Please find the reply of the authors below. The comments, questions, and suggestions of the referees are presented in italics. The response of the authors is in regular font, and implemented changes to the manuscript together with line numbers are marked in dark blue font.

**General comments**

*Earlier studies are cited and discussed in many places, but the comparison to them and the related discussion should be more comprehensive, especially if the reliability of the earlier studies is questioned.*

As differences between numerically simulated properties of wave climate have been thoroughly discussed in several recent studies [e.g. Nikolkina et al. 2014. Multidecadal ensemble hindcast of wave fields in the Baltic Sea, *The 6th IEEE/OES Baltic Symposium Measuring and Modeling of Multi-Scale Interactions in the Marine Environment, May 26–29, Tallinn Estonia*; IEEE Conference Publications, 9 pp., doi: 10.1109/BALTIC.2014.6887854; Hünicke et al. 2015. Recent change – sea level and wind waves. In: The BACC II Author Team, *Second Assessment of Climate Change for the Baltic Sea Basin.* Springer, 155–185; Soomere T. 2016. Extremes and decadal variations in the Baltic Sea wave conditions. In: Extreme Ocean Waves, Pelinovsky E., Kharif C. (eds.). Springer, 107–140], our intention was to focus on novel aspects of our research. However, we agree with the Referee that a wider reflection of matches and mismatches between the results of earlier studies will strengthen the paper, and we shall be happy to expand the relevant sections of the manuscript during revision.

An additional discussion was added to the manuscript (p.8, lines 27-33, p.9, lines 1-5).

*And as the altimeter dataset has been thoroughly validated, it should be indicated, whether the significant findings (trends, spatial patterns) are in the area, where the accuracy of the altimeter data was found to be adequate and if not, how it affects the results and their interpretation.*

Thank you for indicating this aspect. It is true that we implicitly assumed that the accuracy of altimeter dataset is basically the same in the entire interior of the Baltic Sea. This assumption is reasonable because most of in situ data used for validation are located relatively close to the shore, where the altimeter data can be easily distorted, and even then the in-situ data showed a very good correspondence with the altimeter measurements. The most reliable altimeter data are in the south-eastern part of the Baltic Proper. This region has a relatively straight coastline, almost no islands, the very infrequent presence of ice and large spatial extension. We intend to insert the proper explanation into the revised version of the manuscript.

An additional discussion about the satellite altimetry data quality was added to the discussion (p.8, lines 18-26) and data and methods section (p.3, lines 8-14).

*I also suggest that some of the figures would be redrawn to better illustrate the content and support the conclusions made by the Authors. Furthermore, colour scales that better describe the differences and are able to show where the differences are significant between adjacent pixels (for example from cmocean) would better emphasize their content and make their interpretation easier. Some*

Thank you; we shall carefully manage all figures for the revised manuscript.

The color scales of the plots were adjusted. The palette of Fig.2, Fig.4, Fig. 5, Fig. 6 was changed. Fig. 7 was redrawn to match the style of Fig. 3.

**Specific comments**

*Abstract. The abstract could better reflect the content of the paper. The validation of the dataset is not main point in this paper, since it is already published. And is it necessary to name some of the satellites in the abstract? Maybe some more information should be presented about the reliability of the trend and the spatial patterns, since they are major part of this study.*

The abstract will be adjusted as recommended. In particular, it will be made clear that we rely on already cleaned and validated dataset. We are not sure whether removing of all names of satellites is good, but we shall definitely work towards keeping only the core information and towards adding additional information about the reliability of the trends and spatial patterns.

The abstract was modified respectively, the names of satellites removed, added a sentence about a comparison with the visual observations (p.1, lines 9 - 16).

***Introduction****. Has satellite altimeter data been used to evaluate the wave conditions in other regional seas? The references in the introduction (Hemer et al., Young et al.) are focusing more on global oceans or large domains.*

The use of satellite altimeter data for evaluation of wave properties in smaller semi-enclosed water bodies has been scarce. Some papers focusing on the usage of this information for the regional wave climate are mentioned on page 2, lines 16–18. During the review process, several papers addressing this topic have become available, and we, of course, will add the relevant references and discuss the presented results in the introduction of the revised manuscript. The set of such paper involves, e.g. (Patra & Bhaskaran 2016, Trends in wind-wave climate over the head Bay of Bengal region; Kong et al. 2016, Validation and application of multi-source altimeter wave data in China's offshore areas). Some work in this direction has been performed for the Arctic Ocean, namely (Stopa et al. 2016. Wave climate in the Arctic 1992–2014: seasonality and trends: the paper about changes in the Arctic wave climate based on satellite altimetry and modeling, and Liu et al. 2016 Wind and wave climate in the Arctic Ocean as observed by altimeters).

Additional references which recently appeared, are added to the manuscript (p. 2, lines 14-15, lines 19-20).

***Data and methods****. Could the information about the satellites used in this study be presented in a table (name of satellite, period of measurements, coverage, accuracy, ...). It is difficult to gather this information from the text, since it's scattered to many places.*

Thank you, this is a good idea. A table listing all satellites, names, the period of measurements, coverage, and accuracy will be added to the manuscript.

Table 1 is added to the manuscript (page 18), a reference to the table is added (p.2, line 24).

*Page 2, line 21. Here it is said, that there is data from nine satellites, but in the abstract the Authors state that data from ten satellites was used.*

The discrepancy appeared from the fact that there were only a few observations from the Topex/Poseidon mission. As it was not possible to adequately validate these data, the relevant data set was excluded from the analysis. This is discussed in the paper describing the validation of the dataset (Kudryavtseva & Soomere 2016). The text will be amended accordingly to make this aspect clear.

To lessen the confusion, we changed a number of satellites to 9 in the abstract (p.1, line 9).

*Page 3, lines 5–8. Expressions 'less convincing' and 'poorer' are quite general in nature and do not tell the reader, whether there is bias, or larger scatter in the comparison against in-situ data from smaller sub-basins or nearshore location. Although a comprehensive validation is presented in the earlier paper, the summary here should have enough facts (as numbers or with more precise expressions) to give a more comprehensive picture of the altimeter data quality in different areas of the Baltic Sea.*

This part will be re-written using more explicit expressions and more exact quantification.

The part was re-written, the difference between the data quality in the Baltic Proper and coastal areas is discussed in more details, added a sentence that the data very close to the shore showing not good data quality were excluded from the presented analysis (p.3, lines 8-14).

*Page 3, lines 27–28. Which ice product is used to estimate the ice concentration in the Baltic Sea*

*and what is the accuracy of this product? And how it affects the interpretation of results in areas, where there is large variation in the extent of seasonal ice cover?*

The ice concentration measurements (OSI-409-a dataset) were taken from EUMETSAT OSI SAF Global Sea Ice Concentration Reprocessing data [EUMETSAT Ocean and Sea Ice Satellite Application Facility. Global sea ice concentration reprocessing dataset 1978–2015 (v1.2, 2015). Norwegian and Danish Meteorological Institutes, http://osisaf.met.no]. A description of the product, its accuracy, and how the results can be affected by large changes in the variations of the ice cover will be added to the paper.

However, large variations in the extent of ice cover are an intrinsic and deeply nontrivial question in studies of wave climate of partially ice-covered sea areas. The presence of extensive ice cover may render the basic properties such as average wave height almost useless (Tuomi et al. 2011. Wave hindcast statistics in the seasonally ice-covered Baltic Sea, Boreal Environ. Res., 16(6), 451–472). We shall amend the text to cover this aspect as well.

