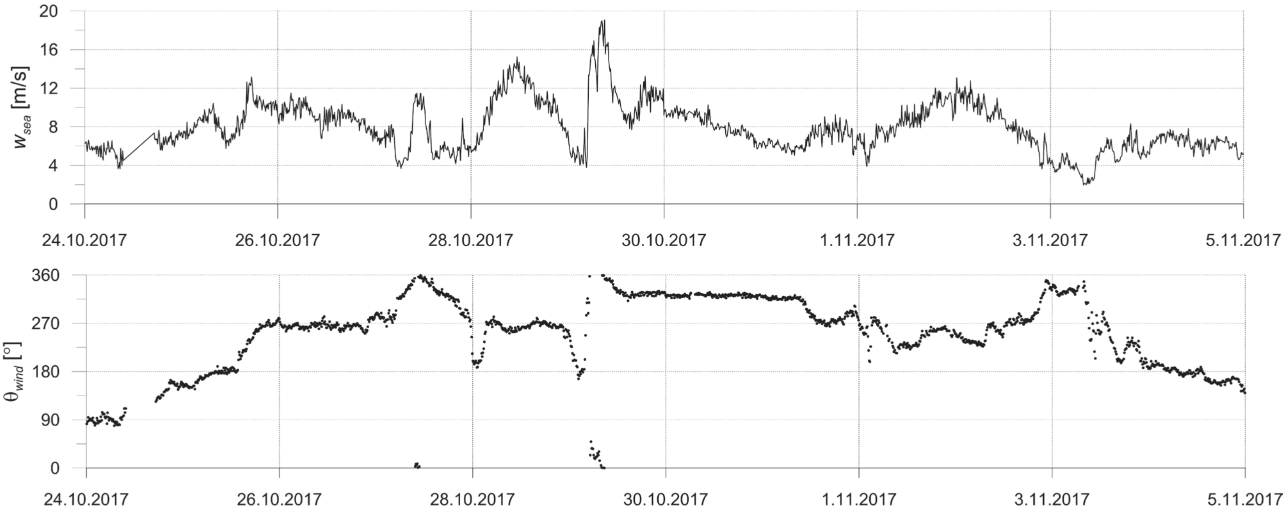

Fig. 4 Mean wind velocity W_{sea} and direction θ_{wind} measured at CRS Lubiatowo from October 24, 2017 to November 4, 2017; W_{sea} recalculated by Eq. (1)

