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ORIGINAL RESEARCH ARTICLE

Assessment of wave climate and energy resources in the Baltic Sea nearshore (Lithuanian territorial water)

Darius Jakimavičius *, **Jūratė Kriaučiūnienė**, **Diana Šarauskienė**

Lithuanian Energy Institute, Kaunas, Lithuania

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Summary The main task of the present research was to analyse wave climate and evaluate energy resources in the Lithuanian territorial waters of the Baltic Sea. Wave and wind parameters were analysed according to long-term measurement site data. Distribution of wave parameters in the Baltic Sea Lithuanian nearshore was evaluated according to wave modelling results. Wave energy resources were estimated for three design years (high, median and low wave intensity). The results indicated that in the coastal area of Lithuania, waves approaching from western directions prevail with mean wave height of 0.9 m. These waves are the highest and have the greatest energy potential. The strongest winds and the highest waves are characteristic for the winter and autumn seasons. In the Baltic Sea Lithuanian nearshore, the mean wave height ranges from 0.68 to 0.98 m, while the estimated mean energy flux reaches from 0.69 to 1.90 kW m^{-1} during a year of different wave intensity. Distribution of energy fluxes was analysed at different isobaths in the nearshore. Moving away from the coast, both wave height and wave power flux increases significantly when water depth increases from 5 to 20 m. Values of the mentioned parameters tend to change only slightly when the sea is deeper than 20 m. In a year of median wave intensity, the mean wave energy flux changes from 1.10 kW m^{-1} at 10 m isobaths to 1.38 kW m^{-1} at 30 m isobaths. The identified differences of wave height and energy along the selected isobaths are insignificant.

* Corresponding author at: Laboratory of Hydrology, Lithuanian Energy Institute, Breslaujos st. 3, LT444003 Kaunas, Lithuania.
Tel.: +370 37 401801. Fax: +370 37 351271.
E-mail address: darius.jakimavicius@lei.lt (D. Jakimavičius).
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1. Introduction

Ocean waves are considered as a clean and renewable source of energy with a tremendous worldwide potential for electricity generation. Essentially all of the energy contained in a wave (95%) is located between the water surface and the top one fourth of the wave length. This energy can be extracted in different ways, which has given rise to a large variety of available and deployed technologies (Kempener and Neumann, 2014). However, no single device or generic type has been proven superior to others and it is likely that different types will suit separate deployment zones that can be exploited (O'Hagan et al., 2016).

The highest global net power (excluding areas where $P < 5$ kW m^{-1} and potentially ice covered ones) is computed for regions of Australia and New Zealand — 574 GW, South America (W) — 324 GW and Europe (N and W) — 286 GW (Mørk et al., 2010). Since seasonal variations are generally significantly larger in the northern hemisphere, the southern coasts of South America, Africa and Australia are particularly attractive for wave energy exploitation (Falcao, 2010).

The Baltic Sea, a relatively shallow inland sea of the Atlantic Ocean, also receives increased attention when marine power resources are being discussed. One of the first attempts to evaluate a technical energy resource for the Baltic Sea was made by Swedish scientists (Bernhoff et al., 2006); the potential calculated by them is in the range of 24 TWh. The report of Henfridsson et al. (2007) stated that annual wave energy is equal to approximately 56 TWh for the Baltic Proper. This result should be considered as the gross wave energy potential for the whole Baltic Sea. The annual average energy flux is estimated to 5 kW m^{-1}. Waters et al. (2009) found that the average energy flux off the Swedish Coast is approximately between 2.4 and 5.2 kW m^{-1}.

A study by Latvian experts (Avotiņš et al., 2008) concluded that the wave potential of the Baltic Sea is satisfactory for converting energy. Soomere and Eelsalu (2014) assessed the wave energy potential of the eastern Baltic Sea and concluded that the best location for wave energy converters is in the nearshore at water depths of 15—20 m. On average, the wave energy flux is 1.5 kW m^{-1} and reaches up to 2.55 kW m^{-1} in selected locations of the north eastern Baltic Proper. The wave energy resources are much smaller (normally around 0.6—0.7 kW m^{-1}) in the interior of the Gulf of Finland and in the Gulf of Riga.

Lithuanian experts also acknowledge that the southeastern Baltic Sea provides a great potential and possibilities for electricity production from offshore renewable energy sources (Blažauskas et al., 2015). The wave power flux for annual wave heights in the Baltic nearshore at Klaipėda varies from 1.6 kW m^{-1} in a high intensity year to 0.4 kW m^{-1} in a low intensity year (Kasiulis et al., 2015).

The assessment of global wave energy potential revealed that the majority of energy can be extracted when significant wave height ranges from 1.5 to 5.5 m and when energy (mean) period is between 7 and 14 s (Mørk et al., 2010). Similar results were published in another study (Lenee-Bluhm et al., 2011): the sea states with the greatest contribution to energy have significant wave heights between 2 and 5 m and energy periods between 8 and 12 s.

High waves are rare in the Baltic as the enclosed nature of the basin means that all wave generation must take place within the basin itself and is therefore limited by the fetches of the basin. In the Baltic Sea, the longest fetches are approximately 800 km (Street et al., 2014). All-time highest significant wave height of 8.2 m was recorded in the Baltic Proper in December 2004 (Tuomi et al., 2011). However, according to most reconstructions, the long-term significant wave height in the open part of the Baltic Proper slightly exceeds 1 m (Soomere, 2016).

At the southeastern part of the Baltic Sea, southwest and west were indicated as the most frequent wave approach directions. These directions also correspond with the typical direction of the strongest and prevailing winds at the Lithuanian coast (Kelpšaitė and Dailidienė, 2011). Average annual wave heights near Klaipėda at 6 m depth for the year of different wave intensity are as follows: high intensity — 0.89 m, median intensity — 0.67 m and low intensity — 0.53 m (Kasiulis et al., 2015).

Various models can be applied to simulate wind-generated waves. One of such models is a third-generation wave model SWAN (Simulating Waves Nearshore) (Booij et al., 1999; Ris et al., 1999), developed at the Delft University of Technology. This software for computing random short-crested wind-generated waves in coastal regions and inland waters is widely used for estimation of wave energy potential (Akpınar et al., 2012; Benassai et al., 2013; Iglesias et al., 2009; Iglesias and Carballo, 2009, 2010; Tsoukala et al., 2016). Another widely used model which simulates the development of the sea state in two dimensions is WAM (Hasselmann, 1988). It was also applied in numerous studies (Iglesias et al., 2009; Mazarakis et al., 2012; Staneva et al., 2016) and is often employed in the Baltic Sea wave investigations (Kelpšaite et al., 2011; Soomere and Eelsalu, 2014; Soomere and Raamet, 2011a,b; Street et al., 2014). The model applied in the current study, the Nearshore Spectral Wind-Wave Module of MIKE 21 (MIKE 21, 2012), describes evolution of wind-generated waves in nearshore areas and was successfully used in wave studies as well (Gopaul and O'Brien-Delpesh, 2006; Johnson, 1998; Tsoukala et al., 2016; Vannucchi and Cappietti, 2016).