A reference to the ice concentration dataset is added (p.3, lines 32-34, p.4 lines 1-5).

*Page 6, line 23. 0.3 degree grid cell (c. 33 km) is quite large considering comparison against coastal visual observations. Have you considered using smaller grid cells, additionally to the present comparison and analysis, or simply selecting the nearest locations from the altimeter data to the locations of the visual observation.*

We are particularly thankful for this question that has led us to the identification of a mistake in our script. Namely, in comparisons of the results of visual observations with those derived from satellite altimetry, the correlation coefficient mentioned in the discussion paper was calculated for a much larger area. Calculating the correlation coefficient for the 0.3-degree grid cell results in a correlation coefficient of 0.61 for Liepaja (9 years of coinciding data) and 0.81 for Ventspils (3 years of coinciding data). A reduction of the grid cell to 0.2 degrees almost does not affect the correlation coefficient for Liepaja (0.60, 9 years of coinciding data) and improves the formal correlation for Ventspils (0.93, 3 years of coinciding data). The further decrease in the grid cell size leaves too few data points. The parts of the manuscript presenting the comparison of the outcome of satellite altimetry with the visually observed wave properties will be changed accordingly.

The part describing a comparison with the visual observations is re-written, describing correlation coefficient and how the change in the grid cell size affects the correlation (p.7, lines 19 - 28).

*Page 6, lines 25–28. The number of match-up pairs in Liepaja and Ventspils should be added. Although, there is a big difference in the number of observations between the early and later years of satellite mission, the tracks and coverage of the satellites are different and it is not clear how this reflects to coastal areas, in which these comparisons are made.*

The number of match-up pairs in Liepaja and Ventspils will be added to the text of the revised version.

The number of pairs was added to the manuscript (p. 7, lines 19 - 21).

*Page 4, lines 15–16. Is the mismatch of inter-annual variation between the present dataset and the datasets presented by Soomere and Räämet and Soomere et al.? It is not quite clear, whether the Authors refer here to the previous sentence or to something else. It is not also clear, why this signals the importance of ice information in wave modelling. Please be more precise in expression and provide analysis/comparison that support these claims.*

The comparison of the dataset presented in the manuscript and the wave modeling results discussed in Soomere and Räämet will be discussed in more detail, and the importance of ice in such comparisons will be clarified in the revised version.

The part was re-written to discuss in more details results presented in Soomere and Räämet (2014) (p. 4, lines 30-32, p.5, lines 1-5).

*Page 4, lines 17–18. "heavily questions the reliability of existing wave reconstruction" – This is*

*quite strong statement and what is its justification. More analysis on the reliability of this reconstruction should be presented before declaring all the existing ones as questionable."*
We will rephrase this phrase.
The sentence is modified accordingly (p.5, lines 5-7).

*Fig 4. The right panel representing the number of observations has some white cells in areas for which there is value presented on the left panel (for example in the Gulf of Finland and Gulf of Riga). If there are no observations for these areas (or does the white color indicate something else), how can the linear trends be calculated and presented?"*
Some points appeared white due to a problem with a color scale in the plotting software. This bug is fixed now. The plot with the number of observations will be changed to the correct one.
The color scale was changed (p. 16, fig. 4b).

*Figures 2 and 4. Why is different pixel size used to present the mean values of significant wave height and the linear trends?*
The linear trends are calculated for the annual mean values, whereas the average significant wave height figure is plotted using all available data over the whole period of observations. The decrease in the pixel size was a compromise to get a reasonable number of data points for each year for each particular pixel.
The pixel size for linear trends and mean significant wave heights were not modified.

*Fig 5b. It is difficult to interpret the colours under the crosses. Is it necessary to have them in the Figure?*
The crosses show statistically significant trends. Therefore, removing them might mislead a reader. We will change the symbol to a dot, so it will be easier to recognize and interpret the colors.
The crosses in Fig. 4a, 5b, 6a, 6b were changed to circles.

***Discussion and conclusions***. *I would expect more discussion on whether the significant changes were found in areas, which showed good accuracy in the validation against in-situ data. How the 'less-convincing' match in the smaller sub-basins affects the interpretation of the results.*
*We will add a more detailed discussion about the changes in the wave heights in the areas with very good accuracy in satellite data and discuss more the results in coastal zones and smaller sub-basins. And what about the coastal areas? They were reported to have 'poorer' quality in the validation. Comparison against visual observation was said to show fairly good qualitative correspondence, but the correlations were quite low.*
As indicated above, we had a bug in the script for evaluation the correlation coefficients between the outcome of satellite altimetry and visual observations. The relevant parts of the text will be adjusted accordingly; in particular, we can speak about very good correspondence, with correlation coefficients >0.6.
An additional discussion about the satellite altimetry data quality was added to the discussion (p.8, lines 18-26).

*Lines 18-20: To my understanding the Baltic Sea is rather small and therefore, there the effect of wind direction might be more important due to changes in fetch. Is this true for all regional seas?*
Thank you, this is a very good observation, and we have tried to stress this aspect in several earlier publications. The strong dependence of wave properties on wind direction in the Baltic Sea mostly stems from the elongated shape of the Baltic Sea and less from its size. However, it is, of course, true that changes in strong wind directions will lead to large variations in the location of highest waves in more regularly shaped basins. To make this aspect clear, we shall add a more detailed comparison of the observed changes in the Baltic Sea with the published changes in other regional seas.
The discussion section was modified (p.8, lines 27-33, p.9, lines 1-5)

# Satellite altimetry reveals spatial patterns of variations in the Baltic Sea wave climate

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**Abstract.** The main properties of the climate of waves in the seasonally ice-covered Baltic Sea and its decadal changes since 1990 are estimated from satellite altimetry data. The data set of significant wave heights (SWH) from all existing ~~ten~~nine satellites ~~is~~, cleaned and cross-validated against in situ ~~buoy and echosounder~~ measurements. ~~Even though several satellite pairs (ENVISAT/JASON-1, SARAL/JASON-2, ERS-1/TOPEX) exhibit substantial mutual temporal drift, and calm situations are ignored, the~~, shows overall ~~picture is~~a very consistent~~.~~ picture. A comparison with visual observations shows a good correspondence with correlation coefficients of 0.6–0.8. The annual mean SWH ~~shows~~reveals a tentative increase of 0.005 m yr$^{-1}$~~,~~. but higher quantiles behave in a cyclic manner with a timescale of 10–15 yr. Changes in the basin-wide average SWH have a strong meridional pattern: an increase in the central and western parts of the sea and decrease in the ~~eastern part~~east. This pattern is likely caused by a rotation of wind directions rather than by an increase in the wind speed.

## 1 Introduction

The wave climate of relatively small semi-sheltered and seasonally ice-covered water bodies serves as a convenient indicator of changes in the atmospheric circulation and the related response of the water masses (Anderson et al., 2015). The associated changes in the wave fields are to a large extent controlled by the interplay of the geometry of the water body, changing winds and the overall reaction of the water masses. For instance, a reduction of the ice cover may strongly affect the wave loads (Tuomi et al., 2011; Ruest et al., 2016) and even small variations in wind properties may lead to marked changes in the wave fields. The analysis of wave properties makes it possible to reveal otherwise hidden changes in the forcing such as regime shifts (Soomere et al., 2015) and to highlight unusual reaction of the impacted environment, both direct (e.g., through an increase in severity of wave conditions, Wahl and Plant, 2015) and indirect (e.g., owing to a reduction in the ice cover (Orviku et al., 2003) or a change in the wave direction (Ashton et al., 2001)).

