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Spatial variations in the wave climate change in the eastern part of the Baltic Sea

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ABSTRACT

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The study presents new evidence of large spatial variations in wave properties along the eastern coast of the Baltic Sea. The short-term (1–3 years) interannual variability of the annual mean wave height is almost coherent along the entire eastern coast in 1958–1986. This coherence is completely lost from about 1987: since then the annual mean wave height at Narva-Jõesuu is in anti-phase with this height in the Baltic Proper. Also, in 1954–1957 the mean wave height in the eastern part of the Baltic Proper gradually decreases but rapidly increases in the Gulf of Finland. The decadal course of wave activity match relatively well each other at Nida and Vilsandi until about 1992, after which the annual mean wave height behavior is completely different at these sites. The largest difference between the long-term course in the wave height is found between Vilsandi (where the wave activity increases by a factor of two in 1987–1997 and decreases even more since then) and Narva-Jõesuu (where the wave activity gradually decreases over the entire observation period).

ADDITIONAL INDEX WORDS: *Wave climate, wave modeling, trends, climate change, Baltic Sea.*

INTRODUCTION

Wave climate and its changes are one of the key elements of physical oceanography and coastal science as wind waves are a major driver of coastal processes. Large changes in the wave climate are unlikely on the open ocean coasts where a substantial part of wave energy arrives in the form of swell waves (Dodet *et al*., 2010; Dragani *et al*., 2010). On the contrary, even small changes to the wind regime may easily lead to large variations in wave properties and extensive consequences for sedimentary beaches developing in fetch-limited conditions of semi-enclosed basins. For example, a change in the predominant wind direction may lead to a substantial increase in the typical fetch length in such basins. In this light, the wave climate is one of the most significant indicators of the changes in wind regime in semi-enclosed sea areas with complex geometry.

The temporal coverage of wave climate studies is usually limited by the length of existing wave time series. Typically, contemporary wave measurements begin from the 1970s. We discuss a unique data set of visual wave observations on the eastern coast of the Baltic Sea that goes back as long as to the mid-1950s. Its potential for the identification of the basic features of wave parameters and for the quantification of the seasonal cycle, inter-annual variations and long-term changes in the annual mean wave height (called wave activity below) has been discussed in (Soomere and Zaitseva, 2007; Kelpšaitė *et al*., 2008; Zaitseva-Pärnaste *et al*., 2009; Räämet *et al*., 2010). The analysis based on data from three observation sites on the north-eastern coast of the Baltic Sea has shown that the long-term course of the wave activity reveals no clear trend and has mostly a quasiperiodic nature, with the interval between subsequent periods of high or low wave activity about 25 years. The northern Baltic Proper was comparatively calm at the end of the 1950s, became slightly rougher in 1965–1975, and then calmer again at the end of the 1970s. A rapid increase in the annual mean wave height (well over 1% per annum) from the mid-1980s to the mid-1990s was replaced by a drastic decrease in the wave activity since 1997 (Broman *et al*., 2006; Soomere and Zaitseva, 2007). The increasing phase in the 1980s and the 1990s matches the analogous trend for the North Atlantic (Gulev and Hasse, 1999) whereas a subsequent decrease is consistent with the results of numerical simulations for the North Sea (Weisse and Günther, 2007). This course in wave activity is also consistent with the course of storminess over most of the North Atlantic and northern Europe. The storminess has gradually increased during most of the 20th century but this trend has ceased by the end of the 20th century (Alexandersson *et al*., 2000). Most of the described variations become evident in wave modeling efforts but the magnitudes of interannual and long-term variations are much larger in the visually observed data sets than in the numerically simulated ones (Suursaar and Kullas, 2009; Räämet *et al*., 2010; Suursaar, 2010).

In this paper, we extend the analysis of historical visually observed wave data to the SE part of the Baltic Sea. Based on a comparison of the existing data from the NE of the Baltic Sea with data from Nida on the coast of Lithuania, we present new evidence of large spatial variations in wave properties along the eastern coast of the Baltic Sea and of substantial decadal changes in the predominant wave propagation direction.