Analysis of different scientific publications showed that there is no detailed evaluation of wave distribution and energy resources in the Baltic Sea nearshore at the Lithuanian coast. Such evaluation would be useful when selecting the potential location for wave energy converters in the future. Therefore, the main task of this research is the analysis of wave and wind parameters according to long-term observation data, mean wave height and energy flux distribution in the Baltic Sea Lithuanian nearshore according to wave modelling results. Wave energy resources were estimated at different nearshore depths in a year of high, median and low wave intensity.

2. Research object and data

The research object is the Baltic Sea nearshore at the Lithuanian coastline. The Klaipėda Seaport, located at a navigable strait, is the northernmost ice-free port on the eastern coast of the Baltic Sea (Fig. 1). The continental coast of the Lithuanian coastline is located north of the port,

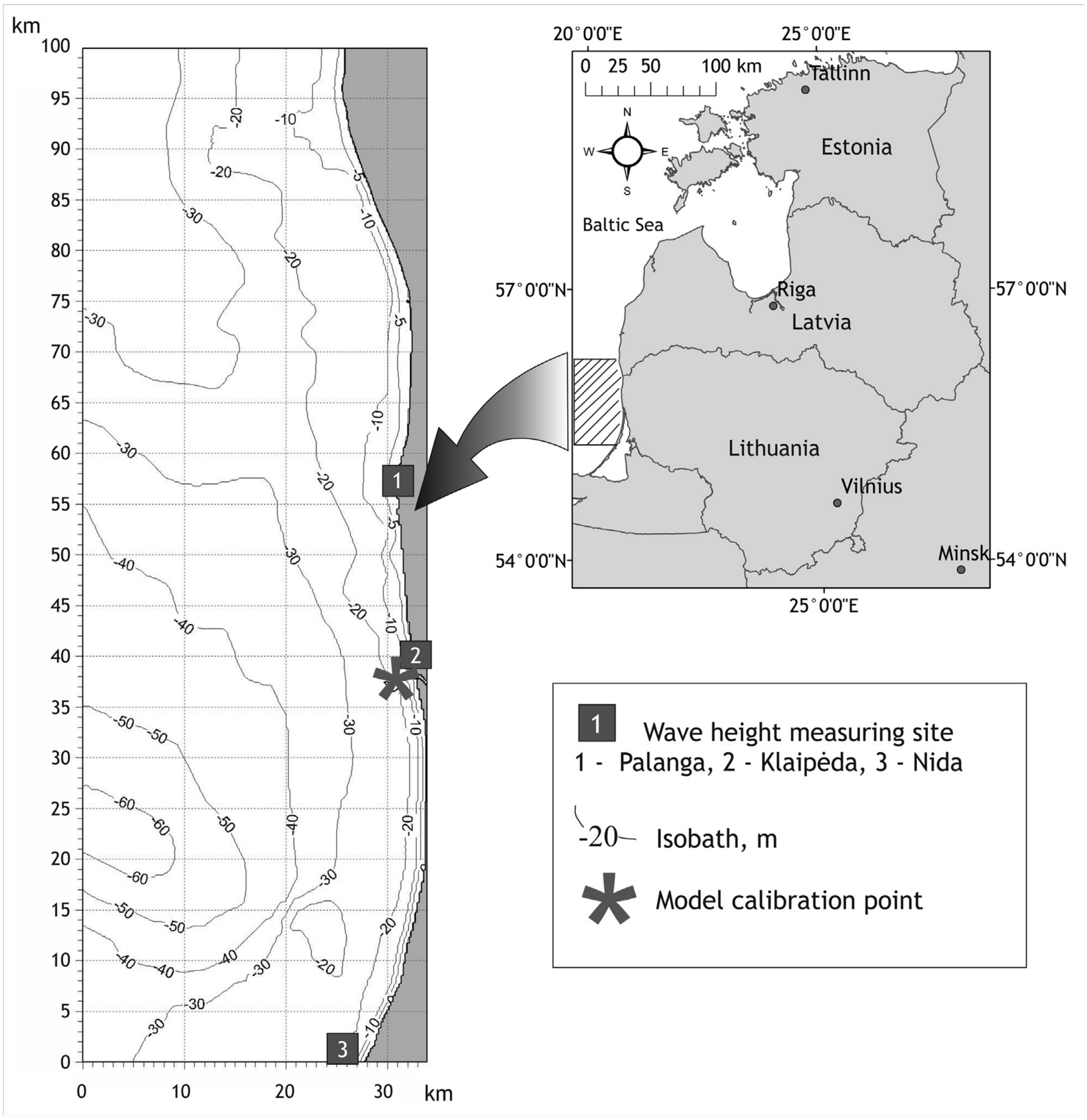

Figure 1 Bathymetry of the Baltic Sea nearshore with marked points of wave height measuring sites.

including the resort cities of Palanga and Šventoji, whereas the rest of the coast belongs to the Curonian Spit national park — a narrow peninsula of large sand dunes and pine forests, included in the UNESCO World Heritage List.

This investigation is concentrated on the wind-generated waves observed in the southeastern part of the Baltic Sea at the Lithuanian coast which can be used for electric energy generation. In order to assess wave energy potential, fluctuations of waves and wind during a long observation period had to be analysed.

In the coastal area of Lithuania, visual wave observations have been executed in three measurement sites (Fig. 1). In the 1950s, visual observations were started in Klaipėda and Nida. The observations in Palanga started in 1993. All of these observations have been continuously carried out until the present day (with some gaps in time). The present investigation is based on the observation data obtained at Klaipėda from 1970, at Nida — from 1972 and at Palanga — from 1993.

Waves are visually observed at a 500—600 m distance from the coast, in the depth of 5—6 m, 2 times a day (in spring and summer at 6:00 and 18:00 UTC + 02:00; in autumn and winter at 6:00 and 12:00 UTC + 02:00). Observations are carried out every day at the same time and in the same place. When carrying out investigations, the observer uses binoculars (with distance increments) and a stopwatch. Visual observations include the estimation of wave direction and height (mean and maximum). Mean wave height values are rounded: values up to 1.5 m height are rounded with an accuracy of 0.25 m; from 1.5 to 4.0 m — with an accuracy of 0.5 m; from 4.0 m — with an accuracy of 1.0 m. The wave period is calculated with an accuracy of 0.1 s. Together with visual wave observations, wind speed and direction are estimated at the selected sites. Wind data from Palanga, Klaipėda and Nida measurement stations (MS) is used in this research.

Wave data for model calibration were obtained from automatic wave measurement station (Fig. 1) for the period from October 2016 to May 2017. The sea depth at the measurement site is 14.5 m. The place of measurement is 200 m west from the southern pier of Klaipėda Seaport. Hourly wave measurements were made using AWAC sensor. Range of this instrument is from −15 to +15 m, accuracy of wave height estimate <1% of measured value/1 cm, and accuracy of wave direction is 2°/0.1°.

3. Methods

The assessment of wave energy resources requires knowledge of wave climate in the researched water territory. Since the research object is wind-generated waves, a relation between wind and wave parameters was identified by applying statistical methods. The modelling of wave propagation in nearshore using Nearshore Spectral Wind-Wave Module of MIKE 21 is possible only in case a close relation between the mentioned parameters exists. Correlation and statistical analysis was applied to analyse wave and wind parameters and estimate their interdependence. Ranges of minimum, maximum, average and 25th and 75th percentiles of the analysed parameters were estimated. Wind and wave roses were created for the analysis of wind and wave parameter variation in the Baltic nearshore at the Lithuanian coast.

