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Wave regime differences along the eastern coast of the Baltic Proper

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Abstract. An effort is made to identify the basic features of subdecadal and decadal changes in the wave climate at different locations in the eastern sector of the Baltic Proper based on the annual mean wave height. Comparison of Vilsandi and Almagrundet data from the northern Baltic Proper with visual observations from the Lithuanian coast during 1993–2005 shows that short-term variations (1–3 years) of the annual mean wave height have a similar nature at all sites but trends of decadal and subdecadal variability are very different in different parts of the Baltic Proper.

Key words: environmental science, wind waves, wave climate, visual wave data, Baltic Sea oceanography.

INTRODUCTION

The properties of wave fields of the Baltic Proper have been discussed in a number of recent studies based on instrumental measurements, numerical simulations, and visual observations (see Kahma et al., 2003; Broman et al., 2006; Soomere and Zaitseva, 2007, and references therein). Waves are usually of relatively moderate height, but are frequently short and steep. The typical wave periods are 3–4 s in coastal areas and 4–6 s on the open sea. Significant wave heights H_S exceeding 4 m occur with a probability of about 1% and wave heights $H_S \geq 7$ m have been registered only five times since 1978. The overall pattern of wave activity follows the well-known anisotropy of wind patterns in this area (Soomere and Keevallik, 2001). Statistically, the highest and longest waves occur in the eastern and north-eastern part of the Baltic Proper (Jönsson et al., 2002, 2005; Soomere, 2003).

There has been discussion on whether wave activity in this area has been increasing in the recent past. On the one hand, Orviku et al. (2003) argue that the apparently increasing storminess in the Baltic Sea has already caused extensive erosion of several coastal sections. This is in accord with the conclusion that the mean wind speed has increased at measurement sites on the southern coast of Finland (Keevallik and Soomere, 2004). On the other hand, the analysis of long-term behaviour of the annual mean wave height at Almagrundet (in 1977–2003) and Vilsandi (in 1954–2005), located at the opposite coasts of the Baltic Proper (Fig. 1), shows that the wave activity (understood below as the annual mean wave height) at both sites increased considerably in the 1980s, was highest at the turn of the millennium, and has quickly decreased since about 1998 (Broman et al., 2006; Soomere and Zaitseva, 2007). Moreover, during the last decade, the annual mean wave height has varied considerably: from about 0.4 m to 1.2 m at Vilsandi and from about 0.5 m to 1.5 m at Almagrundet.

This mismatch of the changes in wind and wave properties is apparently not caused by secular changes in the dominant wind directions (Soomere and Zaitseva, 2007). This conjecture is implicitly supported by the wave data from Lithuania (discussed below), which show almost no long-term changes since 1993. The mismatch is rather induced by changes in certain other properties of the wind fields, such as the duration of winds from different directions or changes in wind patterns related to the shifts of the trajectories of

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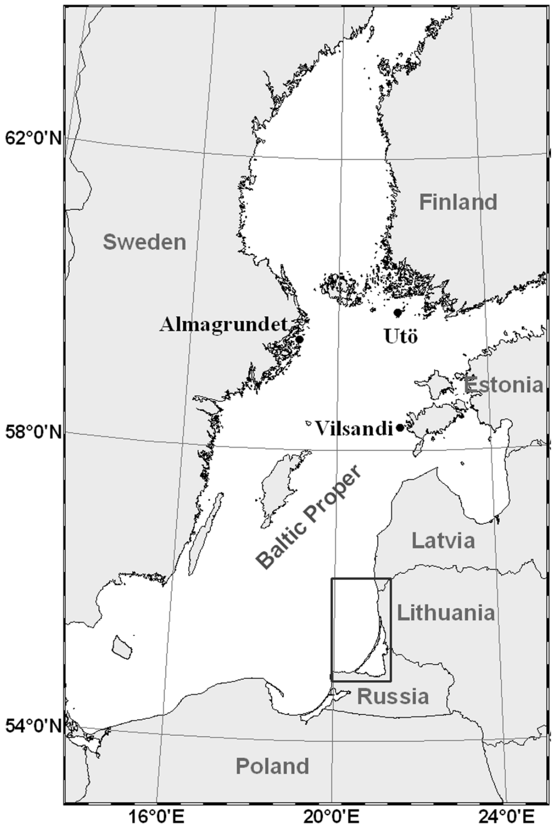

Fig. 1. Wave observation points in the northern part of the Baltic Proper.

cyclones (Alexandersson et al., 1998; Suursaar et al., 2006), which are usually not accounted for in classical climate change studies. Such changes may lead to greatly different variations of wave conditions in different parts of the sea and, in general, to complicated patterns of spatio-temporal variations of wave fields.

