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Long-term spatial variations in the Baltic Sea wave fields

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the eastern and western coasts of the northern Baltic Proper (Broman et al., 2006; Soomere and Zaitseva, 2007; Soomere, 2008). The wave activity shows no considerable changes at the Lithuanian coasts (Kelpšaitė et al., 2008) but has decreased substantially at the south-eastern coast of the Gulf of Finland (Narva-Jõesuu, Räämet et al., 2010).

An equally important characteristic of wave fields is the wave height in strong storms. The storminess in the entire region gradually decreased over the first half of the 20th century, rapidly increased in the 1980s and 1990s (Alexandersson et al., 1998) and probably decreased again at the very end of the 20th century (Alexandersson et al., 2000; Helminen, 2006). These changes apparently become evident in properties of wind waves. Wave heights in strong storms are usually characterised in terms of the thresholds for 5% and 1% of the highest waves in each calendar year (called the 95%-ile and 99%-ile, respectively). There is implicit evidence about an increase in wave heights in extreme storms (Soomere et al., 2008) and in those wave conditions that occur together with high water level and cause the most extensive coastal destructions in this microtidal basin (Orviku et al., 2003, 2009; Tõnisson et al., 2008). Relevant data exist only for a selection of sites (Suursaar and Kullas 2009; Räämet et al., 2010; Suursaar, 2010).

In winter frequent stormy winds and the presence of heavy ice often complicate both visual wave observations and instrumental measurements in the northern Baltic Sea. Floating devices are usually removed well before the ice season (Kahma et al., 2003). As a consequence, the measured wave time series do not contain data from the windiest period that frequently occurs just before the ice cover is formed. Global wave data sets such as KNMI/ERA-40 Wave Atlas (09.1957–08.2002, Sterl and Caires, 2005) have a too coarse spatial resolution ($1.5^\circ \times 1.5^\circ$) for an adequate representation of the Baltic Sea conditions.

We make an attempt to fill this gap by means of high-resolution numerical reconstruction of wave properties over almost four decades. Most of similar attempts in the past cover relatively short periods of a few years (Paplińska, 1999, 2001; Jönsson et al.,

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2002) or concentrate on specific areas (Blomgren et al., 2001; Cieřlikiewicz and Herman, 2002; Soomere, 2003, 2005). A few results of long-term reconstructions of wave fields over the entire Baltic Sea have recently been reported in the international literature (Cieřlikiewicz and Paplińska-Swerpel, 2008; Kriezi and Broman, 2008). However, as yet no comprehensive description of numerically simulated changes in the wave fields has been presented.

Our study deals with spatial patterns of long-term variations in the basic wave properties such as the annual mean wave height and period, and properties of waves in strong storms. The analysis is based on a numerical reconstruction of the wave fields for 1970–2007 with the use of a high-resolution version (grid step about 3 miles) of the wave model WAM and surface-level winds derived from geostrophic wind data. We start from the description of the model setup and definition of the forcing fields. Unlike Martucci et al. (2010), we discuss both the magnitude and the extent of spatial variations in the linear trend in the annual mean and extreme wave heights together with their statistical significance.

2 Wave model and wind forcing

Wave properties over the entire Baltic Sea (Fig. 1) were computed with the third-generation wave model WAM Cycle 4 (Komen et al., 1994) over 38 years (for 1970–2007). The implementation of this model for the Baltic Sea conditions takes the following parameters and processes into account: coastal line of the basin, spatial and temporal variation in wind properties, wave propagation on the sea surface, quadruplet interactions between wave harmonics, whitecapping, shoaling and wave dissipation in shallow areas due to bottom friction. This model gives good results in the Baltic Sea if its resolution is appropriate and the wind information is correct (Tuomi et al., 1999). The triple-nested, high-resolution version of the model (with a grid step of about 500 m) has shown good results also in quite shallow conditions and adequately represents wave properties up to a depth of about 5 m and as close to the coast as about 200–300 m (Soomere, 2005).

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the quality of wind data largely varied over the Baltic Sea, whereas the winds derived from the geostrophic wind data showed, on average, the best performance (Räämet, 2010). Somewhat surprisingly, even high-quality reconstructions of wind fields for two strong storms in this sea in 2001 and 2005, developed by the ECMWF in a $0.25^\circ \times 0.25^\circ$ resolution (L. Cavaleri and L. Bertotti, personal communication, 2009), led to the same quality of wave hindcast as the use of geostrophic winds (Räämet, 2010).