In the assessment of wave energy resources along the Lithuanian coast of the Baltic Sea, energy flux was estimated as follows (Saulnier et al., 2011):

$$P = 0.484 \times H^2 \times T, \tag{1}$$

where P — energy flux, W m^{-1}, H — wave height for each given point for the certain time period as a whole using the mean wave height averaged through this time period, m, T — wave period, s.

In order to assess wave energy resources, it is necessary to model wave parameters in the entire investigated area. Wave propagation modelling was performed using the 2D modelling system MIKE 21 created by the Danish Hydraulic Institute. The Nearshore Spectral Wind-Wave Module (NSW) of this system was applied for the modelling of wind-generated wave propagation parameters in the Lithuanian nearshore of the Baltic Sea. The initial data required for the NSW model (MIKE 21, 2012) includes: (1) depth of the water body (bathymetry); (2) wind speed and direction; (3) boundary conditions in the deepest part of the water area (significant wave height, mean period and direction of the wave, directional spreading index). The NSW model results in each model grid include significant wave height and period, direction of wave propagation and its standard deviation.

A 100 km long and 34 km wide sea territory was selected for the modelling (Fig. 1). A rectangular bathymetric grid of 100 m was chosen. Boundary conditions were described in the cross-section which coincided with the Y axis (in the deepest part of the water territory). Wave refraction and bed roughness that lead to dissipation of wave energy were estimated during modelling.

Wave parameters (significant wave height and period for wind of a certain speed and direction) which are required for the description of model boundary conditions in the deepest cross-section of water territory were estimated from ERA-Interim database (http://www.ecmwf.int/) in the depth of 50 m (N 55°43′55″E 21°4′20″). Hourly data set from the automatic wave measurement station (Fig. 1) and hourly wind parameters from Klaipeda MS of the period from October 2016 to May 2017 were used for model calibration. Hourly parameters of waves (significant wave height and period) induced by strong winds (≥10 m s^{-1}) of NW, W and SW directions were used for the calibration procedure. Directions of such waves and winds are usually similar or differ by no more than 20°. The analysis of wind speed and wave height for selected directions of winds showed (Fig. 2) that the measured wave heights for a specific wind speed could differ significantly (for example, if a west wind blows at a 10 m s^{-1} speed, the measured wave height can vary in the range of 1–3.3 m). Therefore, linear dependences for measured wind speed and wave height were described for the selected wind directions (Fig. 2a–c). There is a tendency that the largest waves form when the winds blow from SW and W directions. Similar tendencies were found in the analysis of the relationship between wind speed and wave period (Fig. 2d–f).

The MIKE 21 NSW model was calibrated comparing the trends of measured values of wave height and period with the modelled ones when strong winds with speeds of 10, 15 and 20 m s^{-1} are blowing from NW, W and SW directions (large circles in Fig. 2). The difference between calculated and measured wave parameters at the automatic station (Fig. 1) is small (Fig. 2), indicating a correct estimation of model boundary conditions (wave height and period).

Wave energy resources were analysed for a separate design year that starts in March of a given year and ends in February of the following year. The design years of high, median and low wave intensity were assigned according to probability distribution (of the data series of 1960–2011) for a year of 5, 50 and 95% probability. The probability of each year (from the data series of 1960–2011) was calculated according to the following equation (Weibull, 1939):

$$P = \frac{m}{n+1} \times 100\% \tag{2}$$

where P — probability, %; m — rank number, n — number of ranked years.

For further analysis, data of wave heights at Klaipėda of 1973–1974, 1994–1995 and 1976–1977 design years (which correspond to high (5%), median (50%) and low (95%) wave intensity years) was used. The mean wave heights of the selected design years are 0.90, 0.67 and 0.53 m respectively. Waves were observed in a depth of 5–6 m.

4. Results

4.1. Analysis of wave and wind parameters according to long-term observation data

Knowledge of wind regime is essential for investigations of wind-generated sea waves. The wind rose of the Baltic Sea Lithuanian nearshore (Fig. 3a) was created using the average daily data from Nida, Klaipėda and Palanga MS for the period of 1993–2011. The wind rose indicates that the westerly direction (SW, W and NW) winds prevail (46.7% of all cases), whereas winds blowing from the south and north are fairly rare. In 75.6% of all observed cases, irrespective of the direction, the winds were weak and did not exceed 6 m s^{-1}. However, when stronger winds were analysed, a tendency of westerly winds was revealed. Winds stronger than 20 m s^{-1} typically do not blow from E, SE and NE.

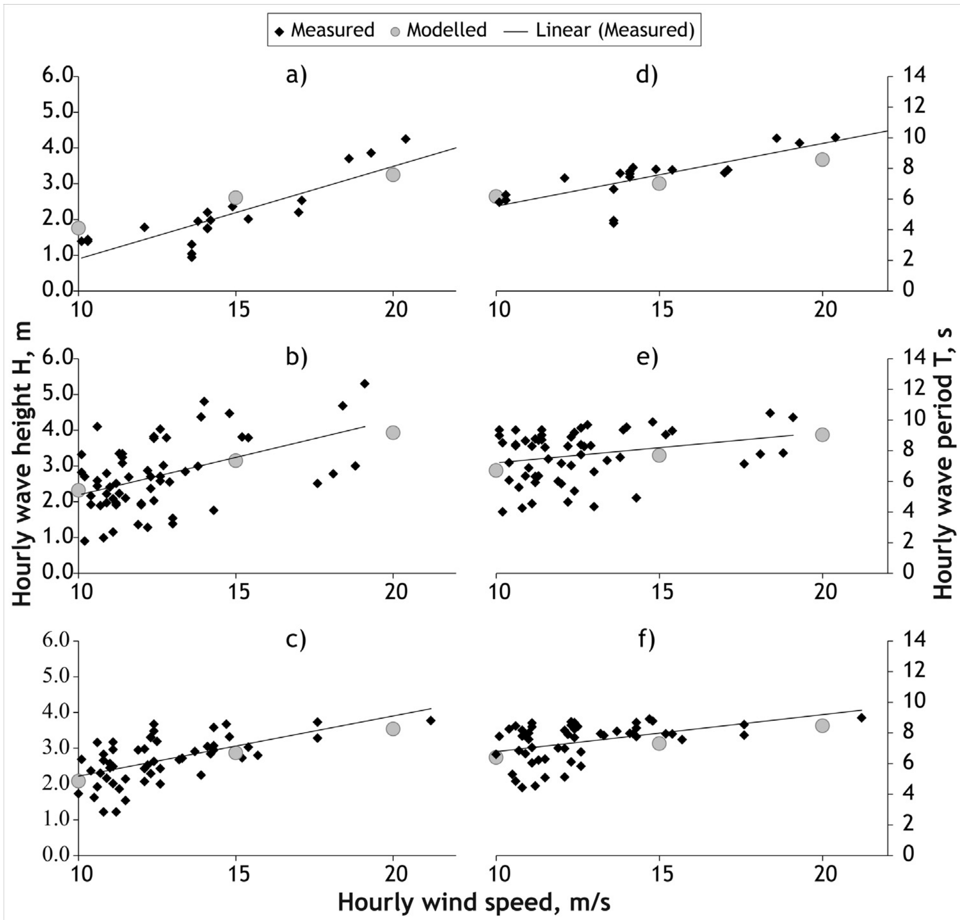

Figure 2 Relationships between wind speed and wave height for NW (a), W (b) and SW (c) wind directions and between wind speed and wave period for NW (d), W (e) and SW (f) wind directions.