The limited size of such water bodies leads to large spatio-temporal variations in the wave properties. Thus, all sources of information about wave fields adequately reflect only wave conditions in the vicinity of the device or observation site. This feature is particularly significant in the Baltic Sea and similar water bodies that host extensive spatial variations in their wave climate (Soomere and Räämet, 2011, 2014). The related biases and uncertainties are generally recognized for several kinds

of data sources such as visual observations from ships (Gulev and Grigorieva, 2006) or coastal locations (Hünicke et al., 2015) but are often overlooked in the analysis of Acoustic Doppler Current Profiler (ADCP) or waverider data (Suursaar, 2015). Moreover, wave measurement devices are often removed well before the ice season (Tuomi et al., 2011).

Wave modelling provides a feasible option to complete the description of the wave climate and its changes. The major
5  limitation is the wind quality. Even though reconstructed wind fields are adequate for the Baltic Sea, replication of the wave climate is still a major challenge for this basin (Tuomi et al., 2011, 2014; Hünicke et al., 2015). An intrinsic reason is the variability of ice cover extension from 12.5 % to 100 % of the sea surface (Leppäranta and Myrberg, 2009). Various decadal reconstructions show qualitatively similar patterns but reveal significant quantitative mismatches between different model outputs (Nikolkina et al., 2014) and between modelled and measured wave data.

10  Here we employ systematically the information about wave properties derived from satellite altimetry to quantify the wave climate of the Baltic Sea in terms of significant wave height (SWH). The relevant observations span today >20 yr and thus provide a valuable source for understanding the course and possible reasons for regional climate changes. Satellite altimetry provides homogeneous and continuous (along a certain line) data about the sea state over large areas in the open ocean (Hemer et al., 2010; Izaguirre et al., 2011; Young et al., 2011). Several recent studies have addressed the options for its use
15  in the Arctic Ocean (Liu et al., 2016; Stopa et al., 2016). It, however, fails to provide information about low waves, is not applicable in the vicinity of land (Høyer and Nielsen, 2006) and is problematic for sea areas with high ice concentrations. It is thus not surprising that it has been only scarcely used to validate model results in the Baltic Sea (Cieślikiewicz et al., 2008; Tuomi et al., 2011). With certain precaution, it has shown good results for basins such as the Mediterranean Sea (Cavaleri and Sclavo, 2006; Galanis et al., 2012), a nearshore region of the Indian Ocean (Hareef Baba Shaeb et al., 2015; Patra and
20  Bhaskaran, 2016), and for a range of regional seas such as the China Sea (Kong et al., 2016), the Arabian Sea (Hithin et al., 2015), the Chukchi Sea (Francis et al., 2011) or the German Bight (Passaro et al., 2015).


## 2 Data and methods

We employ the Radar Altimeter Database System (RADS) database (http://rads.tudelft.nl/rads/rads.shtml) (Scharroo et al., 2013). It provides data from nine satellites 1985–2015 (Table 1) that are uniformly reduced for multiple missions. Doing so
25  diminishes the bias between data from different satellites and makes it possible to examine long-term changes in the wave climate. As several phenomena may substantially affect the quality of satellite altimetry, the consistency of the data has to be carefully checked. The relevant procedures, details about the missions and their temporal coverage as well as validation of the data against the records of waverider buoys and echosounder measurements are presented in Kudryavtseva and Soomere (2016). Here we provide only major aspects that are relevant for the subsequent analysis.
30  Different satellites have various densities of measurements. For example, SARAL and CRYOSAT-2 data fairly densely cover the entire Baltic Sea within each month (Fig. 1a) whereas, e.g., the POSEIDON data have very sparse coverage. We used flags provided by each mission (e.g., bad data because of rain or the presence of sea ice) as well as flags 7 and 11–13 in

the RADS database that warned about possible large errors in range, backscatter coefficient, and SWH. The data with backscatter coefficient >13.5 cdb (generally corresponding to wind speeds of <2.5 m s$^{-1}$) and large errors (>0.5 m, which is about half of the typical Baltic Sea wave height (Tuomi et al., 2011) in SWH normalized standard deviation (std) were excluded. The attitude flag 1 was applied to the GEOSAT data (Sandwell and McAdoo, 1988) and the zero values of SWH

5    recorded by JASON-1 and ERS-1 were removed as likely erroneous ones. The GEOSAT Phase-1 data could not be validated with the available buoy data and were excluded from the further analysis.

Possible biases of SWH for different missions were removed using cross-matching with in situ data and between satellites. The match of altimetry-derived and measured SWH is the best for offshore of the Baltic Proper, less convincing in smaller sub basins such as the Bay of Bothnia or the Gulf of Finland, and poorer in nearshore locations. due to a large number of

10    data points. When compared with the in-situ data the cross-matched pairs showed bigger scatter for the wave-rider buoys and echosounders closer to the shore. For the in-situ measurement sites located less than 0.2° from the coast, the standard deviation of cross-matches showed an increase by 14 %. However, the bigger scatter next to the shore does not affect the results of this study on condition that the data reflecting sea areas separated <0.2° from the coast were excluded from the analysis. The largest amount of matching altimetry and in situ data exists for JASON-1 (Fig. 1b). These sets reveal fairly

15    small scatter, no systematic shift and a fairly small (around 4%) difference. TOPEX tends to overestimate the SWH by about 0.17 m whereas ENVISAT, ERS-1 and GEOSAT Phase 2 tend to underestimate the SWH by 0.15–0.23 cm. The bias is less than 0.06 m for all other satellites. The bias between the SWH from different missions is consistent with the bias derived from comparison with the in situ data. For example, for CRYOSAT-2 and JASON-1 it is 0.04±0.06 m, and for ENVISAT and JASON-1 it is –0.19±0.03 m.

20    The data for the 1990s require additional handling. TOPEX had a switch in electronics in February 1999 which resulted in a shift in the time series. The TOPEX observations since February 1999 showed no bias with JASON-1. However, there is a bias of 0.37 m between ERS-1 and TOPEX for 1991–1996. The buoy data revealed that the ERS-1 underestimated the SWH by 0.18 m and TOPEX overestimated it by 0.17 m in 1991–1996. Several satellites have significant drift in their SWH time series. The highest differences are between SARAL and JASON-2.

25    Even though part of the drift can be related to different frequencies of observations, some of the altimetry data sets eventually are not homogeneous in time. The absolute drift is reasonable (0.13 m for ENVISAT/JASON-1, 0.08 m for SARAL/JASON-2 and 0.05 m for ERS-1/TOPEX) and does not affect the conclusions of this study. The overall corrections, based on the relevant linear regression analysis, are applied to the data: ERS-1 increased by 0.18 m, ENVISAT roseincreased by 0.19 m and divided by 1.06, GEOSAT increased by 0.23 m, JASON-2 data divided by 1.009, TOPEX before February

30    1999 decreased by 0.17 m and after that divided by 1.014 (Kudryavtseva and Soomere, 2016).