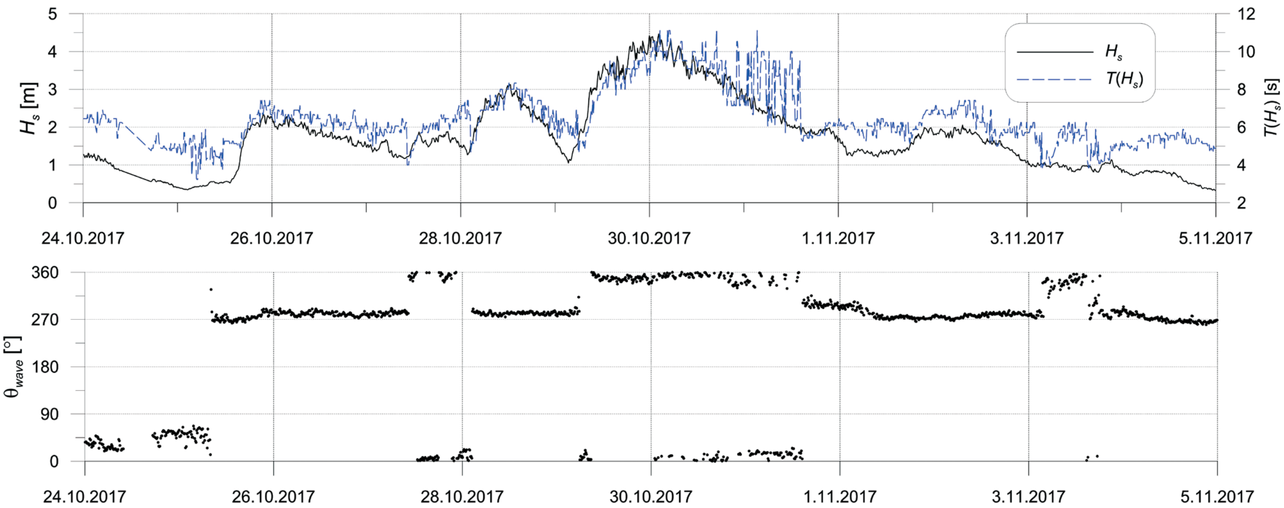

Fig. 5 Deep-water wave parameters (significant wave height H_s, wave period $T(H_s)$ and direction of wave propagation θ_{wave} measured at CRS Lubiatowo from October 24, 2017 to November 4, 2017

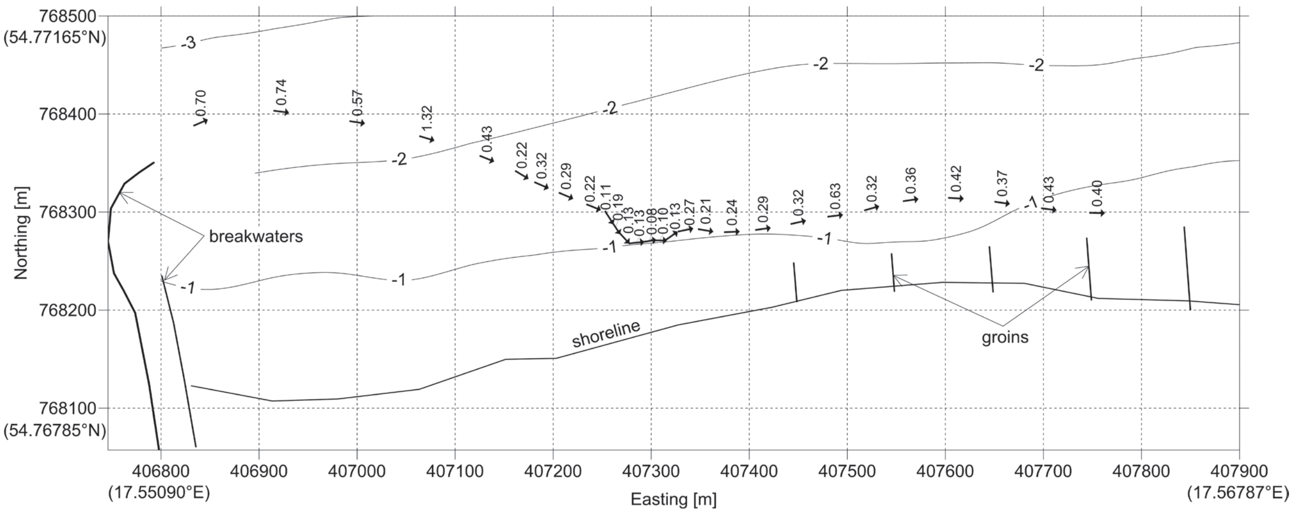

Fig. 6 Fragment of the track and velocities *u* [m/s] of drifter 9 deployed in Łeba on October 26, 2017 at 14:04 UTC; end of measurement at 14:53 UTC (see Table 1 for conditions)

The drifters were deployed many times during the 12 day-long field campaign. They were either released from the harbour breakwaters in Łeba and Władysławowo, 250 m and 350 m from the shoreline, respectively, or transported seawards by a windsurfer near CRS Lubiatowo (see Fig. 2 for these three locations).

On October 26, the wind blowing from W with the mean velocity of about 8–10 m/s generated waves from W with the height H_s attaining about 1.9 m and the corresponding wave-driven longshore currents. On that day, the drifters were released from the harbour of Łeba. Four of the drifters successfully measured and transmitted the variability of their position, making it possible to calculate velocities *u*. The fragment of the track and velocities *u* of one of the drifters are shown in Fig. 6.