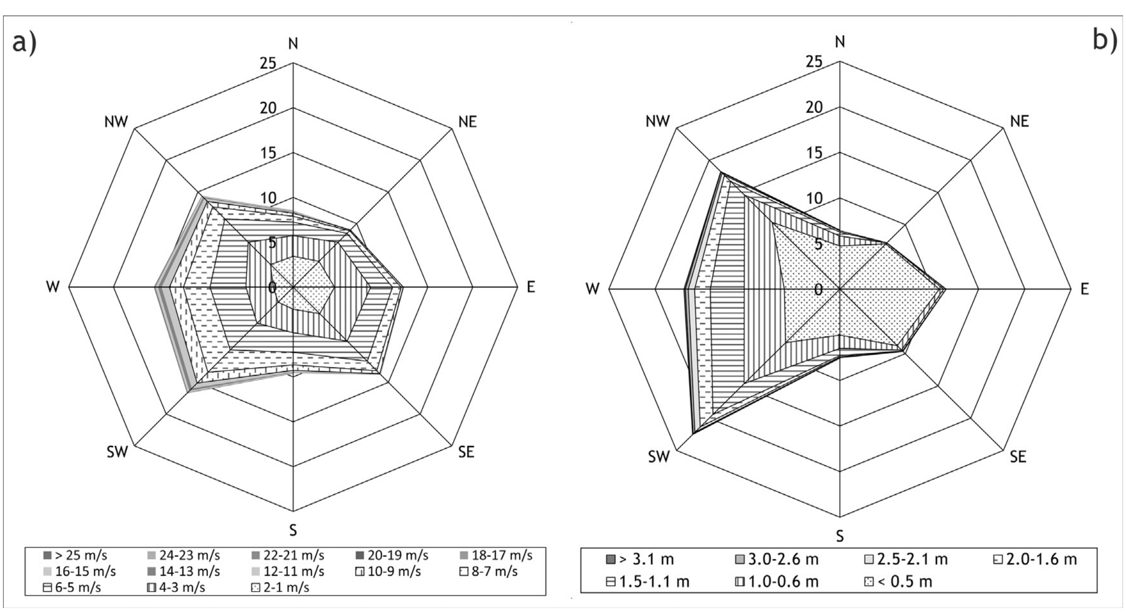

Figure 3 Wind (a) and wave (b) rose in the Baltic Sea Lithuanian nearshore (according to average daily data of Nida, Klaipėda and Palanga).

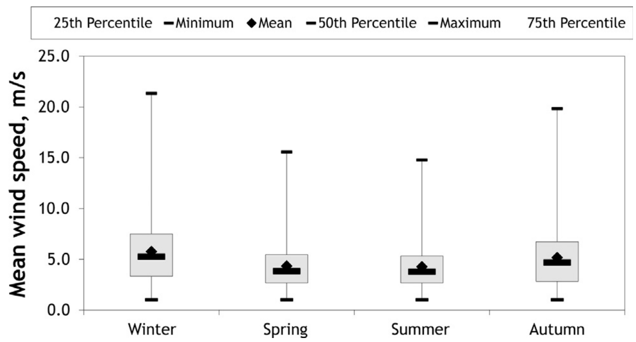

Figure 4 Mean wind speed in different seasons in the Baltic Sea Lithuanian nearshore (according to the averaged daily data of Nida, Klaipėda and Palanga MS).

The daily wind data from Nida, Klaipėda and Palanga MS was used to analyse wind speed in different seasons (Fig. 4). As shown in Fig. 4, the strongest winds are characteristic for the winter and autumn seasons. The greatest values can reach 21 m s^{-1} in winter and 20 m s^{-1} in autumn. Despite the wide range of speed extremes, the average wind speed values differ only slightly. Wind speed values of 25—75% percentile vary from 3.3 to 7.5 m s^{-1} in winter, from 2.8 to 6.7 m s^{-1} in autumn, from 2.7 to 5.4 m s^{-1} in spring and from 2.7 to 5.3 m s^{-1} in summer.

The wave rose (created according to daily wave data from Palanga, Klaipėda and Nida in 1993—2011) (Fig. 3b) shows that waves of westerly directions (SW, W, NW) are the most common (57.7% of all cases), while waves approaching from N and S directions (parallel to the shoreline) are the least frequent (28.3% of all cases). Although 12% of waves are coming from the east, the height of these waves is small (up to 0.5 m). The highest waves are of westerly directions: 7.5% of them are higher than 1 m.

This research concentrates on the analysis of wind-generated waves, therefore the correlation between mean wave height and wind speed had to be defined. Fig. 5 illustrates the variation of annual mean wave height and wind speed near Klaipėda. The variation patterns of both curves are very similar; correlation is equal to 0.84.

There is a close relation between daily data of wave height and wind speed in the investigated areas. Wave data was grouped into 8 classes according to wave directions. Then,

Table 1 Correlation coefficients between wave heights and wind speeds (according to daily data of 1993—2011).

Station	Wave direction							
	N	NE	E	SE	S	SW	W	NW
Nida	0.85	0.19	0.05	0.16	0.73	0.87	0.86	0.86
Klaipėda	0.75	0.58	0.69	0.75	0.82	0.86	0.87	0.80
Palanga	0.69	0.37	0.19	0.43	0.64	0.80	0.84	0.81

the correlation coefficients between the wave heights of a particular direction and the wind speed were calculated. The strongest relation between these two variables was identified near Klaipėda (Table 1). Irrespective of the measurement station, the best correlation was found between the wind speed and heights of waves of western direction.

The seasonal and monthly regimes of mean wave height were studied in order to assess the wave energy potential, i.e. whether mean wave heights are sufficient to be successfully exploited. Scientific literature states that the minimum wave height for energy generation is 0.5 m (EPRI, 2011). The available wave observation data shows that mean wave heights are not always sufficiently high (Fig. 6). The waves along the Lithuanian coast were the highest from October to February. During these months, the average wave values exceeded 0.7 m in all MS. In March and June—September, the mean monthly wave height was close to 0.6 m, while in April and May it was close to 0.5 m.

Wave direction is another parameter important for the installation of wave energy converters. As it is presented in Fig. 7(a—c), waves approaching from western directions are the most dominant in all stations and during all seasons. During an average year, waves of these directions comprise from 54.8% (at Klaipėda) to 59.5% (at Palanga). They mostly prevail in summer (67.3%) and are sparse in autumn (53.2%). Waves of eastern direction occur twice less frequently than waves of western directions. Northern and southern waves are the most uncommon.

Durations of waves of a particular direction and height are essential for the assessment of wave energy potential as well. Fig. 8 shows only waves that are higher than 0.5 m. Waves of western directions emerge as the most intense and frequent

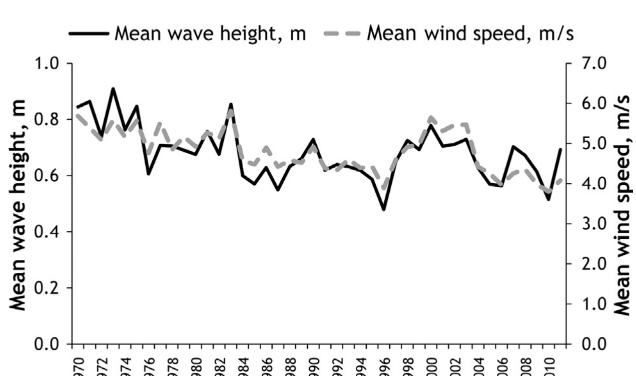

Figure 5 Variation of annual mean wave height and mean wind speed near Klaipėda.