The first step towards identification of such patterns consists in the comparison of the results discussed above with similar long-term data from the southern part of the Baltic Sea. Owing to the above-mentioned anisotropy of the Baltic Sea wave fields, one might expect the greatest changes to happen along the downwind, eastern coast of this water body. As in the eastern part of the Baltic Sea, instrumental measurements of wave properties are almost absent (CMR, 2007; Soomere, 2008), the only available source for such a comparison is visually observed data.

Visual observations from the coast have been frequently interpreted as representing only wave properties in the immediate vicinity of the observation point. Such data always contain elements of subjectivity and are not necessarily homogeneous in time. Usually they have poor spatial and temporal resolutions. They inadequately characterize waves for offshore wind directions and may give a distorted impression of extreme wave conditions because of wave breaking and reflection in shallow water. Visual wave observations are, however, one of the few sources for detecting the wave climate and its long-term changes. Their basic advantage is the large temporal coverage. In the second half of the 20th century, such observations (optionally performed using perspectometers, Soomere and Zaitseva, 2007) were undertaken in many locations on the eastern coast of the Baltic Sea using a standard procedure. An analysis performed by Soomere and Zaitseva (2007) demonstrates that their results – interpreted as regular samples of wave conditions at a site – match instrumentally obtained data and adequately reflect seasonal and long-term changes in wave activity.

In this paper, an attempt is made to identify basic features of long-term changes in the wave climate in the eastern sector of the Baltic Proper. The analysis is based on the comparison of visual observations at the coast of Lithuania in 1993–2005 with the longest wave data series available in the northern Baltic Proper (Almagrundet 1977–2003 and Vilsandi 1954–2005). It starts with the description of the measurement site at Palanga (data from there are apparently the most representative) and provides details that enable assessment of the overall quality of the available data. Next follows an analysis of the long-term variation of wave heights in different parts of the sea.

OBSERVATION SITES AND DATA

Regular surface wave observations along the entire eastern coast of the Baltic Proper were started in the middle of the 20th century in the framework of routine marine observations performed by the USSR hydrometeorological service. Although the number of observation sites and the selection of observed parameters have decreased over the course of time, several sites have been operational almost permanently. However, at this time, only a small fraction of data has been digitized and properly analysed.

The recently digitized data for 1954–2005 from the island of Vilsandi, western Estonia (Soomere and Zaitseva, 2007; see Zaitseva, 2006 for a description of this site and the details of the observation procedure), are the most representative data for the north-eastern part of the Baltic Proper, and with the largest temporal coverage. The longest instrumentally measured wave data from Almagrundet (Broman et al., 2006) apparently characterize well the decadal changes in wave activity in the north-western area of the Baltic Proper.

In Lithuania, wave observations started soon after the establishment of the hydrometeorological station in Klaipėda in 1949 (Klimienė, 1999). Since the 1950s wave properties have been recorded at three observation points (Nida, Klaipėda, and Šventoji, Fig. 2, Table 1)

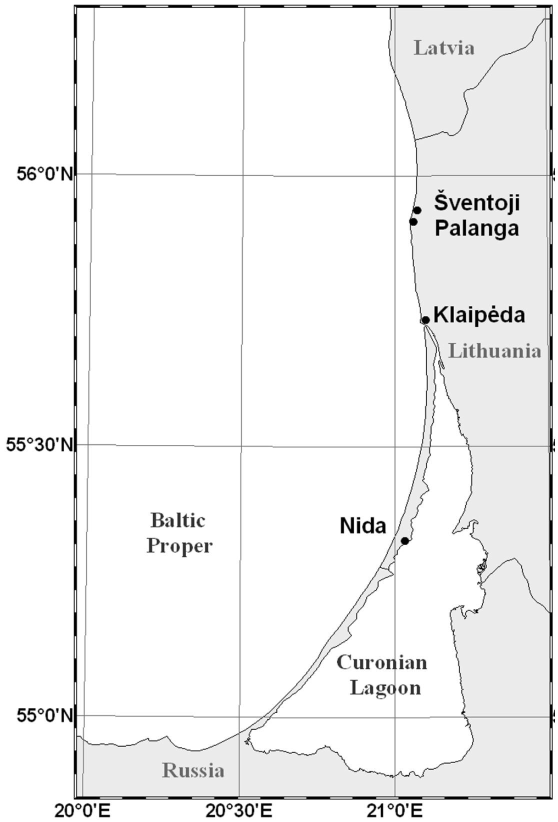

Fig. 2. Wave observation points at the Lithuanian coast.