As can be seen in Fig. 6, the drifter started moving along the shore almost immediately and soon after that approached the shoreline obliquely. Then, the drifter turned in the longshore direction and moved roughly eastwards about 100 m away from the shoreline.

On November 1, wind-wave conditions were somewhat similar: a strong wind was blowing from the W-NW sector, generating distinct longshore currents. On that day, the drifters were deployed in Łeba and in Władysławowo. One drifter from Łeba and two drifters from Władysławowo were successfully trailed. The experiments lasted until November 2. The fragment of the track and velocities *u* of one of the drifters released in Władysławowo are shown in Fig. 7.

As can be seen in Fig. 7, the drifter was transported by currents along the coast of the Hel Peninsula, initially about 300–500 m away from the shoreline, then 1–2 km from the shoreline, and afterwards it started moving further offshore over the deep waters in the Gulf of Gdańsk, roughly towards SE. For purposes of the present study, only the track segment from

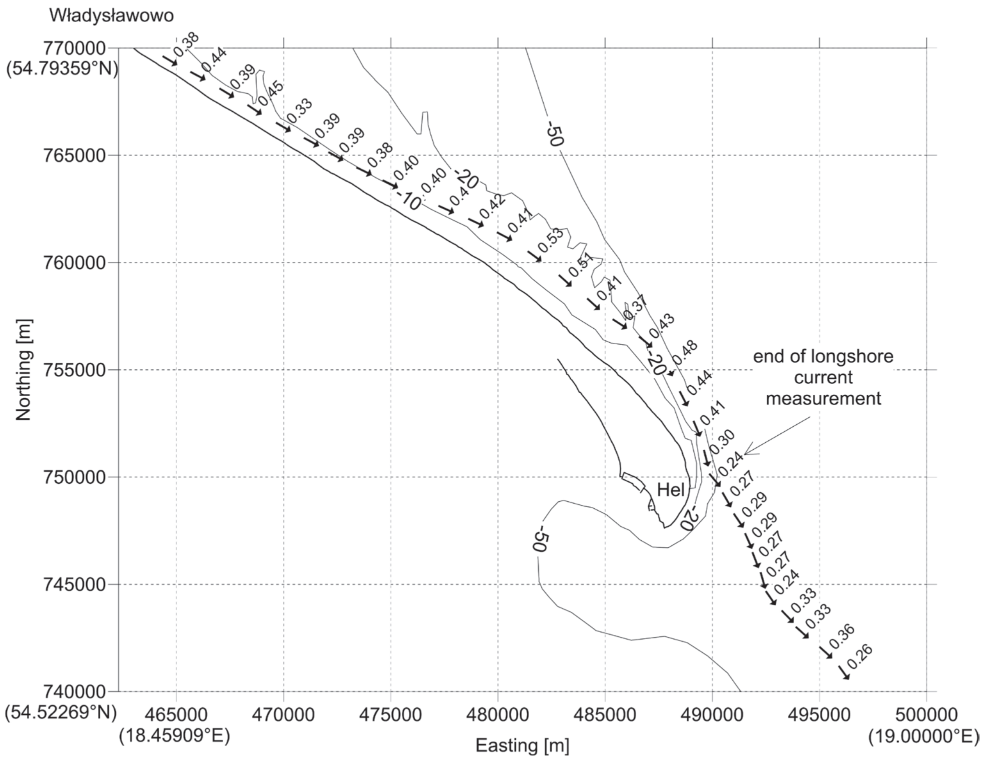

Fig. 7 Fragment of the track and velocities *u* [m/s] of drifter 5 deployed in Władysławowo on November 1, 2017 at 16:56 UTC, end of measurement on November 2, 2017 at 17:26 UTC (see Table 1 for conditions)

Władysławowo to Hel, representing the nearshore current, was considered.