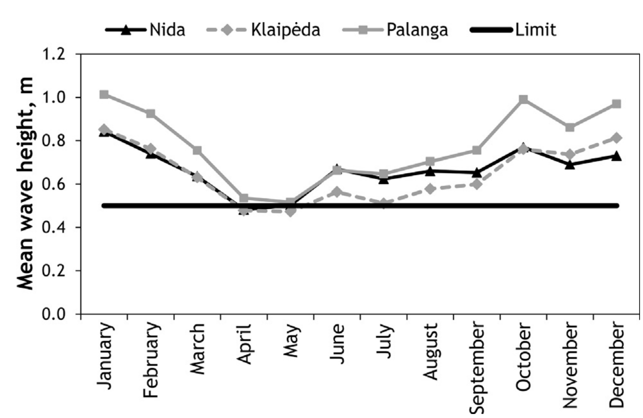

Figure 6 Mean monthly wave heights in the Baltic Sea Lithuanian nearshore (according to the data of 1993—2011).

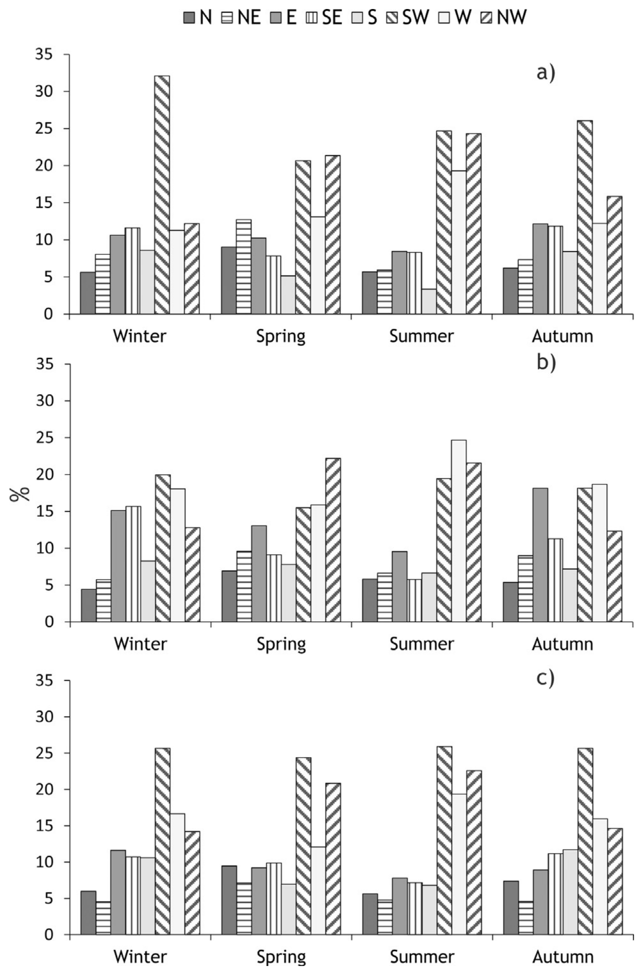

Figure 7 Seasonal variation of different wave directions (a — at Nida, b — at Klaipėda, c — at Palanga).

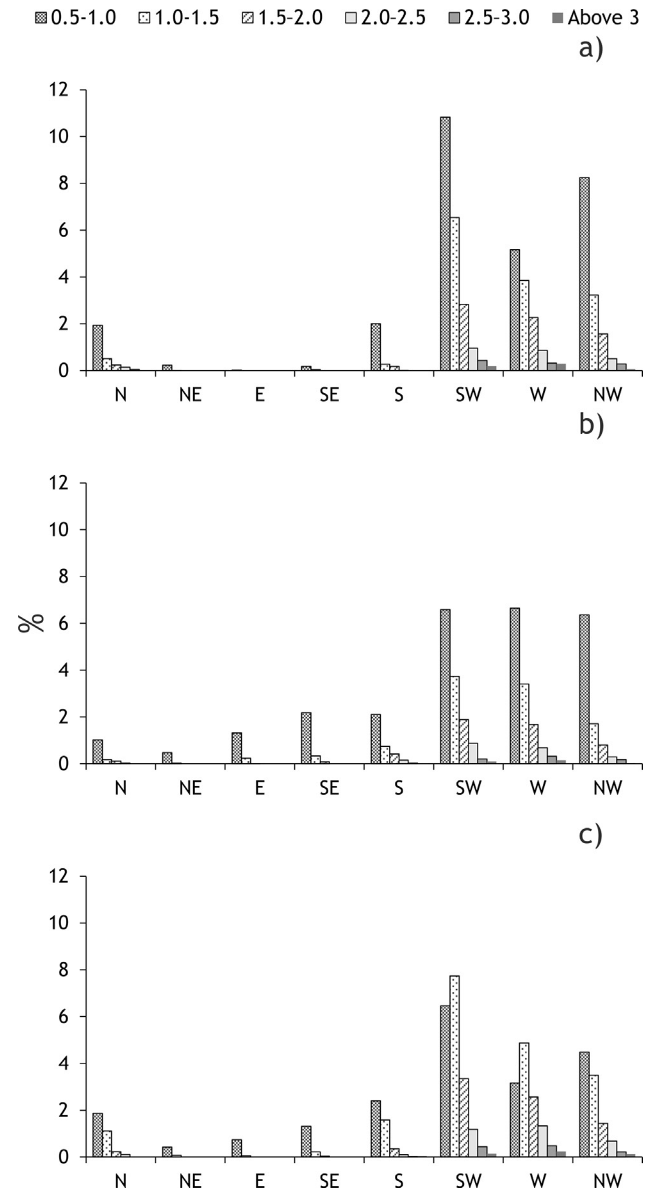

Figure 8 Wave durations (%) in the studied period, according to mean wave height and direction (a — at Nida, b — at Klaipėda, c — at Palanga).

along the Lithuanian cost. In all MS, higher than 3.0 m waves of these directions are observed in 0.5% of cases, while waves in the range of 2.0—3.0 m height occur in 3.4% of cases. Generally, lower than 2.0 m waves approaching from western directions are dominant in the Lithuanian nearshore. The amount of waves approaching from other directions is significantly lower. Daily wave height data of 1993—2011 at Nida, Klaipėda and Palanga was summarised using box diagrams (Fig. 9). Since waves of eastern directions appeared to have small heights and short durations, they were excluded from this analysis. The highest waves usually have SW and W directions. The mean height of waves reaches 1.0 m for waves of W direction, 0.9 m for waves of SW direction and 0.7 m for waves of NW direction. These heights are sufficient for energy generation.

The analysis based on long-term measurement data from three MS revealed the existence of a strong relationship between wind speed and wave height in the coastal area of Lithuania. As the available information of wave parameters from only three sites is not sufficient for a more detailed assessment of wave energy resources, a deeper investigation of propagation of waves in the entire water territory was performed using the MIKE 21 NSW model.