METHODS AND DATA

The analysis is based on four data sets recorded at (i) Nida at the northern part of Curonian Spit (1954–2009, 55°19′N, 21°01′E) in the south-eastern part of the Baltic Sea, (ii) the western coast of

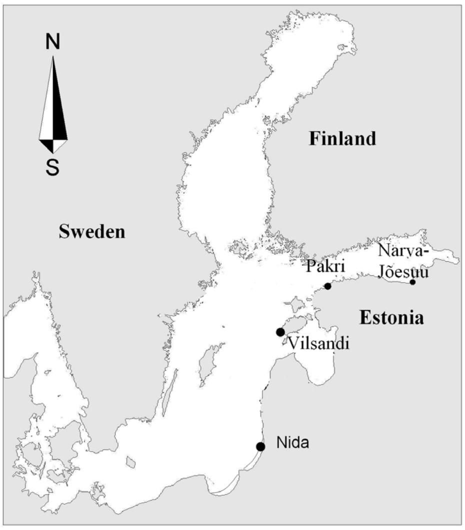

Figure 1. Location scheme of the long-term wave observation points sites on the eastern coast of the Baltic Sea.

the Island of Vilsandi (1954–2008, 58°22′59″N, 21°48′55″E) in the Western Estonian archipelago, (iii) Pakri (1954–1985) in the NW part of the Gulf of Finland (59°23′37″N, 24°02′40″E) and (iv) Narva-Jõesuu in the eastern part of the gulf (1954–2008, 59°28′06″N, 28°02′42″E) (Figure 1).

Systematic wave observations at these sites started in 1954 and have been carried out until today (until 1985 at Pakri) with the use of an identical observation procedure. Observations at Nida reflect well waves approaching from the directions of the largest fetch (west and NW, Kelpšaitė *et al*., 2008). Data from Vilsandi reflect well waves coming from all westerly directions (Soomere and Zaitseva, 2007). Pakri is a relatively deep-water observation site on the southern coast of the Gulf of Finland (Zaitseva-Pärnaste *et al*., 2009). Waves at Narva-Jõesuu usually stem from the Gulf of Finland. The presence of a large river mouth allows wide range of wave approach directions for observations (Räämet *et al*., 2010).

The analysis of visually observed wave data from three Lithuanian sites (Nida, Palanga and Klaipėda) for 1993–2008 shows that the changes to the annual mean wave height occur almost synchronously at these sites. This is not unexpected as the sites are located on the open slightly curved section of the coast with a length of <100 km (Kelpšaitė *et al*., 2008) and spatial changes to the wave climate have a typical scale of at least 200 km for the Baltic Proper (Soomere and Räämet, 2010). For this reason, we interpret the data from Nida as representing the wave climate and its changes for the entire coast of Lithuania.

A description of the observation sites, the procedure of observations and the basic properties of the wave data from the Estonian coasts is presented in (Soomere and Zaitseva, 2007; Zaitseva-Pärnaste *et al*., 2009; Räämet *et al*., 2010; Soomere *et al*., 2011) and we give here only the key information. We only use wave height and approach direction from different observed wave properties. The observational procedure resembles the classical zero-crossing method. The observer noted the five highest waves during a 5-minute time interval and recorded the highest single wave (its height is called the maximum wave height) and the mean height of these waves. As the typical wave periods in the coastal zone of the Baltic Sea are 3–4 s (Broman *et al*., 2006, Räämet *et al*., 2010), the resulting mean wave height is approximately equal to the average height of 3–6% of the highest waves. As the observers' estimates represent the significant wave height well (Gulev and Hasse, 1999), the visually observed data are interpreted as estimates of the significant wave height in the earlier studies (Zaitseva-Pärnaste *et al*., 2009, Räämet *et al*., 2010, among others). As swells of substantial height are infrequent in the Baltic Sea (Broman *et al.,* 2006), the wave approach direction normally represents the direction of the windseas.

The site on Vilsandi reasonably reflects wave conditions for the predominant wind directions (SW and N-NW) in the northern Baltic Proper but gives inadequate data for easterly winds (which are relatively weak and infrequent in this area). As the water depth is only 4–5 m over the area where waves are observed, the highest waves may experience substantial impact of bathymetry and may be already breaking. For this reason, observations of the unreasonably high waves are discarded from the data set (Soomere and Zaitseva, 2007).