On November 3, a relatively weak wind was blowing and moderately high waves were coming from N (see Fig. 4 and Fig. 5). This was the only day throughout the field campaign when conditions for the occurrence of rip currents seemed to be favourable. The drifters were deployed only at CRS Lubiatowo. Four of them were successfully trailed in 8 experiments. Fragments of tracks and velocities of two model drifters released near CRS Lubiatowo are shown in Fig. 8 and Fig. 9.

The drifter track depicted in Fig. 8 shows distinct water circulation, which ends in a seaward-flowing rip current, whereas the winding track of the drifter shown in Fig. 9 is more complicated. Similar multi-directional tracks were observed in the other 4 experiments carried out on November 3. In one of the remaining two cases, a typical longshore current was identified, while in the other case, a combined longshore and onshore flow of water was observed.

The shoreline at CRS Lubiatowo is located on an azimuth of about 69°. Projection of velocity vectors on the cross-shore direction, perpendicular to the shoreline and having an azimuth of 339°, yielded cross-shore velocity components *v*. The streams of water flowing in the offshore direction were qualified as rip currents. The maximum seaward current velocities marked by circles in Figs 8 and 9, amounting to 0.37 m/s and 0.40 m/s, projected on the cross-shore direction yielded the maximum rip current velocities v_{max} equal to 0.22 m/s and 0.26 m/s, respectively. The quantitative and qualitative summary of all successful experiments carried out on October 26, November 1 and November 3 is given in Table 1.

As shown in Table 1 (cf. also Fig. 6 and Fig. 7), the longshore tracks of the drifters deployed in Łeba pass closer to the shoreline than those of the drifters deployed in Władysławowo. Under similar wind-wave conditions (wind and waves from the W sector), the tracks of drifters east of Łeba indicate the longshore wave-driven currents collinear with the wind-driven currents, while the tracks of drifters between Władysławowo and Hel represent the longshore wave-driven currents (directed to ESE) influenced by the wind-driven currents (directed to E).

As it can be seen in Table 1, rip currents were observed when the azimuth of wave approach θ_{wave} was in the range 327°–357°. The calculated mean value of θ_{wave} amounts to 339°, equal to the cross-shore profile azimuth. This denotes, on average, an exactly perpendicular approach of waves to the shoreline.

Distinct water flows directed locally offshore were detected during 6 experiments. These flows resembled typical rip currents, with velocities of up to 0.34 m/s. It is worth noting that nearshore water circulation patterns with rip currents were observed under specific wave conditions, favourable for the appearance of distinct water fluxes not only along the shore, but in the cross-shore direction as well. The results of field investigations presented here largely confirm earlier findings on rip currents in the south Baltic Sea.