4.2. Mean wave height distribution in the Baltic Sea nearshore at Lithuanian coast

In order to model wave propagation in Lithuanian territorial waters, daily wind data (speed and direction) of selected three design years (corresponding to years of high, median and low wave intensity) were used. As it was determined in previous analysis (described in Section 4.1), small, energetically unusable waves (<0.5 m) are formed as a result of winds blowing from NE, E and SE. Therefore, wave propagation modelling was carried out only for the rest of wind directions and for 5, 10, 15 and 20 m s^{-1} wind speeds. Modelling results and a linear extrapolation method allowed to estimate wave parameters when wind speed changes at a 1 m s^{-1} interval from 1 to 20 m s^{-1}. Mean wave heights and periods in each modelled grid for each design year were

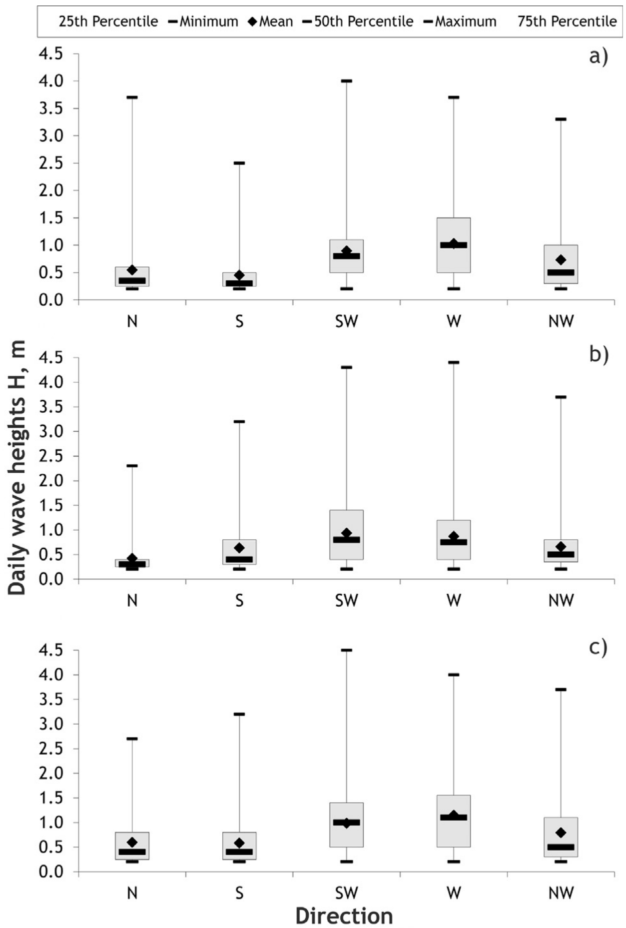

Figure 9 Variation of daily wave heights in the Baltic Sea Lithuanian nearshore (a — at Nida, b — at Klaipėda, c — at Palanga).

calculated using daily wind parameters of the selected year. The estimated wave parameters were used in the assessment of wave energy resources in the Baltic Sea Lithuanian nearshore.

During the analysis of wave propagation modelling results, it was found that wave parameters depend on water depth. Mean wave heights in the nearshore at 10 and 30 m isobaths when winds of 15 m s^{-1} are blowing from different directions are presented in Fig. 10.

To compare wave propagation in a year of high, median and low wave intensity, distribution of wave heights and periods was calculated at 10, 20 and 30 m isobaths in the selected design year (Fig. 11). The lowest waves are characteristic for low wave intensity year (Fig. 11a). In general, mean wave height in the investigated water area reaches 0.68 m and varies from 0.65 m at a 10 m isobath to 0.73 m at a 30 m isobath. In a year of high wave intensity (Fig. 11c), the mean wave height is 0.98 m, while it is equal to 0.94 m at a 10 m isobath and exceeds 1 m at 20 and 30 m isobaths along the coastline (1.03 and 1.05 m respectively). The performed modelling confirmed that regardless of the design year, the mean wave height increases more significantly when the water depth changes from 5 to 20 m, although this increase becomes much less significant if the depth grows. Wave height differences along a particular isobath are not so distinctly expressed: for example, in a year of median wave intensity, the wave height ranges between 0.76—0.82 m at a 10 m isobath and 0.88—0.90 m at a 30 m isobath.

In the assessment of wave energy potential, mean wave height seasonality is also of great importance. A year of median wave intensity was chosen to study this phenomenon in the Baltic Sea Lithuanian nearshore (Fig. 12). It was found that in the investigated area, the greatest waves prevailed in autumn and winter, while the smallest waves dominated in spring and summer.

4.3. Mean wave energy flux distribution in the Baltic Sea nearshore at Lithuanian coast

The mean wave energy flux characteristic (kW m^{-1}) which depends on mean wave height and period was used to assess the wave power potential in the Baltic Sea Lithuanian nearshore. A strong relation between wave parameters and energy flux is observed: the mean power flow increases together with the mean wave height.

Distribution of energy fluxes in the nearshore at different isobaths in a year of different wave intensity is presented in Fig. 13. In a year of high wave intensity, the mean wave energy flux was 1.75 kW m^{-1} at a 10 m isobath, 2.07 kW m^{-1} at a 20 m isobath and 2.16 kW m^{-1} at a 30 m isobath

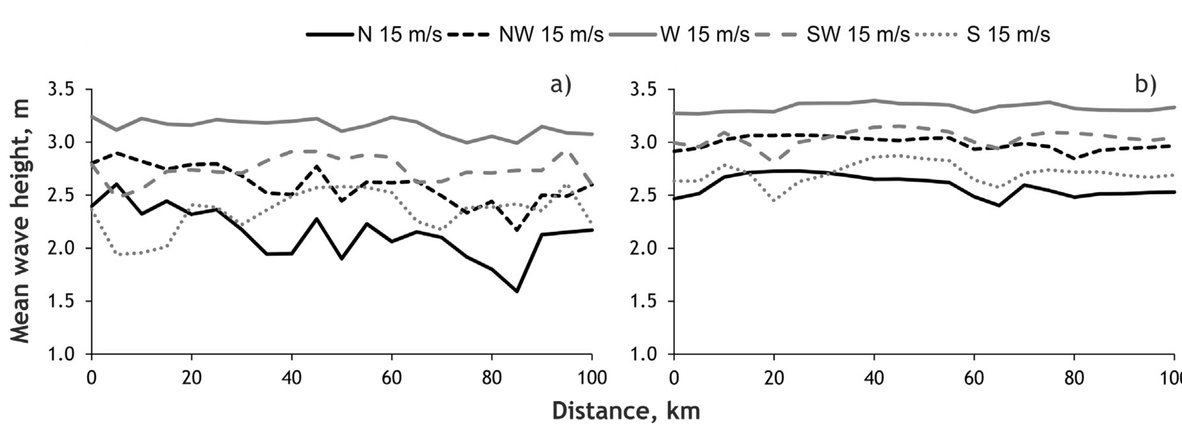

Figure 10 Mean wave heights in the Baltic Sea Lithuanian nearshore, when winds of 15 m s^{-1} of different directions are blowing: at a 10 m isobath (a), at a 30 m isobaths (b).