The observed wave properties represent well the open sea conditions for northerly wave directions particularly at Pakri. The average depth of the area over which the waves were observed was 8–11 m. Waves were observed from a steep cliff 24 m from the mean sea level. The Pakri data set contains the evidence of the roughest ever reliably recorded wave conditions in the Estonian coastal waters. Namely the wave height of 6 m was recorded twice each day on 6–7 August 1967 when a strong NW storm excited extremely rough wave conditions and caused extensive damage to the forests (Zaitseva-Pärnaste *et al*., 2009).

Narva-Jõesuu meteorological station is located on the coast of Narva Bay in the eastern part of the Gulf of Finland. The height of the observation platform (12.8 m above the mean sea level) allows good wave observation conditions over the area located about 200–250 m from the coast. The average water depth in this area is 3–4 m. As waves in the Gulf of Finland are generally much lower than in the Baltic Proper, waves normally do not break in the observation area. The geometry of the coastline at Nida allows proper observations of the wave parameters approaching from the western direction (from the west to N-NW). The observer was standing at a turret located 7 m above mean water level at the coast. The point at which the properties of waves were observed was located about 700 m from the coastline at a water depth of 6–7 m (Kelpšaitė *et al*., 2008).

Wave observations were only performed during daylight hours. The initial observation times in the 1950s and the 1960s (7:00, 13:00 and 19:00 Moscow time (GMT +3 hours)) were later shifted to 6:00, 12:00 and 18:00 GMT according to the WMO guidelines. This shift apparently has no substantial impact on the quality and homogeneity of the data. The potential bias in wave statistics related to the different number of observations per day in different seasons is eliminated by means of using the daily mean wave height at all sites.

There are several gaps in the data from Estonian sites from January to March apparently owing to the presence of sea ice. At least one sensible observation exists at these sites, in average, on about 80% of all the calendar days. The influence of the gaps on the overall wave statistics can be partially removed by means of filling the missing daily mean wave heights by the climatological values for the particular calendar day (Soomere *et al*., 2011). As this procedure only changes the magnitude of the trends but does not alter the overall course of the wave activity for the Estonian sites, we do not apply it here.

The low temporal resolution of visual observations means that they cannot be used for a reconstruction of the time series of the sea state. They are interpreted here as a set of regular samples reflecting the sea state. Since the number of observations is quite large, it is natural to expect that the data reflects the basic features of the wave climate at the site. All the observed and hindcast data sets reproduce the basic features of the northern Baltic Sea wave fields (Kahma *et al.*, 2003; Soomere, 2008; Räämet and Soomere, 2010; Räämet *et al.*, 2010) such as (i) the overall mildness of wave conditions with the long-term mean wave height in the open sea approximately 1 m and in the coastal areas 50–60 cm, (ii) a large proportion of wave conditions with the significant wave heights around 0.5 m, (iii) the most frequent peak periods 4–6 s in the open sea and 2–4 s in the nearshore regions, (iv) the match of the distribution of the most frequent combinations of wave heights and periods with fully saturated wave fields with the Pierson-Moskowitz spectrum and (v) strong seasonal variability in the Baltic Sea wave fields.

RESULTS

The basic properties of wave climatology at these sites match well the numerically simulated values (Räämet and Soomere, 2010). The monthly mean wave height at all sites follows the seasonal variation in wind speed in this region (Figure 2). At Estonian sites the maximum wave height is in October–January with a substantial variability on weekly scales. Seasonal variations of mean wave height at Nida coincide well with those at Estonian coast with May as the calmest and November as the roughest month. An unexpected feature of the seasonal course of wind speed and wave height in this region is that the windiest season is shifted by about 1–2 months with respect to the season with the largest wave activity (Räämet and Soomere, 2010).

Long-term behavior of wave fields

Although there is evidence about gradual increase in the mean wind speed over the Baltic Sea basin (Pryor and Barthelmie, 2003), there is no long-term increase in the annual mean wave heights at any of the observation sites on the eastern coast of the Baltic Sea. Moreover, the overall course of wave activity (Figure 3) reveals no clear long-term trend at the sites reflecting the wave conditions in the Baltic Proper (Nida, Vilsandi and partially Pakri). This feature is consistent with the results of long-term simulations of wave properties in the Baltic Sea basin based on geostrophic winds (Soomere and Räämet, 2010).