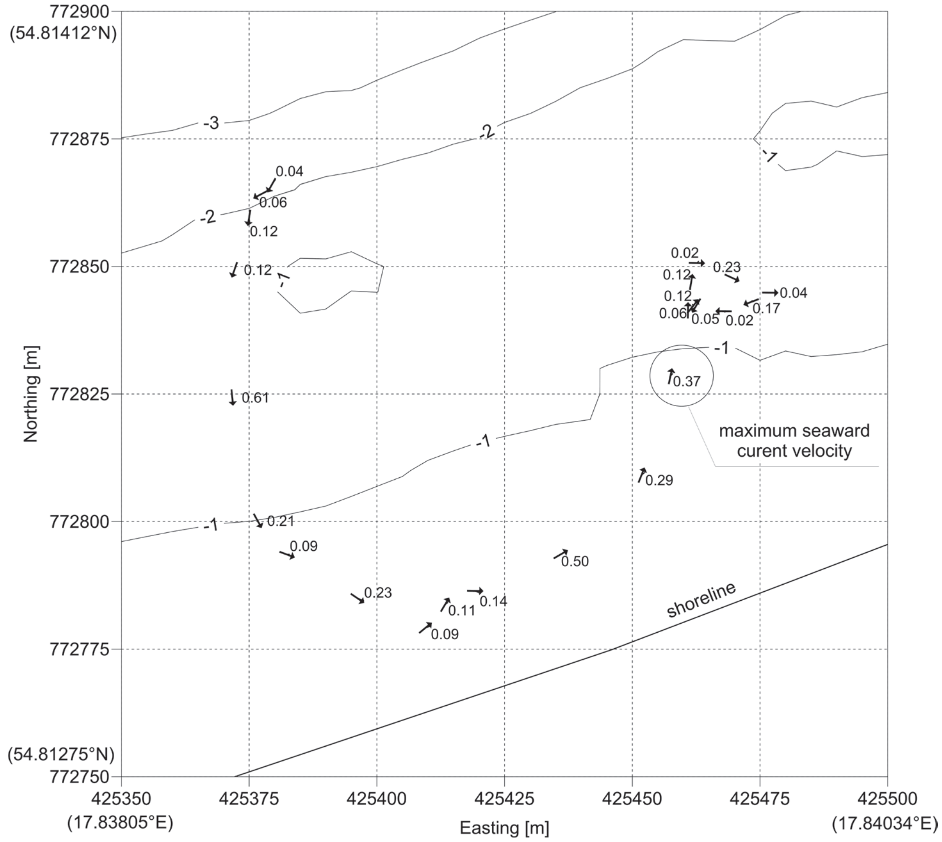

Fig. 8 Fragment of the track and velocities [m/s] of drifter 9 deployed at CRS Lubiatowo on November 3, 2017 at 07:24 UTC, end of measurement at 07:49 UTC (see Table 1 for conditions)

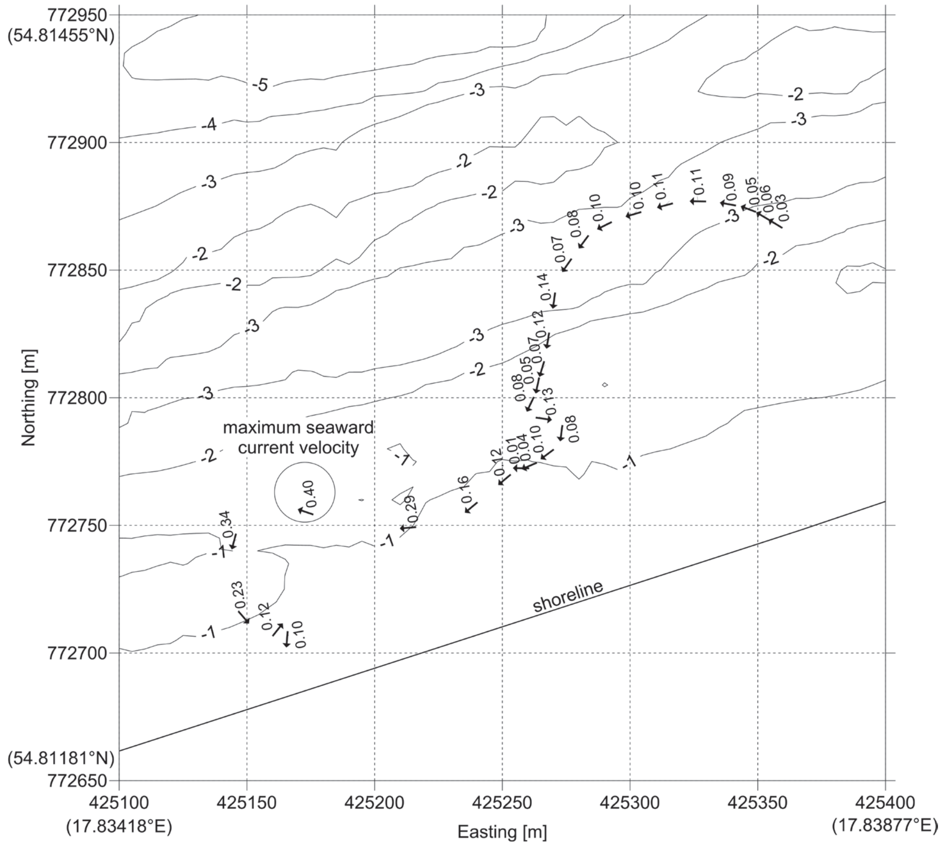

Fig. 9 Fragment of the track and velocities [m/s] of drifter 10 deployed at CRS Lubiatowo on November 3, 2017 at 07:48 UTC, end of measurement at 08:45 UTC (see Table 1 for conditions)