Consistently with earlier analysis, a clear increase in scattering of buoy-satellite cross-matches was found for centroids of the satellite snapshots separated <0.2° from the land. Such snapshots were excluded. The

Large parts of the Baltic Sea are covered with ice each winter. Widespread variations in the extent of ice cover are an intrinsic and deeply nontrivial question in studies of wave climate of partially ice-covered sea areas. The presence of

extensive ice cover may render the basic properties such as average wave height almost meaningless (Tuomi et al., 2011). For cross-matching the wave height data with the ice concentration measurements we used OSI-409-a dataset, taken from EUMETSAT OSI SAF Global Sea Ice Concentration Reprocessing data (EUMETSAT Ocean and Sea Ice Satellite Application Facility. Global sea ice concentration reprocessing dataset 1978–2015, v1.2, 2015. Norwegian and Danish Meteorological Institutes, http://osisaf.met.no). We found that the presence of sea ice starts to affect the SWH values at as low concentrations as 10 %, and the wave heights are somewhat lower when ice concentration exceeds 30 %. The ice flag in the RADS data indicates the ice concentration >50 %. This threshold is appropriate for the Baltic Sea. Still, lowering it to the level of >30 % would result in the additional exclusion of only 0.1 % of the altimetry data. (Kudryavtseva and Soomere, 2016).

## 3 Results

### 3.1 Observed changes and trends

The average SWH of the Baltic Sea in 1991–2015 is in the range 0.44–1.94 m (Fig. 2). As roughly one-third of calmer conditions are excluded from the analysis, the resulting values are clearly overestimated. For example, in a location in the Southern Baltic Proper where Soomere and Räämet (2014) (who underestimate SWH by about 15 %) report the average SWH ~0.7 m, the altimeter SWH is 1.294±0.002 m. The average SWH exceeds by 60–90 % the levels simulated in Soomere and Räämet (2014) and by about 30 % the levels reconstructed by Tuomi et al. (2011). The satellite-derived dataset, however, is expected to reflect adequately spatial patterns and temporal changes in the wave heights and the proportion of severe wave conditions.

Consistently with Tuomi et al. (2011), Soomere and Räämet (2014), Hünicke et al. (2015), the highest waves are found in the eastern and south-eastern Baltic Proper whereas the Gulf of Finland, Gulf of Riga and the (south-)western parts of the sea host much lower wave activity. The match of the frequency of satellite-derived and measured very rough seas is fairly good. Wave conditions with the SWH ≥ 4 m fromform 0.6 % of satellite snapshots in the entire sea whereas this proportion varies from 0.42 % to 1.4 % in various locations (Soomere, 2016). Extremely rough seas (SWH ≥ 7 m) occur twice (0.001 %) in the satellite data: 7.3 m on 31 January 1998 in the southern Baltic Proper and 7.4 m on 01 November 2001 in the northern Baltic Proper. Such wave conditions have been recorded less than 10 times in the entire Baltic Sea since 1978 (Soomere, 2016).

The major qualitative features of the basin-wide average SWH in 1991–2007 (Fig. 3) such as high wave activity in 1992 or 2007 and low wave activity in 1991, 1996 and 2006 match similar features of simulations based on geostrophic winds and ice-free sea (Soomere and Räämet, 2014) and results of visual wave observations (Soomere et al., 2015). However, there is a mismatch in the course of interannual variations and, more importantly, in the signs of trends in the average SWH. This first established in the mentioned studies and those obtained in our analysis. Earlier analysis indicates an increase in the SWH and also in upper quantiles of all signals the importancewave height in the open part of the Baltic Sea (Hünicke et al., 2015).

4

These results are not confirmed by direct measurements (Broman et al., 2006; Soomere et al., 2012) and do not become visible in the outcome of fetch-based models (Suursaar, 2015). Also, the analysis of Soomere and Räämet (2014) show no significant trend in mean wave heights integrated over the entire Baltic Sea. Instead, the Baltic Sea wave fields exhibit extensive decadal-scale variations that are out of phase in different sub-basins. In contrast, our study shows a tentative

5    positive trend. It is worth to note, however, that the modelling results in partially ice ~~information for wave modeling~~ covered seas are affected by how the ice is treated in the modelling process (Tuomi et al., 2011; Ruest et al., 2016) ~~but also heavily questions the reliability of existing wave reconstructions~~ and different runs often exhibit large discrepancy in the results (Nikolkina et al., 2014).

The number of single altimetry observations per year is <12 000 in 1991–1992, in the range of 20 000–31 500 in 1993–2001

10    and >30 000 since 2002~~.~~ (Fig. 3d). This suggests that the data until 1992 are only conditionally usable to highlight long-term changes in the wave properties. For this reason, we only consider trends in the wave activity since 1993. The linear trend for 1993–2015 (based on 683 707 measurements) is 0.005 m yr$^{-1}$ at a 98 % significance level. It is consistent with a similar pattern in the 90th and 99th percentiles for the North Atlantic (Bertin et al., 2013) but is clearly weaker than analogous trends extracted from numerical simulations using modelled wind fields (Hünicke et al., 2015) and disagrees with wave

15    properties reconstructed using geostrophic winds (Soomere and Räämet, 2014). Consistently with Bertin et al. (2013), this trend is superimposed by marked interannual variability. As most of the increase is caused by variations in the 1990s, it does not necessarily mirror the long-term changes adequately. A similar trend in 2000–2015 is 0.002 m yr$^{-1}$. A large value of the relevant $p$-value ($p = 0.5$) signals that no significant changes in the basin-wide average SWH have occurred during the last 15 yr.

20    **3.2 Testing the presence of trends**

Following Wang and Swail (2001), an additional test to check the reliability of the whole-basin long-term trend in wave heights of 0.005 m yr$^{-1}$ was performed using the Mann-Kendall test since the least square fitting of a regression line is sensitive to gross errors and non-normality of the parent distribution (Sen, 1968). The Mann-Kendall test (Mann, 1945; Kendall, 1955) is a nonparametric test for non-randomness of the data. The method is sensitive to the autocorrelation in the

25    data (von Stork and Navarra, 1995). Therefore, a bootstrapping of the data was performed *("boot"* R package, version 1.3.17) with 5000 runs. For each run, a Mann-Kendall test was applied *("Kendall"* R package, version 2.2) and the results of the trial were averaged.

The average wave heights showed a significant autocorrelation of 0.4 with the lag of 1 and 2 years, whereas the higher percentiles showed no evidence for the serial correlation. The Mann-Kendall test disproved the presence of a trend in the

30    basin-wide wave height annual means, 90th, and 99th percentiles (tau-statistics is 0.01, 0.03 and 0.005, correspondingly). This conjecture is consistent with the results of WAM simulations using geostrophic winds (Soomere and Räämet, 2014). We also checked the basin-wide annual means, 90th, and 99th percentiles for each separate season and also did not find any significant trends with the bootstrapped Mann-Kendall test.

The scarcity of changes in the basin-wide SWH and 90th and 99th percentiles agrees with wave properties reconstructed using geostrophic winds (Soomere and Räämet, 2014). Interestingly, spatial variability of changes in these quantities is much weaker than similar variability in trends extracted from numerical simulations using modelled wind fields (Hünicke et al., 2015) and ~~pattern~~ in the 90th and 99th percentiles for the North Atlantic (Bertin et al., 2013). The overall course of SWH is cyclic with a timescale of 15–20 yr as suggested already by Broman et al. (2006). The higher percentiles of SWH reveal different patterns of temporal variation (Fig. ~~3~~3a, b). Even though they exhibit formal increasing trends, the changes are not statistically significant and have either cyclic or sawteeth-like nature with markedly different time scales: 15–20 yr for the 75th percentile and much shorter, 3–4 yr for the 90th and 99th percentiles.

Simulations based on geostrophic winds indicated a complicated spatial pattern of statistically significant trends in the SWH in 1970–2007 (Soomere and Räämet, 2011). The largest increase in the SWH was identified near the Latvian coast of the Baltic Sea and a steep decrease in an area to the south of Gotland.