A clear decreasing trend in the wave activity is evident in Narva-Jõesuu data. This trend may be related to an asymmetric decrease in the length of the ice season in the Gulf of Finland mostly during relatively calm seasons (Sooäär and Jaagus, 2007) or, more probably, to a substantial increase in the frequency of SW winds over Estonia (Kull, 2009). This turn in wind directions means that the frequency of winds corresponding to very short fetches has considerable increased at Narva-Jõesuu. The related changes to the wave field become more clearly evident in the long-term course of the highest waves (Soomere *et al.*, 2010).

Spatial pattern of quasiperiodic variations

Interestingly, a quasi-periodic variation with a typical time scale of 25–30 years can be identified in the longest data sets from the Baltic Proper (cf. Soomere and Zaitseva, 2007). An increase in the mean wave height at Vilsandi and at Pakri for a few years from the year 1960 and an overall slow decrease until the mid-1970s is observed at both sites.

The annual mean wave activity shows an interesting spatio-temporal pattern (Figure 3). The short-term (1–3 years) interannual variability is almost coherent at all sites in 1958–1986. In particular, variations in the wave activity at Pakri are the most similar to those at Vilsandi: there is almost perfect match of short-term variability in the annual mean wave heights and a high correlation coefficient (0.58) between these values in 1957–1985 at Vilsandi and Pakri. This coherence is completely lost from about 1987: since then the annual mean wave height at Narva-Jõesuu is in anti-phase with the height in the Baltic Proper. An analogous loss of coherence that is evident in 1954–1957 is discussed below in some detail.

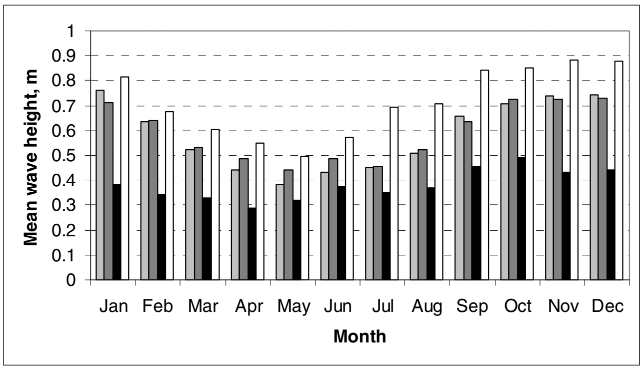

Figure 2. Seasonal variations in wave heights at Vilsandi (light grey bars), Pakri (dark grey bars), Narva-Jõesuu (black bars) and Nida (white bars).

The largest differences in the decadal course in the wave height become evident between Vilsandi (where the wave activity increases by a factor of two in 1987–1997 and decreases even more since then) and Narva-Jõesuu (where it gradually decreases over the entire observation period). There is even more drastic difference in the long-term behavior of the wave properties in the southern and northern parts of the Baltic Proper. Namely, the temporal course in the wave activity at Nida and Vilsandi match relatively well each other until about 1993. Further on the annual mean wave height behaves completely differently at these sites: there is a drastic decrease in the wave heights at Nida for 1990–1995 and a gradual increase starting from about 1996. This behavior becomes even more surprising when one compares it with the long-term changes to the wind speed in the northern Baltic Proper where the annual mean wind speed has gradually increased since the 1960s (Figure 4).