Table 1. Wave measurement and observation sites

Site	Coordinates	Method	Data available
Almagrundet	59°09′N, 19°08′E	Inverted echo-sounder	1977–2003
Vilsandi	58°23′N, 21°51′E	Visual observations	1954–2005
Nida	55°18′N, 21°00′E	Visual observations	1993–2005
Palanga	55°55′N, 21°03′E	Visual observations	1993–2005
Klaipėda	55°42′N, 21°07′E	Visual observations	1993–2005

along the Lithuanian coast. The observation site at Šventoji was active until the mid-1970s, after which the station was moved to Palanga. As the observing conditions, routine, and the overall properties of the coast and the nearshore are very similar at these sites, this move obviously did not cause inhomogeneity of the data set. The observation diaries and databases are now kept in the Centre of Marine Research (CMR) in Klaipėda. Observations at all Lithuanian sites and at Vilsandi were made using the same methodology over a half-century. This feature also suggests that the data sets are generally homogeneous and that the comparison of wave properties extracted from these sets is adequate.

The Palanga, Klaipėda, and Vilsandi observation sites are fully open to the dominant wind directions (SW and NNW), but are mostly sheltered from waves excited by eastern (offshore) winds. The geometry of the coastline at the town of Nida permits proper observation of only properties of waves approaching from the western direction (W–NNW). As the observer was located just a couple of metres above waterline at Vilsandi and the water depth at the wave observation point was about 4 m (Soomere and Zaitseva, 2007), waves higher than 4 m could not be adequately recorded at that site.

At Nida, the observer was standing at a turret located 7 m above the mean water level at the coast. The point at which the properties of waves were observed was about 700 m from the coastline at a water depth of 6–7 m (CMR, 1958; Klimienė, 1999). At Klaipėda, waves were observed from the stations located on the coast about 3 m above the mean water level. The point at which wave properties were estimated lay about 500 m from the coastline.

At Palanga, observations were made from the Palanga Sea Bridge, a light jetty standing on pillars, presently with its surface about 3 m above the water level and extending to 470 m offshore. Waves were observed in a 6–7 m deep area. This location made it possible to minimize shallow-water effects on the observed wave field and to use the bridge pillars as an additional fixed scale for estimates of the wave properties. As Palanga lies on an almost straight coastline, the directional extent of adequately observable waves is the largest of the Lithuanian sites. For these reasons the wave data from Palanga are probably the most representative for the Lithuanian coastline (Klimienė, 1999).

Wave observations were only performed during daylight hours at the Lithuanian sites. The initial observation times in the 1950s and 1960s were 7:00, 13:00, and 19:00 Moscow time (GMT +3 hours) (Gidrometeoizdat, 1985), which were later shifted to 6:00, 12:00, and 18:00 GMT according to the guidelines of the World Meteorological Organization (WMO, 1981). This shift apparently has no substantial impact on the quality and homogeneity of the data.

There is a difference in the detail of observation routines at Lithuanian observation stations and Vilsandi that becomes evident during the winter season. Namely, the short duration of daylight allowed only one observation per day at Vilsandi while at Lithuanian observation stations almost always two sensible observations (at 6:00 and 12:00) could be made. The potential influence of this difference on the interpretation of the wave activity during different seasons and on the comparison of data from the two sites is eliminated by means of using the daily mean wave height at all sites as recommended by Soomere and Zaitseva (2007).

The duration of a wave storm seldom exceeds 10 h in the Baltic Proper (Broman et al., 2006). Therefore, even the strongest storms, if they were not long enough or occurred during a night or were accompanied by low visibility, are not necessarily represented in the data set. Consequently, the observations cannot be used for a reconstruction of the time series of the sea state. Instead, they are interpreted as a set of regular samples reflecting the state of the sea. Since the number of observations is quite large, the data reflect the basic features of the wave climate at the site.

The data set from Lithuanian observation stations contains information about wave direction, the maximum and the mean wave height, and the wave period. Unlike at Vilsandi, wave periods were recorded at Lithuanian sites only if these were larger than 7 s. Since wave conditions with such periods form a clear minority of the Baltic Sea wave fields (Kahma et al., 2003; Broman et al., 2006; Soomere, 2008), only a few periods of data were registered and they will not be analysed in this article.