The simulations described below were performed with the use of wind data constructed on the basis of geostrophic winds. These data, although they smooth out a large number of local variations in wind properties, are free of local disturbances to the air flow by coastal topography and errors in ground wind speed measurements. The key arguments for their use are that they are highly homogeneous in time and that they represent the impact of global wind patterns which are mostly responsible for the wave climatology.

The geostrophic wind components with a moderate spatial resolution of $1^\circ \times 1^\circ$ provided by the Swedish Meteorological and Hydrological Institute (SMHI) were first interpolated to a medium resolution (about 6 nautical miles) grid. The data are available once in 6 h before September 1977 and once in 3 h since then. The geostrophic wind speed was multiplied by 0.6 and the direction turned 15° anticlockwise to yield an approximation of the wind at the 10 m level. This approximation, equivalent to one of the options analysed in Bumke and Hasse (1989) in which stability questions of the air flow are ignored, is becoming increasingly popular in studies of circulation and wave patterns in the Baltic Sea (Andrejev et al., 2004; Zhurbas et al., 2008; Myrberg et al., 2010). The resulting wind information was used as the input to the wave model during the relevant 3 or 6 h time intervals and interpolated to the higher resolution wave modelling grid internally in the WAM model.

A detailed description of the performance of the model against instrumental wave measurements and visual wave observations is given in Räämet et al. (2009, 2010), Räämet and Soomere (2010) and Räämet (2010). The model (i) underestimates to a certain extent wave heights in the range of 0.7–1.5 m but (ii) adequately represents

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the distribution of the higher waves, (iii) gives qualitatively similar results in terms of short-term variations in the visually observed annual mean wave heights, (iv) provides satisfactory match of the timing and maximum heights in high wave events and (v) reproduces well the overall statistics of wave conditions (incl. the relevant probability distributions) and their seasonal variations.

On average, the model apparently underestimates the long-term average wave height and in many cases failed to reproduce the duration of rough seas. This underestimation may partially stem from the particular choice of the coefficient (0.6) in the procedure of reduction of the geostrophic winds. This choice was mostly verified by comparison of the measured and modelled wave heights in relatively rough seas (see Figs. 3 and 4 of Räämet and Soomere, 2010). A certain bias in the estimates of the long-term magnitude of wave intensity, however, is obviously insignificant in terms of the changes in wave properties described below.

3 Spatial distributions of long-term wave properties

The basic features of the spatial pattern of numerically simulated average wave heights in the Baltic Sea for 1970–2007 have been discussed by Räämet and Soomere (2010). Therefore we provide here only a short overview of these features. As expected from the properties of predominant winds in the area, the distribution of the long-term average significant wave height (Fig. 2) is asymmetric with respect to the axes of the two largest sub-basins – the Baltic Proper and the Bothnian Sea. The open part of the Bothnian Sea has quite high wave intensity, comparable to that in the northern Baltic Proper. The eastern part of the Bothnian Sea has clearly higher waves (>0.8 m on average) than its western area.

In the northern Baltic Proper the wave activity is the highest along the coasts of the Western Estonian Archipelago and Latvia. The average wave heights are relatively low along the coasts of Lithuania, Kaliningrad district of Russia and north-eastern Poland. This is somewhat unexpected as these areas have a relatively long fetch. The Gulf

of Finland hosts clearly smaller wave activity, with the average wave heights about 0.7 m only at its entrance and in its central part and about 0.6 m in the rest of the gulf, consistently with an estimate for the vicinity of Tallinn Bay (0.56 m, Soomere, 2005). The largest values of the average wave height only slightly exceed 0.6 m in the Gulf of Riga.

An interesting feature is that the spatial pattern of the areas with large wave activity has several local maxima and is quite different for the southern and northern parts of the Baltic Proper. In average, the wave heights are the largest south of Gotland and east of Öland (around 56° N, 18° E), and in the Arkona basin.