To assess where the changes appear locally in the Baltic Sea in our data set, we constructed maps of fitted linear trends for 1996–2015 (Fig. 4a). The presence and credibility of these changes can be to some extent evaluated based on the number of observations for each pixel used to calculate the trends (Fig. 4b). For the map of linear trends, the SWH values from single satellite altimetry snapshots were averaged for each time interval over a grid of 40×40 pixels, each pixel 0.4×0.3°. Only pixels that involve ≥8 recordings are taken into account to avoid errors due to false averaging. The map of number of observations per each 40×40 pixels (Fig. 4b) shows that the number of satellite measurements is almost uniformly distributed across the Baltic Sea with systematically fewer observations next to the coast. Therefore, if trends similar to these in the western part were also present in the eastern part of the Baltic Sea, they should have been visible in the satellite altimetry data set.

Even though a certain increase in the wave activity has occurred in almost entire sea (Fig. 4a), the changes in the SWH reveal a strong spatial pattern. The changes are minor or indistinguishable in smaller sub-basins. An increase in the SWH in areas open to the North Sea is apparently connected with an increased level of storms and swells in the North Atlantic (Bertin et al., 2013). Importantly, a significant increase is observed in the western sections of the northern Baltic Proper, to the southwest of Gotland and in the south-western part of the sea. An application of the Mann-Kendall test showed similar results (Fig. 5a). A decrease is observed in many locations near the eastern coast of the sea. Even though these changes are not directly comparable with the outcome of numerical simulations for single decades (Soomere and Räämet, 2014), they show a pattern that radically differs from the usual perception of a gradual increase in the wave activity in the eastern Baltic Sea (Hünicke et al., 2015) and has also clear mismatch with trends established for 1970–2005 (Soomere and Räämet, 2011).

To rule out that the observed east–west pattern of trends can in principle be caused by ~~homogeneity~~inhomogeneity of observations in time and space, a simulated dataset was created as

$$H_s = 0.005 \text{ m yr}^{-1}\, t + b + err, \qquad (1)$$

where $H_s$ is the simulated significant wave height, $b = -10.39$ is the intercept, and *err* is a normally distributed random error with a standard deviation of 0.5 m. The $H_s$ data were selected for exactly the same locations and times as the real

dataset. Then the same data analysis procedures were applied to the simulated dataset. The results are shown in Fig. 5b on the same 40×40 pixels grid as in Fig. 4. Significant trends are retrieved both with linear regression and Mann-Kendall method for the whole Baltic Sea basin, suggesting that time and space inhomogeneity in data could not result in an observed east-west pattern of trends.

5    To additionally check the possible masking effect of short-term fluctuations in the wave heights (Fig. 3), we applied the described analysis for three shorter consecutive periods: 2009–2011 (Period 1), 2011–2013 (Period 2), and 2013–2015 (Period 3). There was a substantial increase (up to 0.73 m, equivalent to ~~4 sigma~~ $4\sigma$ (fourfold std) variation, the false positive rate is 0.003 pixels per map) in the SWH between Period 1 and Period 2 in the northern Baltic Proper (Fig. 6a). During the subsequent Periods 2 and 3, the SWH almost reverts to the level in Period 1. The maximum decrease is 0.70 m

10  (std is 0.17 m, which shows a difference of ~~4.1 sigmas,~~ $4.1\sigma$, the false positive rate at ~~4 sigma~~ a $4\sigma$ level is 0.01 pixels per map).

The established patterns of variations in the SWH in Fig. 4 suggest, in contrary to numerical simulations described in (Hünicke et al., 2015), that a very slow increase or even a decrease in the SWH has occurred along the eastern coast of the sea. As no long-term instrumental wave record exists for this region (Hünicke et al., 2015), we check this result against

15  visually observed wave properties near the Latvian coast (Fig. 1a). Data sets with acceptable quality are available at two sites: Ventspils (57.4°N, 21.53°E) and Liepaja (56.47°N, 21.02°E) until 2011 (Soomere, 2013). The yearly averages of visually observed SWH show a fairly good qualitative correspondence with satellite altimetry data within 0.3° from these sites ~~after 2003~~ (Fig. 7). The correlation coefficient between annual average SWH from the two data sets is $r = 0.$~~66~~1 at Liepaja, based on 10 yr of coinciding data (2002–2011) and ~~r = 0.3 at~~ 444 cross-matching pairs in total. At the Ventspils site

20  (where the data quality of visual observations is lower, Soomere, 2013) the correlation is $r = 0.81$ in ~~2003~~2009–2011, with 354 pairs. The ~~match is worse (r = 0.3) at~~ lower correlation coefficient between the satellite altimetry data and visual observations can be a result of a lower number of matched pairs at this location (44.4 pairs/yr in Liepaja and ~~poor (r = 0.1) at~~ 118 pairs/yr in Ventspils ~~for 1991–2011 because of frequent mismatch in~~on average). To test the ~~two data sets in 1996–2002. An improvement~~effect of the grid cell size on the correlation coefficients, we have checked the cross-matches within

25  0.2° and 0.1° from ~~2003 onwards may reflect a substantial increase in the altimeter data from ~20 000 per year~~Liepaja and Ventspils observation sites but did not find a significant change in the correlation coefficients. For example, a reduction of the grid cell to ~~~50 000~~0.2° almost does not affect the correlation coefficient for Liepaja (0.60, 9 years of coinciding data) and improves the formal correlation for ~~the whole Baltic Sea in 2002–2003~~Ventspils (0.93, 3 years of coinciding data).


## 4 Discussion and conclusions

30  We estimated for the first time the main properties of wave climate of the entire Baltic Sea based on two decades of satellite altimetry records. Even though the resulting values of the long-term average SWH are biased towards higher waves (because

records of low wave conditions are systematically ignored), the estimated average SWH reasonably matches the outcome of numerical simulations and in situ records. The long-term SWH over the entire sea exhibits a statistically significant increase by 0.005 m yr$^{-1}$. However, the presence of such a trend was not confirmed by the non-parametric Mann-Kendall test. ~~This~~A possible reason for the failure of this test is that the trend in question is superimposed ~~to~~on marked interannual variations (consistently with the overall pattern of exceptionally high interannual variability in the winter over the entire North Atlantic (Woolf et al., 2002)) and a cyclic course of the overall wave activity and higher quantiles of SWH on a time scale of 15–20 yr.

The commonly accepted reasons behind the possible increase in the Baltic Sea wave heights are~~:~~ i) a reduction of sea ice in northern parts of the sea and ii) an increase in the wind speed (Hünicke et al., 2015). Both these reasons should lead to a spatially inhomogeneous increase in the wave heights, first of all in seasonally ice-covered northern part of the Sea and along the eastern segments of the basin where the predominant south-westerly and north-north-westerly winds usually create the severest wave conditions. Our analysis reveals an unexpected strong meridional pattern of changes: the wave heights have increased in the western offshore of the sea and have decreased (or exhibit no changes) along the eastern nearshore. It is, therefore, unlikely that a discernable increase in the wind speed has occurred in this region. This among other things means that a greater level of storms and swells (Bertin et al., 2013) may only characterize some parts of the North Atlantic. This is consistent with the conclusion that the basin-wide average geostrophic wind speed has not increased over the entire Baltic Sea (Soomere and Räämet, 2014).