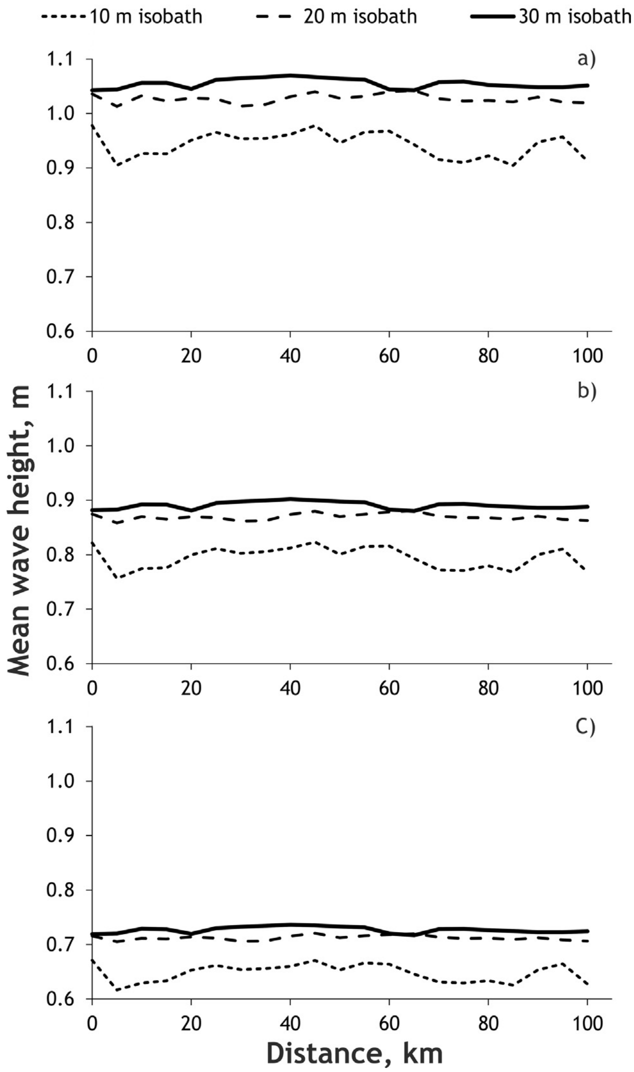

Figure 11 Distribution of mean wave heights at 10, 20 and 30 m isobaths in the Baltic Sea Lithuanian nearshore in a year of high (a), median (b) and low (c) wave intensity.

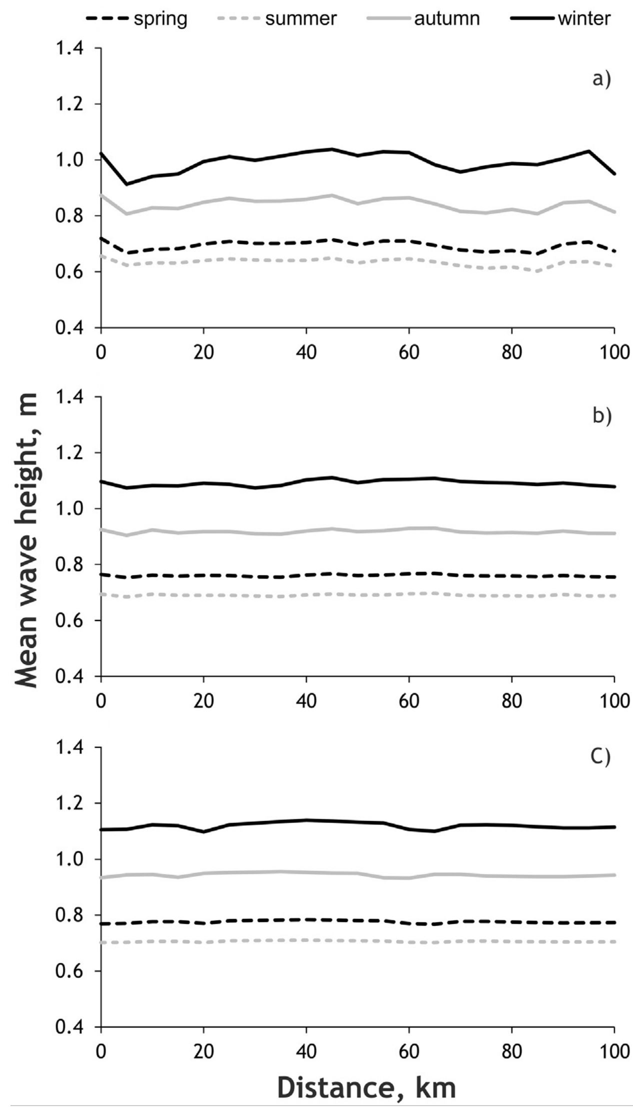

Figure 12 Seasonal distribution of mean wave height in the Baltic Sea Lithuanian nearshore in a year of median wave intensity (1994—1995): at 10 m (a), 20 m (b) and 30 m (c) isobaths.

(Fig. 13a). In a year of median wave intensity, the energy flux at the mentioned isobaths was 1.10, 1.32 and 1.38 kW m^{-1} (Fig. 13b) respectively. In a year of low wave intensity, the energy flux at the mentioned isobaths was 0.64, 0.77 and 0.80 kW m^{-1} (Fig. 13c) respectively. The mean wave energy flux of the entire investigated water territory varied from 0.69 to 1.90 kW m^{-1} in years of different wave intensity. The analysis of wave energy flux along the coastline revealed greater differences at 5 and 10 m isobaths (where deviation from the mean value comprised $\pm$12 and $\pm$8% respectively) than at 20 and 30 m isobaths (where these differences were insignificant, i.e. $\pm$3%).

In the Baltic Sea nearshore, the seasonal distribution patterns of mean wave energy flux and wave height are very similar. The highest energy potential is observed during the autumn and winter seasons, while the lowest potential is observed in spring and summer (Fig. 14). For example, in winter of a year of median wave intensity at a 20 m isobath, the mean wave energy flux was 2.49, in autumn — 1.47, in spring — 0.96 and in summer — 0.96 kW m^{-1} (Fig. 14b). Similar tendencies of the seasonal distribution were identified at 10 and 30 m isobaths as well.

5. Discussion and conclusion

Wind-generated wave energy production in the Baltic Sea is only taking its first steps: most of researchers are still concentrated on theoretical assessments of the potential (Bernhoff et al., 2006; Blažauskas, 2013; Henfridsson et al., 2007; Kasiulis et al., 2015; Soomere and Eelsalu, 2014). The findings of the present study enhance our understanding of wave climate in the Lithuanian territorial waters of the Baltic Sea and could help selecting appropriate nearshore water territories for effective harvesting of sea wave energy. This study was designed to assess the wave climate and energy resources in the Baltic Sea nearshore at the Lithuanian coast.