The modelled wave periods match well the measured periods: while typical peak periods according to measurements are 4–6 s in the open sea (Soomere, 2008), the average peak periods from simulations are about 4 s. Relative variations in the average periods over the Baltic Sea basin are of the same order of magnitude as similar variations in wave heights. The distributions of periods to some extent match those for the wave height: in both cases they are asymmetric, with the greatest values in the eastern part of the Baltic Proper and the Bothnian Sea. The predomination of south-westerly winds in this area (Mietus, 1998) suggests that the largest wave periods should usually occur in the northern Baltic Proper. The long-term maxima of both peak and mean periods (Fig. 3), however, are found in the southern Baltic Proper.

4 Patterns of long-term changes in average wave properties

The existing evidence about changes in the overall wave intensity is highly controversial and reveals largely different trends in various parts of the Baltic Sea (Broman et al., 2006; Soomere and Zaitseva, 2007; Kelpšaitė et al., 2008; Soomere, 2008). We calculated the relevant trends in the following manner. For each of the 11 545 sea points, first the annual mean significant wave height was calculated from the simulated hourly values. This quantity is called (overall) wave intensity (or activity) in what follows. A linear trend was then found for these 38 estimates of the annual wave intensity for each

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year. The change in the wave height was calculated as the difference between the values for this trendline for the beginning and end years of the simulations. Finally, the statistical significance of the trend for each sea point was found with standard methods in terms of the relevant p -value.

5 The simulation reveals a complicated pattern of changes in the wave climate in the Baltic Sea. The largest changes in the modelled wave activity occur in the southern Baltic Proper. The increase in wave heights in the Arkona basin is consistent with the reported gradual increase in the modelled wind speed over this sea area (Pryor and Barthelmie, 2003, 2010). Surprisingly, the most drastic decrease in wave intensity
10 occurs in a neighbouring area between the islands of Öland and Gotland, and to the south of these islands down to the Polish coast. A considerable increase in wave activity is also signified by the model near the coast of Latvia, between the Åland Archipelago and Sweden, and in the sea area between the Bothnian Sea and the Bothnian Bay. There is also slight increase in wave activity in both the Gulf of Riga and
15 Gulf of Finland.

Interestingly, the spatial pattern of the described changes is largely uncorrelated with the areas of high and low wave intensity. The area of high waves in the Arkona basin exhibits an increase in wave heights while the wave activity in the neighbouring similar area is decreasing at an almost the same rate (about 10 cm, that is, up to 15% in 40
20 years). Another area of intense waves near Latvia also reveals an increase in wave heights. The areas subject to significant changes in wave heights to the south and north of the Bothnian Sea host an average wave intensity. Somewhat unexpectedly, the model shows almost no changes for the north-eastern Baltic Proper and along most of the Polish coast.

25 The spatial distribution of the pointwise calculated statistical significance of the modelled changes (Fig. 5) suggests that the wave regime in the five discussed areas have experienced clear changes over the simulation interval. The significance is the highest, about 99% for the area to the south of Bornholm. The other four areas have typical values of this measure over 90%.

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The numerically simulated changes in wave periods (not shown) follow the pattern of changes in wave heights: periods have become longer in the eastern part and shorter in the western part of the Baltic Proper. These changes, however, are quite small, maximally a couple of tenths of seconds and thus can be neglected in practical applications.

In other words, the performed calculations suggest that quite substantial variations in long-term wave heights have taken place but no great increase in the typical wave periods has occurred in the Baltic Sea over the last four decades.

5 Wave properties in strong storms

Recent research into long-term variations in the largest waves (Suursaar and Kullas, 2009; Räämet et al., 2010; Suursaar, 2010) has shown quite limited changes for selected locations along the Estonian coast. Some results, derived from simple fetch-based wave models and one-point forcing (Suursaar and Kullas, 2009; Zaitseva-Pärnaste et al., 2009), indicate a pronounced increase in the 90%-ile and 99%-ile for a location near the coast of the Western Estonian Archipelago, whereas Suursaar (2010) has identified a decrease in the annual mean wave height on the northern coast of Estonia.