~~The~~The established meridional pattern of trends in the wave heights does not reflect the variations in the density of altimetry observations as shown by the synthetic trend test (Fig. 5b). Also, the short-term changes on the timescale of ~3 yrs are located in the Baltic Proper (Fig. 6a, Fig. 6b), where the density of the observations is the highest. It is also not likely that the identified patterns represent systematic errors in the data set. The data used in the study were carefully cross-validated and all low-quality data excluded from the analysis. This concerns as measurements in the nearshore locations (<0.2° from the land), sea areas with ice concentration >30 %, backscatter coefficient >13.5 cdb, and all entries with errors >0.5 m in normalized SWH (see Kudryavtseva and Soomere, 2016 for more details). An implicit support to the validity of the established trends and their spatial patterns is a high correlation between visually observed wave properties and SWH derived from satellite altimetry for locations directly offshore from the coastal observation sites.

In this context, it is remarkable that no statistically significant trend in the SWH can be identified for the south-eastern part of the Baltic Sea. This area evidently provides the most reliable altimetry data in the Baltic Proper. This vast region of the open sea has a relatively straight coastline. It hosts no islands and ice cover appears infrequently. It is natural to expect that any systematic change in the wind speed would generate an associated change in the wave heights in some part of this region. Therefore, the likely reason for the discussed pattern of changes is a rotation of the direction of moderate and strong winds. This alteration is driven by major changes in the spatial distribution of low-pressure systems over the North Atlantic and Arctic Ocean (Lehmann et al., 2011).

Even though wind direction is often considered as a secondary parameter in climate studies, the impact of rotation of wind patterns on wave fields is a generic issue (Hemer et al., 2010). This effect is comparatively strong in regional seas and large lakes with an elongated shape (Niu and Xia, 2016) where veering of the prevailing winds may lead to large changes in the fetch length. The presented results suggest that its changes in wind direction may serve as the predominant driver of regional
5   climate changes (Hemer et al., 2010, in such water bodies (Anderson et al., 2015).

## Data availability

The satellite altimetry data are retrieved from the Radar Altimeter Database System (RADS) database (http://rads.tudelft.nl/rads/rads.shtml) (Scharroo et al., 2013). Annual observed wave heights in Fig. 7 are extracted from Soomere (2013).

10  **Author contribution**

N. Kudryavtseva performed the analysis of satellite altimetry data, wrote sections that address this analysis and prepared most of the images. T. Soomere compiled literature overview and developed the comparison of altimetry data with existing numerical simulations and visual observations. The Results and Discussion section were written together.

## Acknowledgements

20  **References**

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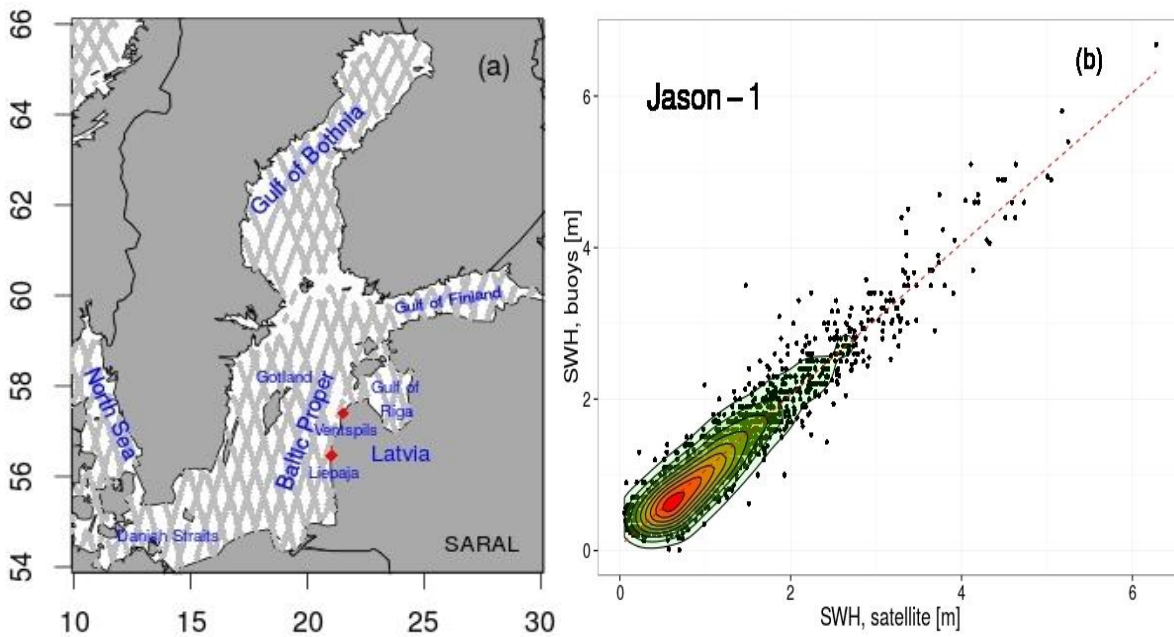
**Figure 1: Validation of satellite altimetry data, (a) an example of monthly visits of SARAL satellite to the Baltic Sea region, (b) a comparison of SWH derived using JASON-1 and in situ data. Adapted from Kudryavtseva and Soomere (2016).**
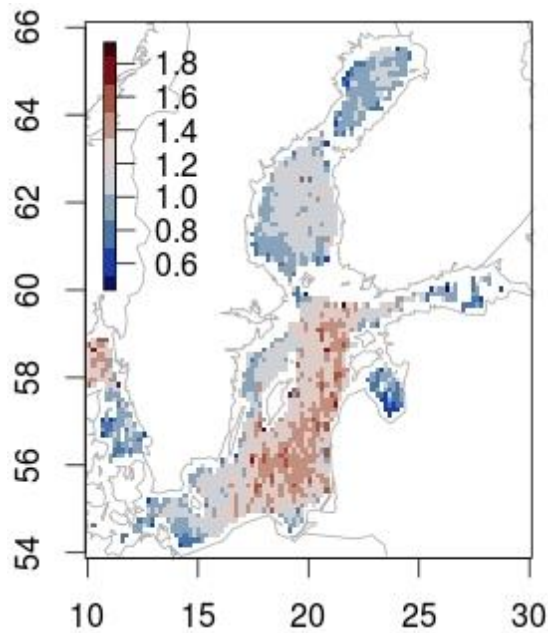