The wave height observation procedure mirrors the background idea of the classical zero-up/downcrossing method (IAHR, 1989) in which the wave height is directly inferred from the surface time series at a fixed point as the distance from the wave trough to the crest. The observer noted the five highest waves during a 5-minute time interval with an accuracy of 0.25 m for wave heights less than 1.5 m, 0.5 m for wave heights from 1.5 to 4 m, and 1 m for higher waves. The highest single wave and the mean height of these five waves were filed (Soomere and Zaitseva, 2007). As the typical wave periods in the Baltic Proper are 3–6 s (Kahma et al., 2003; Soomere, 2008), the observed wave height therefore, formally, corresponds to the mean height of about 5–10% of the highest waves during each observation period. The experience with the visual observations, however, proves that the observer's estimate represents rather well the significant wave height (Gulev and Hasse, 1998, 1999), the latter being approximately equal to the mean height of one-third of the highest waves. The particular interpretation of the measured or observed characteristics is, however, not important in the analysis below, where we concentrate on temporal evolution of wave heights.

The frequency of different wave heights at Vilsandi resembles analogous distributions for wave heights in semi-sheltered bays such as Tallinn Bay of the Baltic Sea (Soomere, 2005). These distributions have a very high percentage of almost calm situations corresponding to offshore winds. Another (probably observer-specific) feature of visually measured wave statistics is that the percentage of wave heights slightly above 1 m, 1.5 m, etc. is considerably larger than the number of wave conditions slightly below these values (Soomere and Zaitseva, 2007). This peculiarity has frequently been recorded by older semi-visual observations of wind speed with the use of weather vanes and is to some extent visible in wave statistics from Palanga (Fig. 3) for wave heights around 1 and 2 m, but not in Nida data.

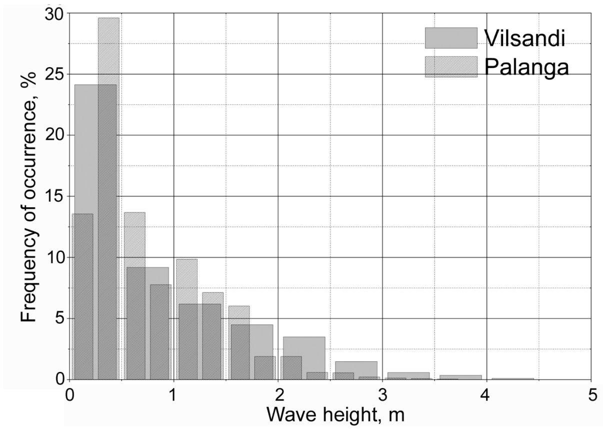

Fig. 3. Frequency of occurrence of different wave heights at Vilsandi (resolution 0.5 m, wide bars) and Palanga (resolution 0.25 m, narrow bars).

Calm conditions dominate at Vilsandi (Soomere and Zaitseva, 2007) but not at Palanga where 0.25–0.5 m high waves are the most frequent, and the entire distribution of wave heights resembles the distributions in the open parts of the Baltic Sea (Soomere, 2008). Yet, a large fraction of (almost) calm situations apparently reflects the near-coastal conditions. As expected, at Klaipėda and Nida, where the observations were made from the coast and thus the details of the sea state were more difficult to observe, the most frequent observations are of almost calm conditions (wave heights below 0.25 m).

Relatively small waves (0–0.5 m) form almost a half of the observations at all Lithuanian sites, where the median wave height is close to 0.5 m as at Vilsandi. Waves 1–2 m in height also occur with an appreciable frequency whereas waves over 2 m form less than 5% of all observations. The distributions of wave heights at Klaipėda and Nida are similar to those at Vilsandi. The shape of the occurrence frequency distribution of wave heights along the Lithuanian coast suggests that wave observations are generally reliable and that they more or less adequately reflect wave conditions in this part of the Baltic Proper.

DECADAL VARIATIONS

The digitized wave data set from Nida, Klaipėda, and Palanga covers the years 1993–2005. This period contains a most interesting sub-period, 1998–2005, during which a rapid decrease in the annual mean height was observed in the northern sector of the Baltic Proper

(Broman et al., 2006; Soomere and Zaitseva, 2007) after a considerable increase at the end of the 1980s and the beginning of the 1990s. The total variation of the annual mean wave height during the last two decades was almost fourfold: from about 35 cm in 1984 up to 1.2 m in 1995 (Fig. 4). At the same time the annual mean wind speed over the northern Baltic Proper was apparently increasing gradually (Fig. 4).