The above discussion of the spatial patterns of changes in the overall wave activity suggests that these somewhat controversial results may be caused by an inappropriate choice of the relevant sites. For this reason we studied spatial variations in extreme wave heights based on the simulated values of the 99%-ile and the 95%-ile of significant wave height for each calendar year. As the variations in these two parameters are almost identical, we only present the results for the 99%-iles (Fig. 6), called extreme waves below. These values were calculated over the entire set of hourly wave heights for each year. An estimate of the long-term value of the relevant wave height was then found as an average over the annual values. Finally, the pattern of trends in extreme wave heights and its statistical significance was calculated pointwise similarly to the trends in average wave intensity.

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The highest extreme waves occur in the areas with the highest overall wave intensity: in the Arkona basin, south of Gotland, in the north-eastern Baltic Proper and in the eastern Bothnian Sea (Fig. 6a). It is an expected outcome, having the same reasons as those discussed earlier for the average wave heights. These areas have the longest fetch and the relatively low elevations in Denmark apparently damp much weaker the winds blowing from the North Sea than high elevations in Sweden. The changes in extreme wave heights are almost identical to the changes in average wave heights (Fig. 6b). Consistently with the results of Suursaar and Kullas (2009) and Suursaar (2010), a notable decreasing trend in 99%-iles occurs near the North Estonian coast (which is opposite to a gradual increasing trend in the average wave height) and a slight increase in the heights of extreme waves in the nearshore of the Western Estonian Archipelago.

6 Conclusions

The described features indicate that certain substantial changes in both average wave intensity (in terms of the annual mean significant wave height) and extreme wave conditions (understood as the wave height occurring with a probability of 1–5%) have occurred over the Baltic Sea since the 1970s. Interestingly, there is a very minor change in the spatially averaged wave height and almost no changes in the wave periods.

However, major changes in both average and extreme wave properties have taken place in different regions. An increase in wave activity in the Arkona basin is not unexpected because the wind speed in this area has grown markedly over the last decades (Pryor and Barthelmie, 2003, 2010). A decrease of the same magnitude in the neighbouring sea area to the north-east of Bornholm is, however, counter-intuitive and further research is necessary to confirm this result of wave modelling. Such a complicated pattern of spatial changes is not completely unexpected as many studies have shown that the magnitudes of the trends in wave properties can greatly vary in different sea areas (Weisse and von Storch, 2010; Martucci et al., 2010, among others). It is, however,

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notable that a steep decrease in wave heights may occur in open sea areas adjacent to those hosting an equally steep increase in wave heights.

Ironically, most of the wave observation and measurement sites from where long-term data are available (on the eastern coast of the Baltic Sea, on the coasts of the Baltic Proper and in the Gulf of Finland, Fig. 1) are located in areas where the simulations revealed almost no long-term changes in wave properties. We are looking forward to digitising the historical wave data from Latvian coastal observation sites which may confirm the simulated long-term changes.

The wind data used in our simulations apparently somewhat underestimate the magnitude of the annual mean wave heights but the values for the higher percentiles of wave conditions are realistic (Räämet et al., 2009). Moreover, it is natural to assume that a large part of long-term changes in wave fields are tightly related to similar changes in the air pressure patterns and the geostrophic winds even in areas where ageostrophic components or specific wave generation conditions (Pettersson et al., 2010) are at times or in places decisive. Therefore, the performed simulations evidently capture realistically the slopes of the relevant trends in wave parameters.

A key message from the described results is that many seemingly controversial trends and variations established in wave properties at different sites to a large extent reflect the natural spatial variability in the Baltic Sea wave fields. In this context, it is highly intriguing that in some areas the trends in the long-term average wave heights and in the highest wave properties are different.

Although it is obvious that the described changes are driven by wind fields, the background reasons and future extension of the resulting spatio-temporal variability in wave properties remain largely concealed. Clearly, a simple increase in the wind speed or a gradual turn in the predominant wind direction over the entire basin is not sufficient to produce such an extensive and strong pattern of variations in wave conditions. It is quite natural to expect that the reaction of the sea surface to changing wind conditions is generally a nonlinear process and the response in terms of the wave field is not necessarily exactly follows the changes in the wind field similarly to the quite weak

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correlation between the temperatures of the air and surface water in the Black Sea (Shapiro et al., 2010). Most probably, different regions of the Baltic Sea basin have experienced widespread but essentially different changes in wind properties. For example, during the last 40 years there has been a significant increase in the frequency of south-western winds and a decrease in southern and eastern winds all over Estonia (Kull, 2005). Such a change may be responsible for a large part of the increase in wave activity in the northern Baltic Proper as it leads to a systematic increase in the typical fetch length in this basin. This alteration, though, cannot explain the rapid variations in wave heights in the southern Baltic Sea