5  **Figure 2: Average significant wave height [m, color scale] in the Baltic Sea in 1993–2015 from satellite altimetry. The approximate pixel size is 0.2×0.1° (100×100 pixels grid).**
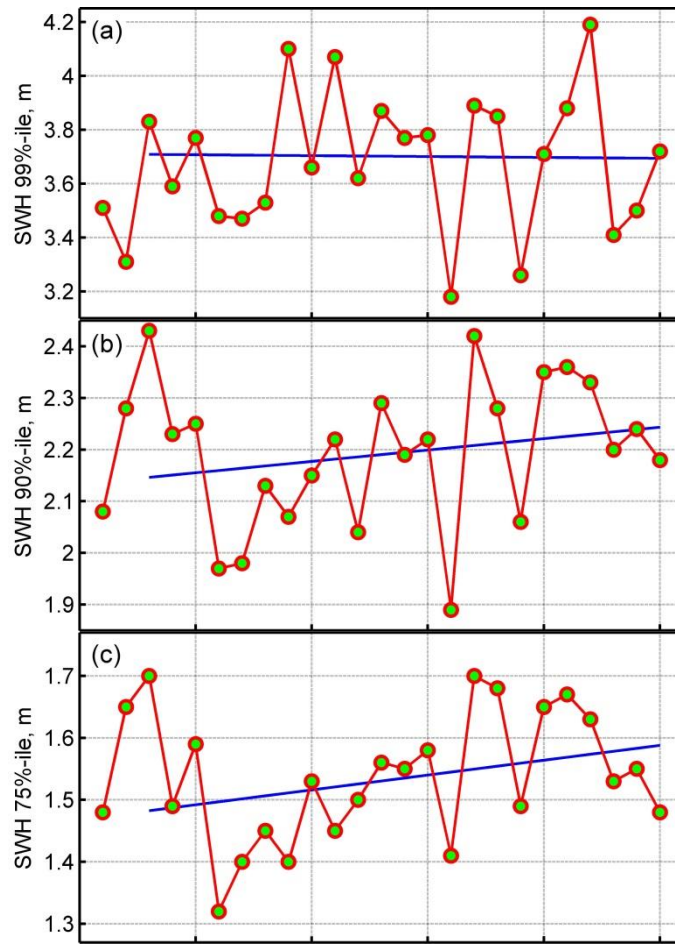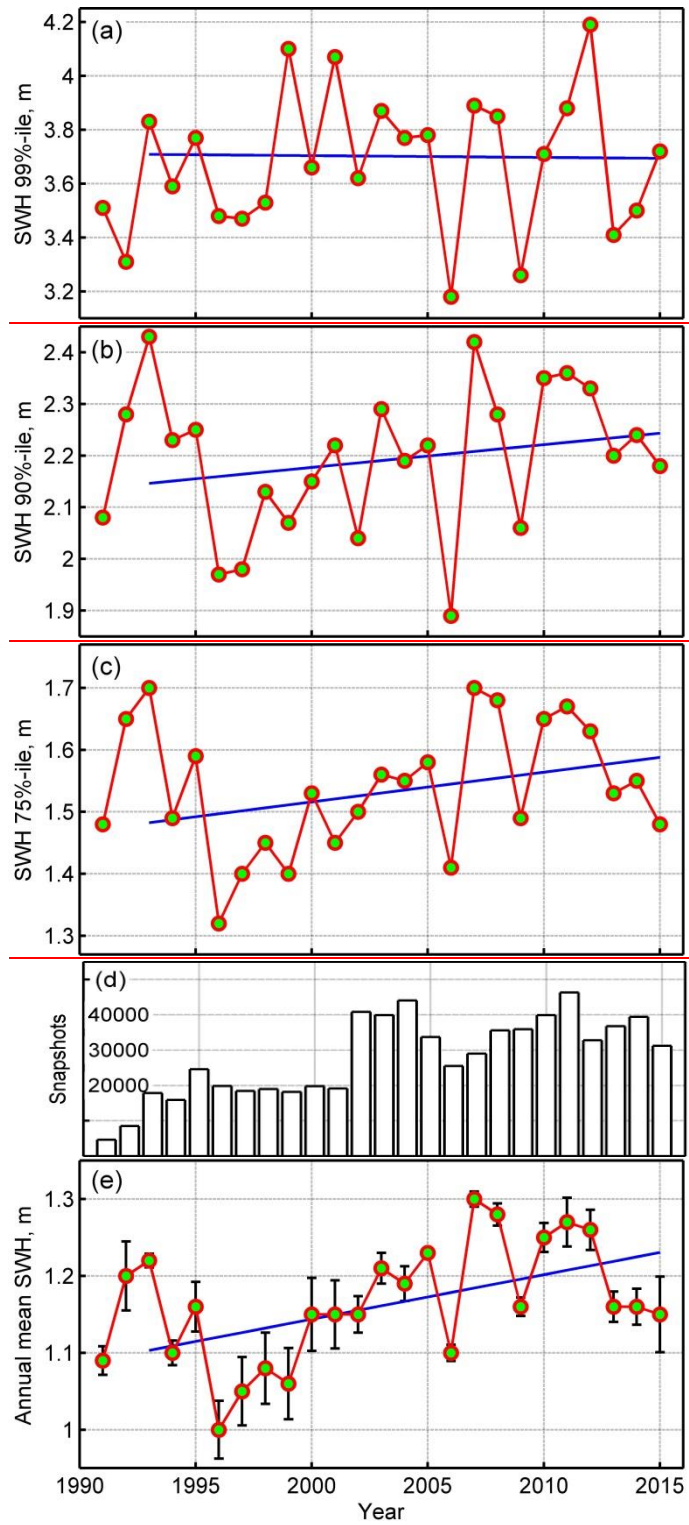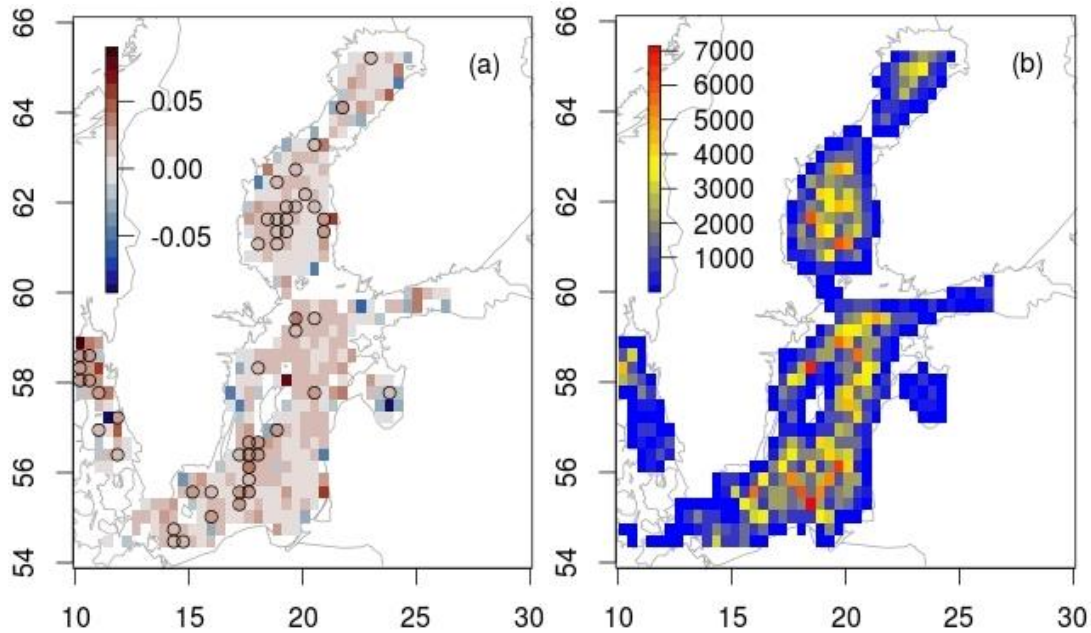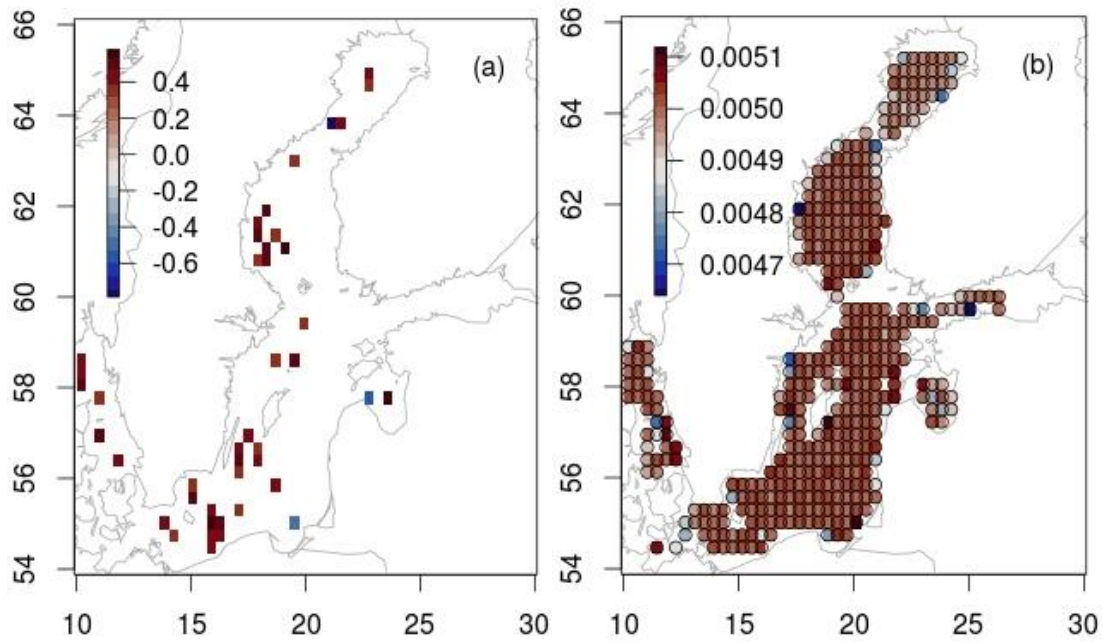
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**Figure 5: Spatial variability of wave climate in the Baltic Sea, (a) Mann-Kendall tau statistics of trends in SWH in the Baltic Sea in 1996–2015, winter months, from altimetry measurements (pixel size 0.4×0.3°). The data are shown only for statistically significant (at a >95 % level) increase or decrease in the SWH, (b) Trends found in synthetic data generated for the same positions and times as the studied satellite altimetry dataset in 1996-2015 (pixel size 0.4×0.3°). The data were created to uniformly follow a positive trend of 0.005 m yr$^{-1}$. Crosses indicate statistically significant trends (at a >99 % level).**
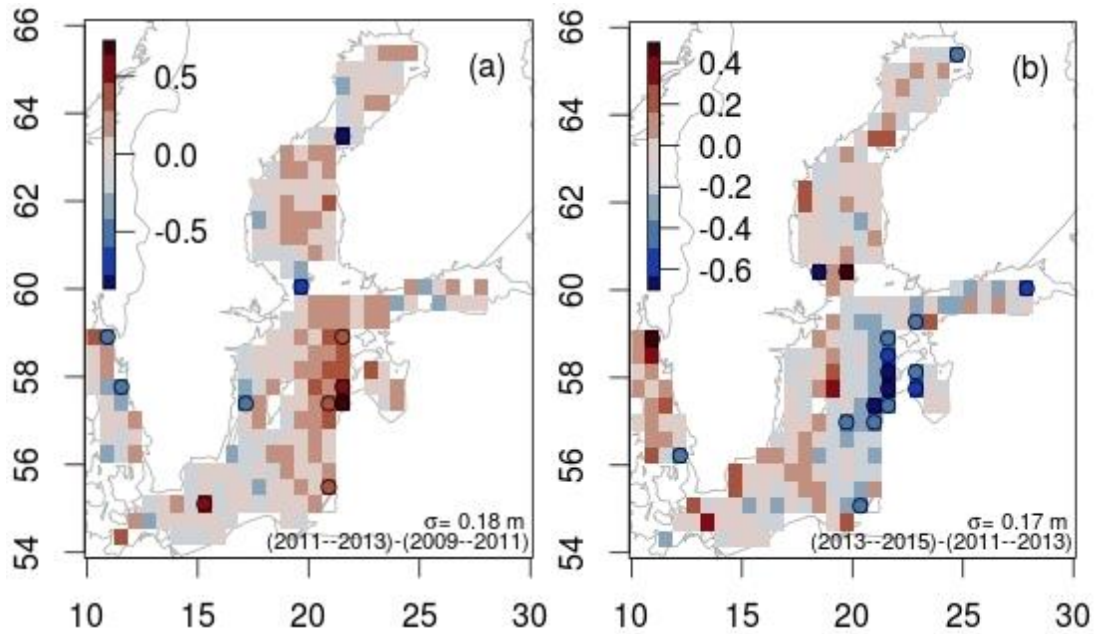