The newly presented data from Nida show the largest difference in the data from first three years of visual observations (1954–

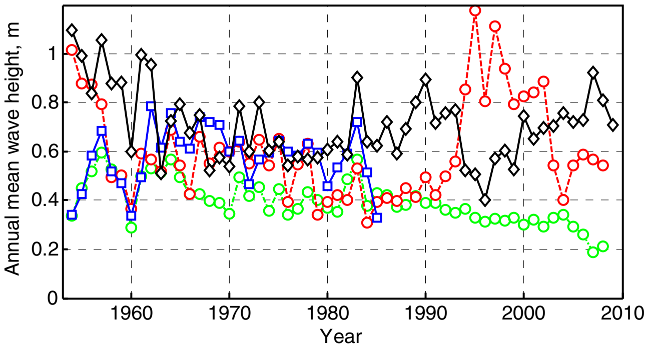

Figure 3. Annual mean wave height at Vilsandi (circles on dashed line), Pakri (squares) Narva-Jõesuu (grey circles) and Nida (diamonds). Notice that data from Pakri at 1985 do not contain information about the windiest season (October–December) and apparently underestimate the wave activity for this year.

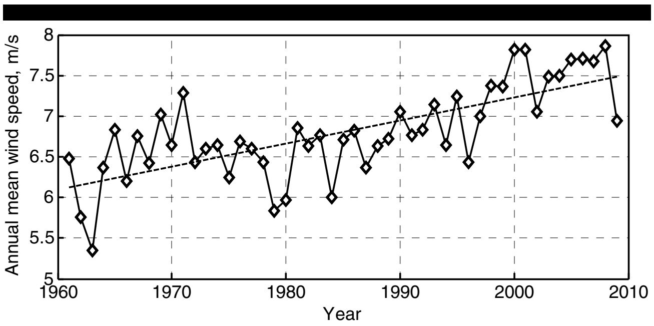

Figure 4. Long-term variations in the annual mean wind speed at Utö (1961–2009) and the relevant trendline. The average increase in the annual wind speed is 2.84 sm/s/year.

1956) in a new light. In the previous analysis the deviation in the wave height at different sites was related to a systematic overestimation of wave heights at Vilsandi during the first years of the observations (Soomere and Zaitseva, 2007). The rapid decrease in the wave activity in the Baltic Proper (at Nida and Vilsandi) in the mid-1950s is actually consistent with an analogous decrease in the number of storm days in the Baltic Sea region during the same period (Bergström *et al*., 2001). The difference in the data from the Baltic Proper and the Gulf of Finland (reflected by data from Pakri and Narva-Jõesuu) may indicate an associated turn of the winds creating largest waves at different sites.

Changes in wave directions

It is natural to expect that the directional structure of approaching waves follows the prevailing winds and the geometry of the observation sites. This is particularly true for widely open sites such as Vilsandi (Figure 5) where a two-peak distribution of wave directions follows the well-know two-peak wind pattern in the northern Baltic Proper where strong winds blow from the SW or from N-NW (Soomere and Keevallik, 2001). The situation is different at more sheltered sites such as Nida or Narva-Jõesuu (Figure 4) where the fetch for some strong winds is very short. Waves mostly approach from the SW–NW direction at Nida and from a much wider range at Narva-Jõesuu.

The directional distributions of wave approach show a certain interannual and decadal variability for Vilsandi and Nida but reveal no substantial long-term changes of the predominant direction. The existing shifts and changes to this distribution in Figure 5 apparently are connected with the changes in the observation conditions such as a change in the observation site at Vilsandi (Soomere and Zaitseva, 2007).

The predominant wave directions have, however, exerted quite large changes at several observation sites whereas the contemporary wave models do not represent such turns (Räämet *et al*., 2010; Kelpšaitė *et al*., 2011).

For example, relatively small changes (but still substantially affecting the course of coastal processes) have been identified for the Lithuanian coast for the years 1993–2008 (Kelpšaitė *et al*., 2011). The most pronounced changes in the predominant wave direction have occurred in Narva Bay (Figure 5) where the most frequent approach direction of waves has turned by more than 90° since the 1970s (Räämet *et al*., 2010). Waves mostly approached from the W–NW direction until about 1965. The predominant approach direction moved almost to the north for the 1970s. Further on, it turned considerably, to the SW over the 1980s and has been mostly from the south within the latter decade. The most frequent observed propagation direction, therefore, has changed by more than 90° over the half-century of the observations (Räämet *et al.,* 2010).