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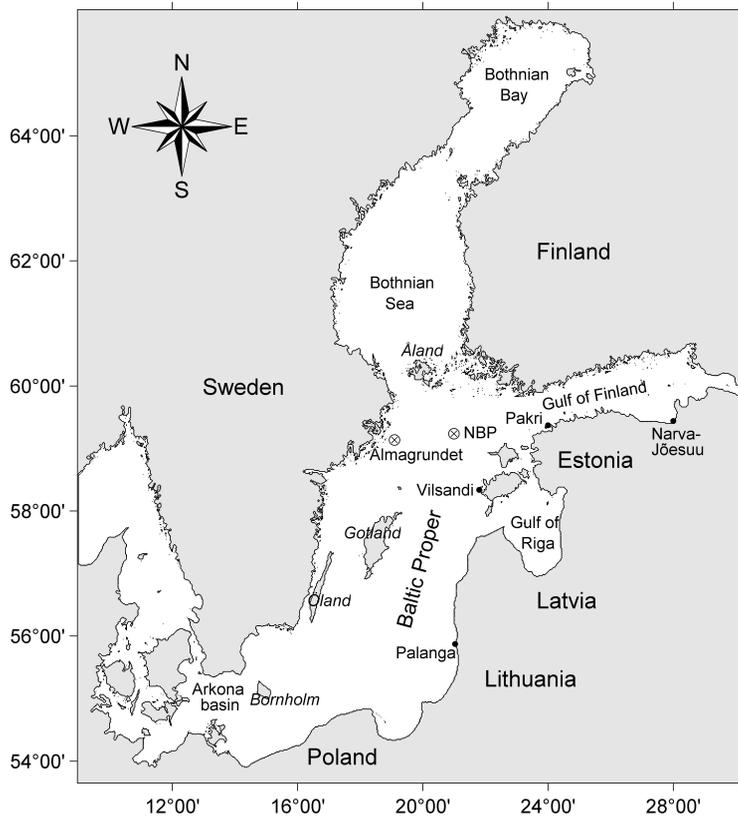


Fig. 1. Location scheme of the Baltic Sea and wave measurement and observation sites on the eastern and northern coasts of the Baltic Proper and the Gulf of Finland.

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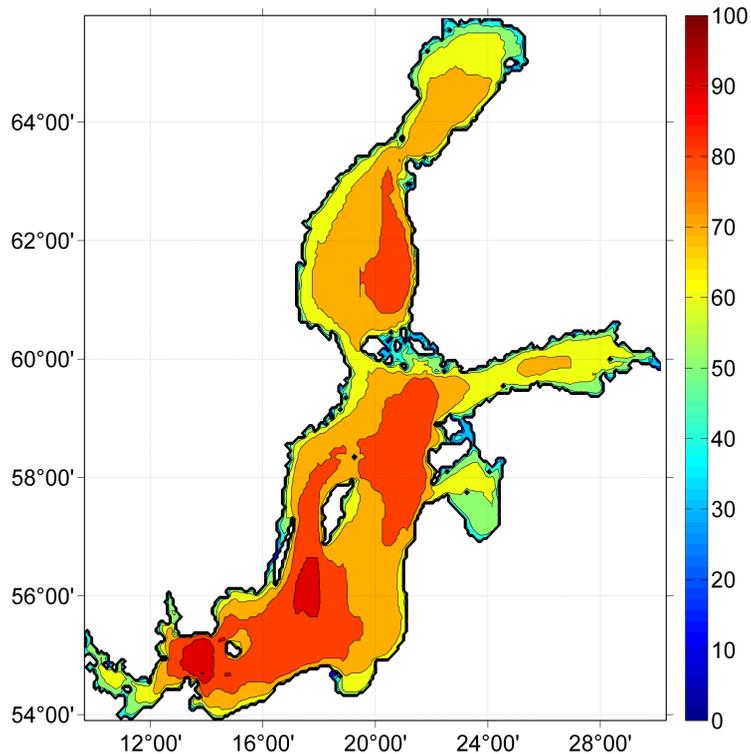


Fig. 2. Numerically simulated average significant wave height (colour bar, cm; isolines plotted after each 10 cm) in the Baltic Sea in 1970–2007 (from Räämet and Soomere, 2010).