The overall mean observed wave height is the lowest at Nida (Fig. 5), probably because the coast at Nida is partially sheltered from the dominant SW winds. The decadal variation of the annual mean wave height is largely similar at all three Lithuanian observation sites. Both short-term variations (with the time scale of 1–3 years), as well as the decreasing trend in wave heights in the mid-1990s and a slight increase at the turn of the millennium, are basically in phase in all stations. The calmest year was 1996 at all sites when the annual mean wave height was as low as 0.3 m at Nida. This

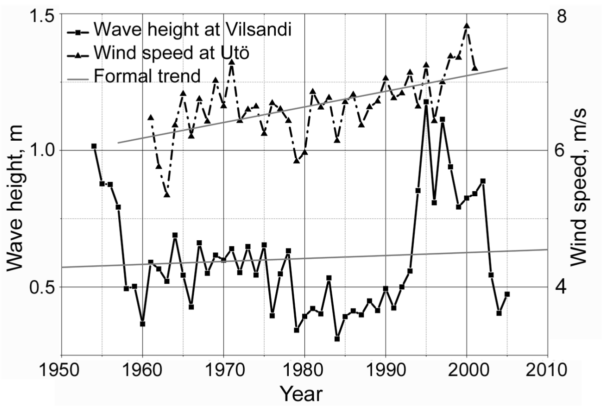

Fig. 4. Annual mean wave height at Vilsandi Island (Soomere and Zaitseva, 2007) and wind speed at Utö (Broman et al., 2006).

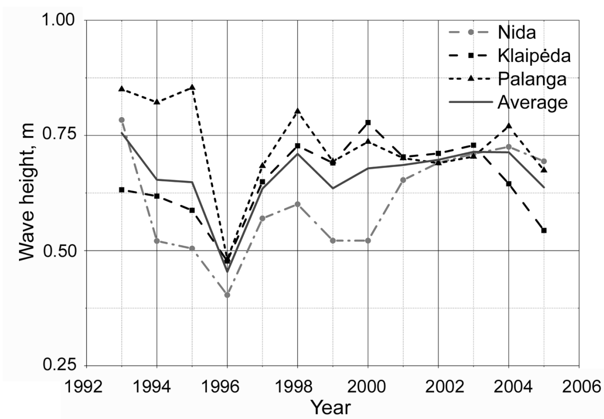

Fig. 5. Annual mean wave height at Klaipėda, Nida, and Palanga. The average over three Lithuanian stations is shown with a solid line.

coherence of changes in wave heights suggests that the site-specific changes and variations of wave intensity along the Lithuanian coast (with a total length of 90 km) are minor. In other words, the wave regime along this coastal section can be reasonably characterized by average wave properties along the entire coast.

A comparison of annual mean wave heights (Fig. 6) shows that the overall course of wave activity in Lithuania and at Vilsandi and Almagrundet mostly coincides in short timescales (1–3 years). Years with relatively low (e.g. 1996) and high (e.g. 1997–1998) wave activity become evident at all sites in the mid-1990s. This feature also suggests that all sites reasonably reflect long-term variations of wave activity in the neighbouring open sea areas.

Unlike at Vilsandi, the annual mean wave height at the Lithuanian coast shows relatively low interannual variation. The fluctuations of the mean wave height in Lithuania are from about 45 cm in 1996 to about 70 cm in 1993–1995 and 2003–2004. At the same time at Vilsandi the average wave heights vary between 40 cm in 2004 and 1.2 m in 1995. Such large variations of the annual mean wave height can also be observed in instrumentally measured data sets. For example, the annual mean wave height at Almagrundet decreased from 1.45 m in 1997 to 0.625 m in 2003.

The measurement sites at Almagrundet and Vilsandi are both open to a large part of the dominant winds (Broman et al., 2006; Soomere and Zaitseva, 2007). The more or less coherent temporal behaviour of wave activity at these sites (Soomere, 2008) suggests that (i) they adequately represent the overall changes in the wave regime and (ii) these changes have the same pattern in the entire northern part of the Baltic Proper.

