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Spatial patterns of quality of historical wave climate reconstructions for the Baltic Sea

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We address the accuracy of replication of wave properties of the Baltic Sea using two wave climate simulations for the period of 1970–2007. Both are based on the spectral wave model, WAM, with a resolution of 3 nautical miles in hypothetical ice-free conditions. One of them used adjusted geostrophic wind fields from the Swedish Meteorological and Hydrological Institute database and the other applied high-resolution COSMO-CLM 4.8 winds. The outcome of both simulations is compared with available instrumentally measured wave heights. Simulations using geostrophic winds systematically underestimated wave heights, whereas the hindcast using COSMO winds tended to overestimate wave heights. The simulation with COSMO winds provides an acceptable match with measured data in the entire sea. The hindcast forced with geostrophic winds is only adequate at the latitudes of the Gulf of Finland.

Introduction

The Baltic Sea is a region of great challenge for wave researchers as properties of wave fields reflect the combination of wind direction and the geometry of the water body at specific locations much more than in other, less geographically variable water bodies. The conditions of slanted fetch are frequent here (Pettersson *et al*. 2010) and the presence of extensive archipelago areas (Tuomi *et al*. 2014) may cause strong enough deviation from the traditional spectrum of waves to have a measurable effect on the definition of the significant wave height (Björkqvist *et al*. 2019). The seasonal ice cover may affect the very meaning of common average wave properties (Tuomi *et al*. 2011). Wave climate studies are becoming increasingly important in the context of global climate change as due to the complex shape of the sea, the wave properties reflect not only changes in the wind speed or general storminess (Alexandersson *et al*. 1998), but also changes in the wind direction (Soomere *et al*. 2015) and modification of storm tracks (Lehmann *et al*. 2011).

Wave fields in the Baltic Sea exhibit high spatio-temporal variability due to the complexity of the geometry of the sea, anisotropy of the wind regime, seasonal variability of wind speed and the occasional presence of ice cover (e.g.,

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Jönsson *et al*. 2002, Soomere 2003, Broman *et al*. 2006, Björkqvist *et al*. 2018). The wave climate is one of the most important indicators of the wind regime and local climate change in semi-enclosed sea areas (Weisse and von Storch 2010). Considerable changes in the wave climate may greatly influence processes on the sedimentary coasts in the eastern and southern parts of the Baltic proper (Orviku *et al*. 2003).

Basin-wide average wave properties such as the annual mean wave height over the entire Baltic Sea exhibit certain decadal-scale variations but do not show any significant trend. This feature is characteristic for both modelled wave fields (Soomere and Räämet 2014, Björkqvist *et al*. 2018) and wave data retrieved from satellite altimetry (Kudryavtseva and Soomere 2017). This property is not applicable for single locations. The wave climate has extensive spatial variability (Schmager *et al*. 2008, Soomere and Räämet 2011) and it also shows regime shifts (Soomere and Räämet 2014). The existing measured and visually observed data indicate that changes in the Baltic Sea wave climate have been modest since the late 1950s through to the late 1980s (Broman *et al*. 2006, Soomere 2013). The situation changed drastically in the 1990s when rapid changes in the annual mean wave heights appeared synchronously in both the eastern and western part of the northern Baltic proper (Broman *et al*. 2006, Soomere 2013) but there were no significant changes in wave heights on the Lithuanian coast (Kelpšaite *et al*. 2008).

Some of these changes were inconsistent with some of the recorded wind data. For example, the wind speed on the island of Utö (that reflects open sea wind conditions well) showed a slight increase in the 1980s–1990s (Broman *et al*. 2006). The changes only partially matched the temporal course of storminess in the Baltic Sea region: it was relatively severe in the early 20th century, became milder in the middle of the century, more severe again in the 1980s and 1990s and probably again milder at the turn of the century (Alexandersson *et al*. 2000, Helminen 2006). An intensification of coastal processes at the end of the 20th century apparently occurred because of shortening of the ice period (Orviku *et al*. 2003, Tõnisson *et al*. 2008, Orviku *et al*. 2009, Ryabchuk *et al*. 2011). Winter ice cover makes instrumental wave measurements problematic. Floating devices are usually removed from the sea before ice formation (Kahma *et al*. 2003). As a result, the measured time series do not include data from the windiest period and some reconstructions of severe wave storms cannot be complemented with field observations (e.g., Osinski and Radtke 2020).