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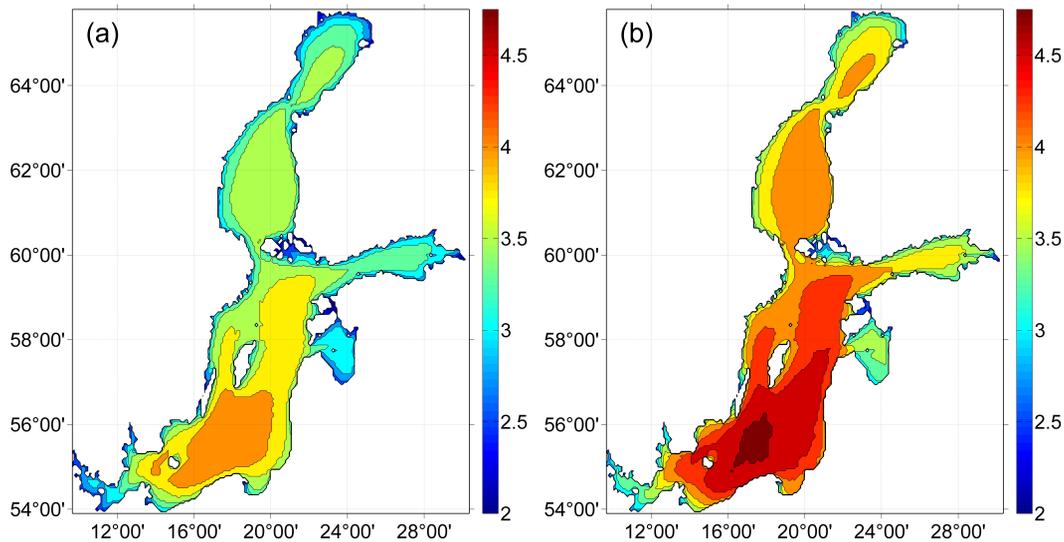


Fig. 3. Numerically simulated mean **(a)** and peak **(b)** periods (s; isolines plotted after each 0.5 s) in the Baltic Sea in 1970–2007.

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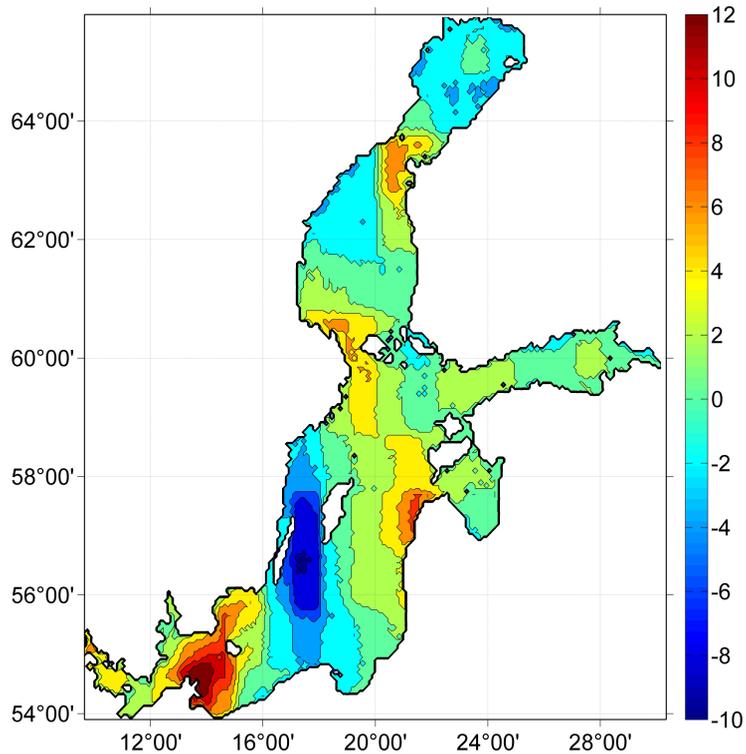


Fig. 4. Long-term changes in the significant wave height (cm, isolines plotted after each 2 cm) for 1970–2007.