A remarkable feature is that the variations of wave activity in the southern and northern parts of the Baltic Proper within the study period differ considerably. This

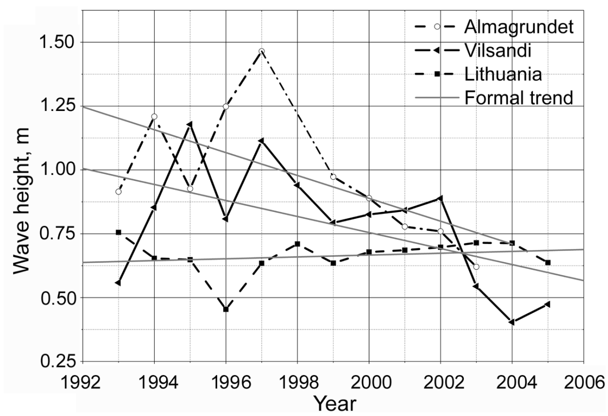

Fig. 6. Annual mean wave height at Vilsandi (Soomere and Zaitseva, 2007), Almagrundet (Broman et al., 2006), and the average over three Lithuanian stations. Data from Almagrundet in 1998 are missing (Broman et al., 2006).

difference becomes evident firstly in the overall pattern of changes in wave intensity and secondly in the form of opposite trends of decadal and subdecadal wave activity.

Apart from the relatively low wave activity at the Lithuanian coast in 1996, no great changes in the average wave height occurred during the entire period of 1993–2005. The linear regression line for these years shows a slight (albeit statistically not significant) increase in the wave heights. On the other hand, overall wave intensity in the northern part of the Baltic Proper exhibits drastic subdecadal variations (Fig. 6).

While the increase in wave activity at Vilsandi and Almagrundet in 1993–1995 (1997) can be interpreted as a direct reaction of the sea surface to the increase in wind speed over the northern Baltic Sea (Fig. 1), the wave intensity in Lithuania decreases during these years. On the other hand, wave activity at Vilsandi and Almagrundet experiences steep decrease (by up to 5 cm/year or about 10% on average) starting from 1997. The overall trend of mean wave heights is therefore opposite in the southern and northern parts of the eastern coast of the Baltic Proper.

CONCLUSIONS

Analysis of the observation conditions and basic features of wave data suggests that visually collected data from Lithuania represent relatively well the general features of the open sea wave fields. They apparently reflect the basic properties of the wave climate in this area, such as a moderate overall wave activity (with the annual mean wave height usually well below 1 m) and the presence of years with exceptionally low wave activity (the annual mean wave height as low as 0.4 m).

The main outcome from the comparison of Vilsandi and Almagrundet data with those from the Lithuanian coast is that the basic properties of (sub)decadal variability and relevant trends in the overall wave height are very different in different parts of the Baltic Sea. The wave activity at the coasts of the northern Baltic Proper showed drastic variations in the 1990s and at the turn of the millennium (Broman et al., 2006; Soomere and Zaitseva, 2007), but did not change much at the eastern coast of the southern part of the Baltic Proper. The overall wave intensity quickly decreases starting from about 1998 in the northern part of the Baltic Proper, but only changes insignificantly at the Lithuanian coast, actually showing there a slight increase. At the same time, short-term (2–3 years) variations of the wave intensity frequently are more or less in phase at all sites.

Although one cannot restore the exact course of wave properties over time from wave data obtained visually in hydrometeorological stations because of the low temporal resolution of the observations and their intrinsic uncertainties, these observations have been found to reflect satisfactorily the basic properties of the wave climate and its changes (Soomere and Zaitseva, 2007; Gulev and Hasse, 1998, 1999). The dissimilarity of the trends in the overall wave activity in the southern and northern parts of the Baltic Proper, combined with the mismatch of the temporal trends in wave heights and the overall gradual increase in the average wind speed in the area, suggests that the changes in local (wind) climate in the area in question may become evident in very different forms. Further examination of historical wave data from different regions of the sea may shed some light on the spatial patterns of changes in the wave regime in the Baltic Sea region.

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Läänemere idaranniku lainetuse režiimi muutlikkusest

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On analüüsitud tuulelainete aasta keskmise kõrguse muutumist aastail 1993–2005 Läänemere idarannikul lainetuse visuaalsete vaatluste alusel. Mere põhjaosa (Vilsandi ja Almagrundeti) andmestiku võrdlus Leedu rannikul registreeritud andmetega näitab, et lainetuse lühiajaline (1–3 aastat) muutlikkus on mere põhja- ning lõunaosas enamasti sarnase iseloomuga. Lainetuse režiimi pikaajalise muutlikkuse (4–10 aastat) trendid on mere eri osades erimärgilised.