DISCUSSION AND CONCLUSIONS

The performed analysis shows that interannual, decadal and long-term variations and trends may be completely different not only in different sub-basins of the Baltic Sea but also in different parts of its major body – the Baltic Proper. The switch from the in-phase behavior of short-term interannual variability in the wave activity around 1990 suggests that there has been a certain change in the nature of wind and wave storms in the entire Baltic Sea basin. While storms before 1990 have created high waves more or less simultaneously in the entire sea, since then stormy years in the Baltic Proper correspond to relatively calm years in the Gulf of Finland and *vice versa*. A more drastic difference in wave regimes

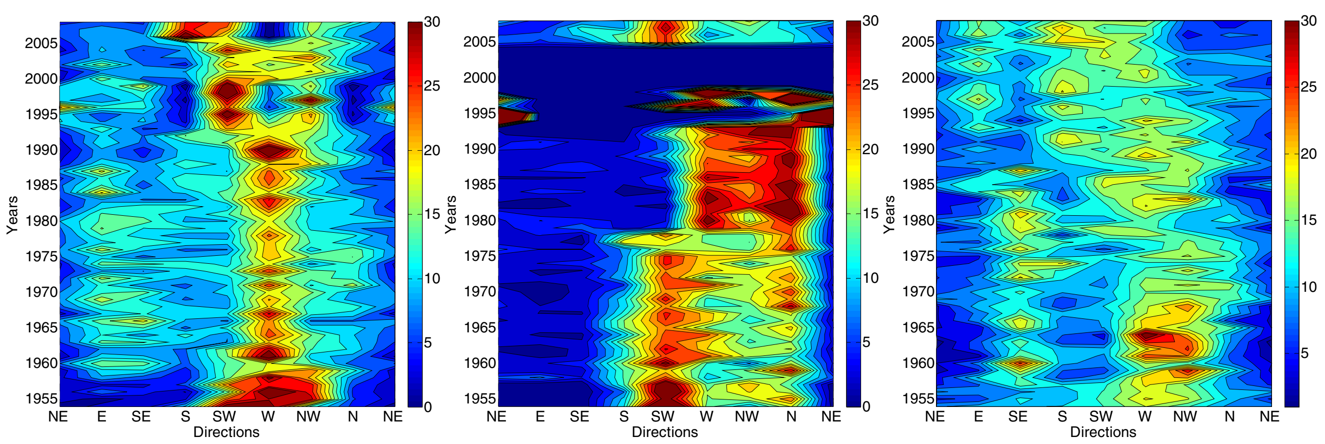

Figure 5. Temporal course in the directional distribution of wave approach directions at Nida (left panel), Vilsandi (middle panel) and Narva-Jõesuu (right panel, from Räämet *et al*., 2010, with permission from the Estonian Academy Publishers) in 1954–2008 (% of all wave conditions in a calendar year). Notice that the number of recorded wave directions has decreased substantially at Vilsandi from 1992 and at Nida from 1998. The relevant distributions of different approach directions are not reliable for 1992/1998–2008. A shift in the distribution for Vilsandi at the end of the 1970s is apparently connected with a change in observation conditions.

becomes evident at the turn of millennia in the Baltic Proper.

While until the 1990s the decadal variations in the wave activity have been mostly similar for both the northern (Vilsandi) and southern parts (Nida) of this water body, these variations are completely different during the last two decades. There is a drastic decrease in the wave heights at Nida for 1990–1995 and a gradual increase starting from about 1996.

A probable reason for a part of the described changes is connected with gradual changes to the directional structure of predominant winds in the areas adjacent to the Gulf of Finland. The recent analysis by Kull (2005) shows that during the last 40 years there has been a significant increase in the frequency of SW winds and a decrease in southern and eastern winds all over Estonia. Such a change leads to a systematic increase in the typical fetch length for the northern part of the basin.

A highly interesting feature is that the gradual increase in the annual mean wind speed in most of the Baltic Sea basin (Pryor and Barthelmie, 2003) does not become evident in the long-term behavior of the annual mean wave height. This feature suggests that the Baltic Sea wave fields are more sensitive to other changes to the wind properties such as the change in wind direction and the corresponding change to the fetch length (Soomere *et al*., 2010). The discussed loss of coherence in the short-term interannual wave activity from the 1980s may be related with a shift of the typical trajectory of low-pressure systems over the Baltic Sea.

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