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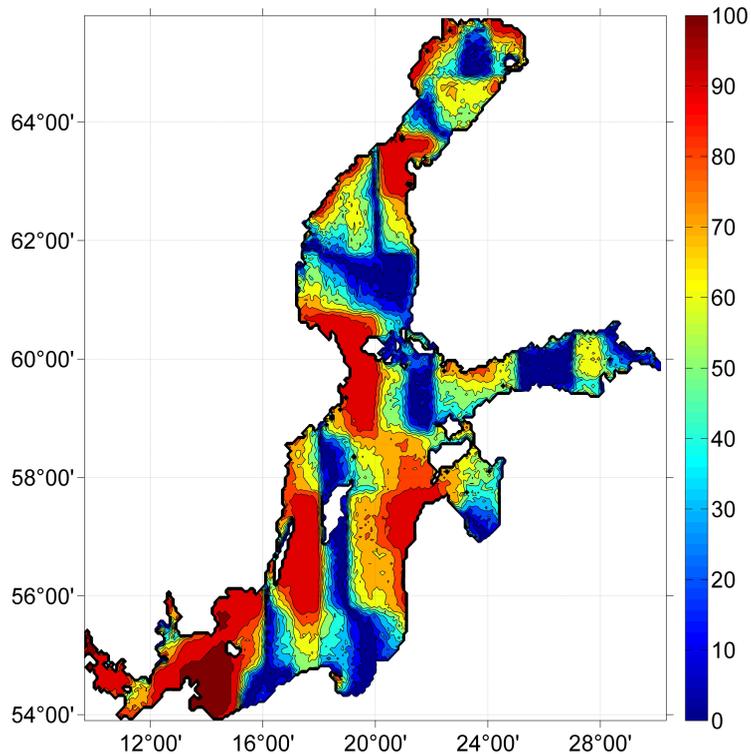


Fig. 5. Statistical significance (%) of the changes presented in Fig. 4 in terms of $100 \times (1-p)$, where p is the relevant p -value for the particular sea point.

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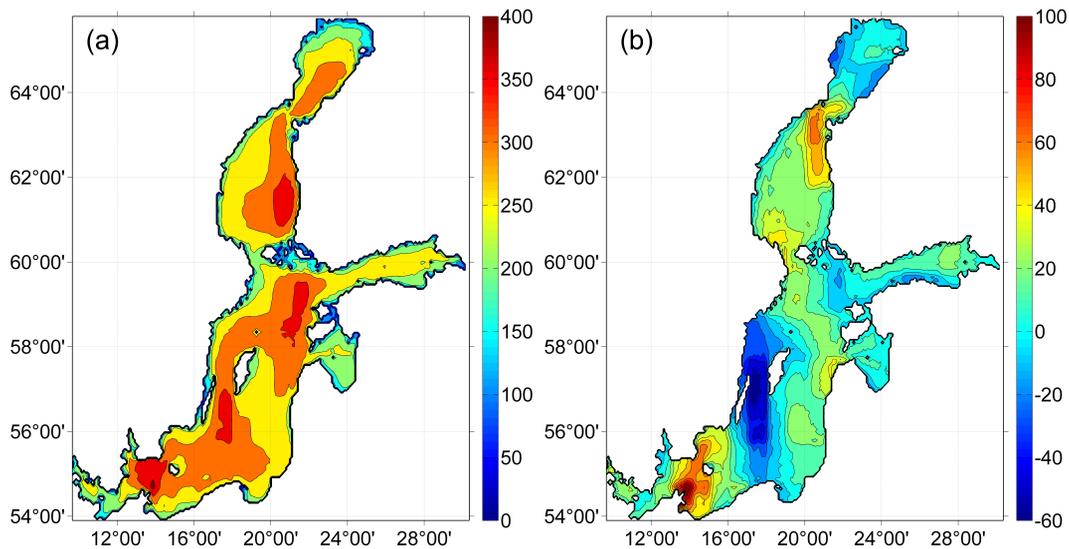
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Fig. 6. (a) Long-term 99%-ile of significant wave height (cm; isolines plotted after each 50 cm) and (b) its linear trend in the Baltic Sea in 1970–2007 (cm; isolines plotted after each 10 cm).

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