Table 1 Shoreline direction θ_{shore} at drifter deployment locations, parameters of waves (H_s, $T(H_s)$, θ_{wave}), winds (W_{sea}, θ_{wind}), longshore currents (mean velocity u_{mean}, maximum velocity u_{max}, distance from the shoreline x), rip currents (maximum rip current velocity v_{max}) measured at CRS Lubiatowo

Deployment date	Drifter no.	Deployment location	θ_{shore} [°]	Time [UTC]	H_s [m]	$T(H_s)$ [s]	θ_{wave} [°]	W_{sea} [m/s]	θ_{wind} [°]	Type of current identified	u_{mean} [m/s]	u_{max} [m/s]	x [m]	v_{max} [m/s]
26 Oct 2017	8	Łeba	81	13:57–16:20	1.68–1.87	5.7–6.7	276–286	8.0–10.3	254–271	longshore	0.39	0.92	50–250	n/a
	7	Łeba	81	14:03–18:39	1.68–1.87	5.9–6.7	276–286	8.0–10.3	254–271	longshore	0.22	1.00	50–300	n/a
	9	Łeba	81	14:04–14:53	1.73–1.77	6.5–6.7	280–283	8.0–9.5	257–271	longshore	0.35	1.32	80–270	n/a
	2	Łeba	81	14:25–14:56	1.74–1.86	6.5–6.7	280–286	8.0–9.7	257–267	longshore	0.46	0.72	40–260	n/a
1 Nov 2017	8	Łeba	81	12:35–07:11 (02.11.2017)	1.26–1.99	5.1–7.4	266–279	7.9–13.1	222–264	longshore	0.53	1.26	50–600	n/a
	5	Władysławowo	121	16:56–17:26 (02.11.2017)	1.39–2.01	5.0–7.4	266–284	6.3–13.1	227–288	longshore	0.39	0.54	300–2000	n/a
	7	Władysławowo	121	17:02–21:27 (02.11.2017)	1.24–2.06	5.0–7.4	266–287	3.9–13.1	227–317	longshore	0.35	0.48	300–3300	n/a
3 Nov 2017	4	Lubiatowo	69	07:30–08:00	0.99–1.07	4.4–5.7	327–345	2.5–3.8	336–348	rip current	n/a	n/a	n/a	0.34
	4	Lubiatowo	69	09:35–10:09	0.90–0.99	5.3–6.1	330–344	2.1–2.7	238–290	rip current	n/a	n/a	n/a	0.14
	9	Lubiatowo	69	07:24–07:49	1.00–1.07	4.4–5.3	334–345	2.7–3.8	336–348	rip current	n/a	n/a	n/a	0.22
	9	Lubiatowo	69	09:24–09:49	0.94–0.99	5.3–6.1	337–344	2.1–2.7	238–290	longshore	0.14	0.24	30-50	n/a
	9	Lubiatowo	69	10:00–10:59	0.87–0.96	5.3–6.3	330–353	2.4–3.4	204–285	rip current	n/a	n/a	n/a	0.15
	10	Lubiatowo	69	07:48–08:45	0.94–1.00	5.0–5.9	327–345	2.0–3.1	306–348	rip current	n/a	n/a	n/a	0.26
	10	Lubiatowo	69	09:29–12:28	0.82–0.99	5.1–6.3	330–357	2.1–5.4	204–290	rip current	n/a	n/a	n/a	0.25
	11	Lubiatowo	69	09:04–14:02	0.82–1.01	5.1–6.3	330–357	2.1–6.8	204–291	longshore	0.21	0.28	200–600	n/a