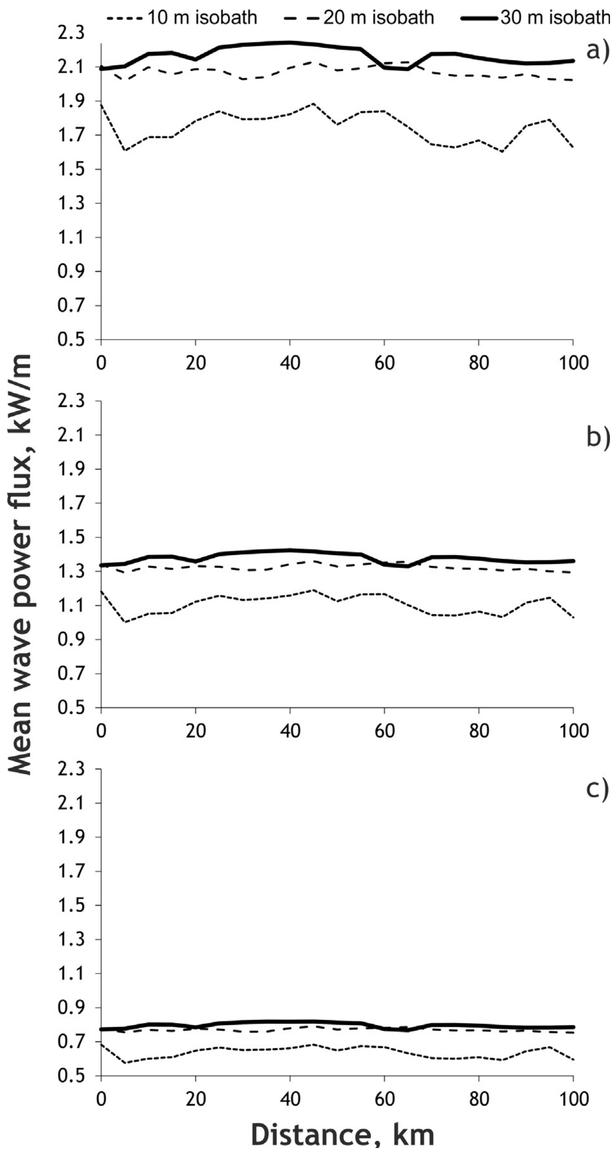

Figure 13 Distribution of mean wave energy flux at 10, 20 and 30 m isobaths in the Baltic Sea Lithuanian nearshore in a year of high (a), median (b) and low (c) wave intensity.

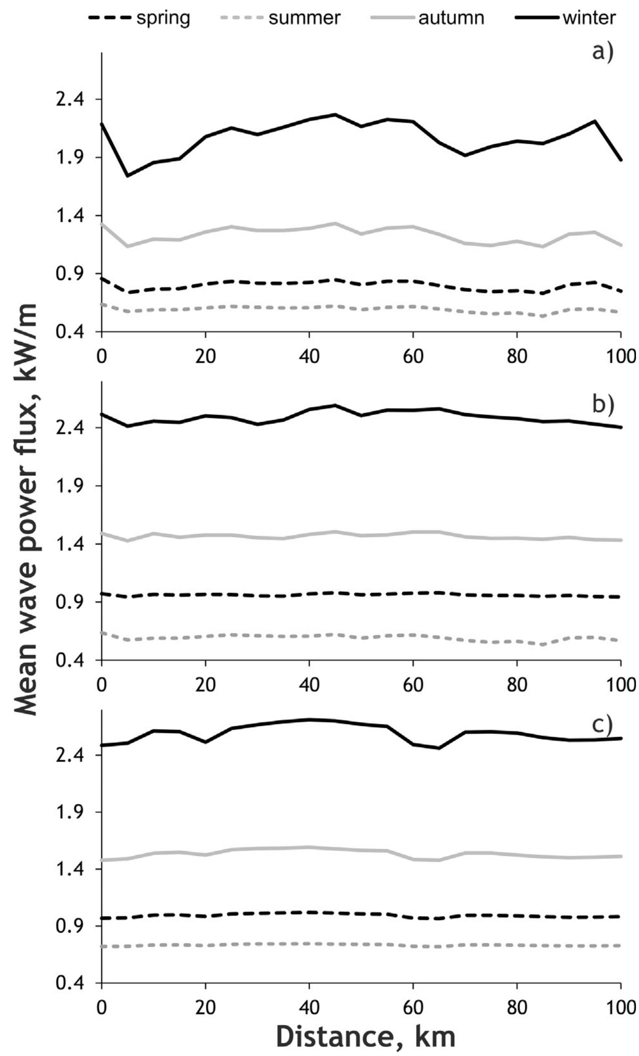

Figure 14 Seasonal distribution of mean wave energy flux in the Baltic Sea Lithuanian nearshore in a year of median wave intensity (1994—1995): at 10 m (a), 20 m (b) and 30 m (c) isobaths.

It was determined that 57.7% of the waves observed in the Baltic Sea Lithuanian nearshore are of western directions (SW, NW and W), while waves of eastern directions are less dominant (28.3%) and waves of S and N directions are the rarest (comprising 7.6% and 6.4% respectively). The mean waves approaching from western directions have the greatest heights and reach 0.9 m, whereas mean wave heights are 0.6 m for waves approaching from southern direction, 0.5 m for waves from northern direction and 0.3 m for waves from eastern direction. The predominant westerly wind directions which generate the highest waves in the eastern part of the Baltic Sea are underlined in other scientific studies (Bernhoff et al., 2006; Henfridsson et al., 2007; Kelpšaitė and Dailidienė, 2011) as well.

The analysis of observation data revealed a seasonality of wind speed and wave height: the strongest winds and the highest waves are characteristic for winter (5.7 m s^{-1} and 0.85 m) and autumn (5.1 m s^{-1} and 0.76 m), while the weakest winds and the lowest waves are inherent in spring (4.7 m s^{-1} and 0.56 m) and summer (4.7 m s^{-1} and 0.62 m). These results are also in line with those of previous studies (Street et al., 2014).

In the current study, it was determined that in a year of high wave intensity, the mean wave height reaches 0.98 m, while in a year of median wave intensity it reaches 0.83 m. In a year of low wave intensity, the mean wave height is 0.68 m. The greatest wave heights were identified in areas with water depths equal to or greater than 20 m. In a year of different wave intensity, the mean wave height in such depths ranges from 1.04 to 0.72 m, whereas in shallower waters it ranges from 0.93 to 0.63 m.

The present assessment of wave energy resources in the Baltic Sea Lithuanian nearshore indicated that the mean wave energy flux was equal to 1.21 kW m^{-1} in a year of median wave intensity. The value of wave energy flux depends on seasonality in the same way as wave height. In a year of median wave intensity, the largest energy fluxes were estimated in winter (2.38 kW m^{-1}), while smaller ones were identified in autumn (1.41 kW m^{-1}) The smallest energy fluxes were estimated in spring and summer (0.92 and 0.68 kW m^{-1} respectively). Prior studies of the Baltic Sea wave power potential delivered similar results: about 1.5 kW m^{-1} in the nearshore regions of the eastern Baltic Proper (Soomere and Eelsalu (2014) and from 0.4 kW m^{-1} to 1.6 kW m^{-1} in the Baltic nearshore at Klaipėda (Kasiulis et al., 2015)).

The completed study confirmed that irrespective of the design year, both wave height and wave power flux increase more significantly when water depth increases from 5 to 20 m. Values of the mentioned parameters tend to change only slightly when the sea gets deeper than 20 m. These findings match those identified in other studies, such as the study performed by Soomere and Eelsalu (2014), who stated that the best location for wave energy converters is in the nearshore at water depths of 15—20 m. The identified differences of wave height and energy along the selected isobaths were insignificant.

The results obtained from the modelling of wave propagation according to the created methodology can be used for preliminary assessment of wave energy resources in the selected design year in any place of the Baltic nearshore.

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