**Figure 6: Local spatial variability of wave climate in the Baltic Sea, (a) Changes (m) in the average SWH from 2009–2011 to 2011–2013, (b) Changes (m) in the mean SWH from 2011–2013 to 2014–2015. Crosses indicate the pixels hosting a statistically significant (at a >95 % level) increase or decrease.**
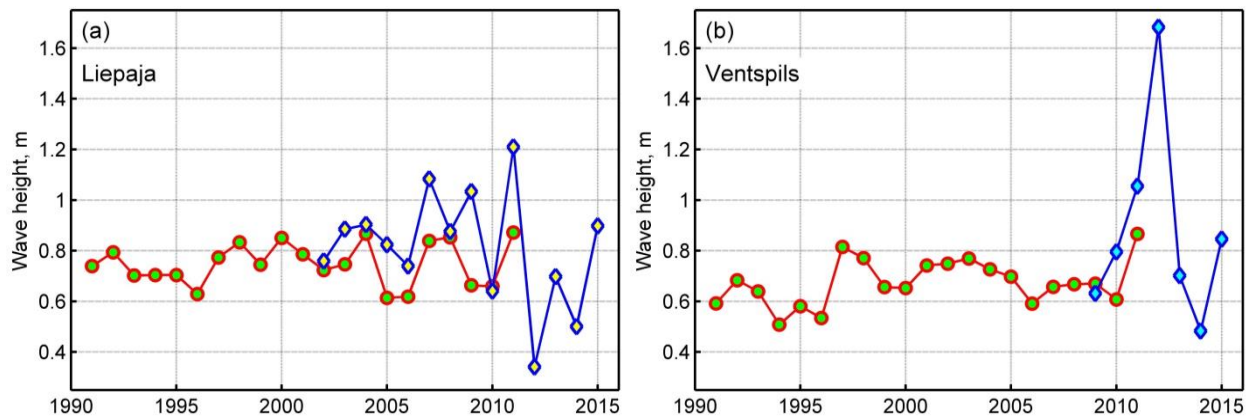
17

**Figure 7: Comparison of average annual SWH obtained using visual observations (circles) at Liepaja (a) and Ventspils (b) and multi-mission altimetry data (diamonds, shifted down by 0.4 m to ease a comparison).**

Table 1. Description of satellite missions used in the paper. As the number of observations made by the Topex/Poseidon mission was small it was not possible to adequately validate these data (Kudryavtseva & Soomere 2016), the relevant data set is not used in the analysis presented in this paper.

| Satellite | Period of observations | Accuracy [m] | Repeat cycle [d] |
|---|---|---|---|
| GEOSAT | 1985–1989 | 0.10 | 17.05 |
|  | 2000–2008 | 0.10 | 17.05 |
| ERS-1 | 1991–1996 | 0.05 | 3/35/168 |
| TOPEX | 1992–2005 | 0.02 | 9.9156 |
| POSEIDON | 1992–2002 | 0.02 | 9.9156 |
| ERS-2 | 1995–2004 | 0.03 | 35 |
| ENVISAT | 2002–2012 | 0.03 | 35 |
| JASON-1 | 2002–2013 | 0.02 | 9.9156 |
| JASON-2 | 2008–2015 | 0.02 | 9.9156 |
| CRYOSAT-2 | 2010–2015 | 0.05 | 369 |
| SARAL/ALTIKA | 2013–2015 | 0.02 | 35 |