FINAL REMARKS AND CONCLUSIONS

The coastal region of CRS Lubiatowo can be regarded as typical of the south Baltic sandy coast (Ostrowski *et al*. 2016). The experimental results obtained in the autumn of 2017 are in agreement with earlier findings reported by Szmytkiewicz (2002), Schönhofer (2014) and Ostrowski *et al*. (2016), according to which longshore currents predominate in this area, while rip currents are nearshore water circulations occurring relatively rarely, under specific wave conditions, during which deep-water waves approach the shore almost perpendicularly. It should be noted that both wave-driven longshore currents and rip currents occur in the shallow-water region, particularly in the surf zone. The present results also to some extent confirm previous quantitative findings concerning wave-driven currents in the south Baltic Sea.

Longshore currents, characterised by velocity vectors lying approximately parallel to the shoreline, were detected by the drifters when the deep-water waves were propagating distinctly not perpendicularly to the shore. The significant wave height and the corresponding wave period varied from 1.26 m to 2.06 m and from 5 s to 7.4 s, respectively. The mean longshore flow velocities measured during various experiments amounted to 0.22–0.53 m/s, with a maximum of 1.32 m/s.

Multi-directional drifter tracks were observed only on one day, when waves approached the shore perpendicularly. The significant wave height and the corresponding wave period varied from 0.82 m to 1.07 m and from 4.4 s to 6.3 s, respectively. The velocities of rip currents identified within the winding tracks ranged from 0.14 m/s to 0.34 m/s. It is worth noting that the waves inducing longshore currents were much higher than the waves generating rip currents, while the periods of all these waves were similar. Thus, rip currents were generated by relatively longer waves (of smaller steepness).

The above conclusion is the major outcome of the presented study. It appears that deep-water waves of similar heights can generate different nearshore currents. The deep-water waves propagating not perpendicularly to the shore are subject to refraction and breaking. The longshore wave-driven current is always generated in such conditions. Certainly, the wave energy dissipated during breaking also gives rise to the appearance of more or less intensive cross-shore currents in the surf zone. If the deep-water waves propagate perpendicularly to the shoreline, the cross-shore current (undertow) predominates. In specific conditions, when deep-water waves of smaller steepness occur, rip currents can be generated.

The experimental results concerning rip currents yield the following conclusions for the multi-bar south Baltic shore, namely:

- the probability of rip currents is higher when long waves (of smaller steepness) occur;
- rip currents occur most often when the deep-water significant wave height H_s is in the range 0.7 m–1.5 m, and the corresponding wave period amounts to about 5 s or more;
- the highest velocities of rip currents are attained when H_s values are in the range 0.8 m–1.1 m;

- rip currents can develop only when waves approach the shore perpendicularly (or almost perpendicularly);
- rip currents reach velocities of 0.1 m/s to 0.4 m/s.

It has been confirmed that the occurrence of rip currents is a rare phenomenon on the south Baltic coast. It was only on one day during the entire 12 day-long field campaign that conditions favoured the generation of water circulation patterns resembling rip currents.

It is worth pointing out that the rip current issue in the south Baltic seems interesting not only to coastal researchers, but also to entire coastal communities. During each summer season, several cases of drowning are claimed by mass media to have been caused by nearshore currents. As strong typical offshore directed currents, such as undertow, develop during storms, no one enters the water in such conditions. It appears that rip currents occur under mild or moderate wave conditions, when many beach users are willing to swim in nearshore waters. The present findings can therefore be useful for the improvement of swimmers' safety in the south Baltic Sea regions. It can be proposed, for instance, to forbid swimming at guarded beaches not only under severe wave conditions but under moderate conditions as well. It is also worth considering installation of tables with warnings about hazards caused by the nearshore wave-driven currents.

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