Because instrumental measurements and visual observations have limited temporal and spatial coverage, numerical modelling is one of the few viable ways to replicate the Baltic Sea wave climate. Today, there exist a number of contemporary third-generation wave models capable of reproducing two-dimensional spectrum of wind waves (e.g., WAM, SWAN, WAVEWATCH III, WWM). In this study, we rely on simulations using the WAM model. This model gives good results in the Baltic Sea conditions if its resolution is sufficient and the wind information is of reasonable quality (Tuomi *et al*. 1999, Tuomi 2008, Björkqvist *et al*. 2017).

The most critical issue in contemporary wave modelling is the quality of wind information. This is particularly important in the Baltic Sea. Over the last two decades, the quality of wind field data and analyses have significantly increased the accuracy of wave climate modelling (Björkqvist *et al*. 2018). But still, the wave climate reconstructions show quite large differences between the modelled and measured data as well as between the results of different model runs (Nikolkina *et al*. 2014). For example, the HIRLAM model often underestimated the wind speed in the past (Jönsson 2005). The MESAN reanalysis also tended to underestimate wind speeds (Häggmark *et al*. 2000). The first multi-decadal reconstructions of wave patterns for the period 1970–2007 using adjusted geostrophic winds clearly underestimated wave heights (Räämet *et al*. 2010, Räämet and Soomere 2010).

Another serious problem with the reconstruction of a reliable wave climate of the Baltic Sea is the winter ice cover (Kahma *et al*. 2003, Leppäranta and Myrberg 2009, Tuomi *et al*. 2011). Reconstructions under hypothetical ice-free conditions give a reasonable representation of the wave conditions in the southern Baltic Sea and also provide a satisfactory representation of the true wave field in the middle of the Baltic proper. However, in the northern Baltic Sea, determining the parameters of the wave climate is a major challenge (Tuomi *et al*. 2019) because some commonly used measures such as the annual mean wave height may be misleading. Also, the quality of some wind data sets varies over this water body. For example, the MESAN wind data is more accurate near Sweden but less reliable at a larger distance from the shore (Räämet *et al*. 2009).

Numerous wave hindcasts have been performed for the Baltic Sea over the last decade (e.g., Tuomi *et al*. 2011, Soomere and Räämet 2011, Björkqvist *et al*. 2018). They all show a similar spatial pattern of wave properties (except for the southern Baltic Sea) but produce different quantitative results. Recent wind and wave reconstructions exhibit a good match in the entire Baltic Sea basin (Björkqvist *et al*. 2018). The reliability and accuracy of older simulations may vary over different regions. In order to make use of these reconstructions, e.g., in an ensemble of hindcasts, it is necessary to estimate their accuracy in different parts of the Baltic Sea. However, some of these reconstructions (e.g., those based on geostrophic winds) cannot be extended through to the present and verified against newer measured data because of lack of homogeneous wind information.

The goal of this study is to evaluate the spatial variation in the quality of wave climate reconstructions for 1970–2007 based on instrumental wave measurements of the entire Baltic Sea. Most of these measurements only cover short time intervals and thus are not suitable for estimates of long-term wave properties and their (e.g., decadal) variations. However, their use sheds light on the reliability of wave climate reconstructions and makes it possible to compare, at least qualitatively, the outcome of older reconstructions with newer hindcasts.

We focus on two model runs using different wind data sets. One (historical) hindcast was forced with geostrophic winds and thus expected to highlight changes in wave fields that mirror similar changes in global wind patterns. Even though such forcing ignores most of local features of the wind fields, land-sea differences and the surrounding surface roughness, it follows the large-scale distribution of air pressure and thus provides a reasonable proxy of long-term changes to the wind fields. The other forcing is taken from the COSMO hindcast (Geyer 2014). Both runs are performed using the WAM model under hypothetical ice-free conditions. The model results are compared to the wave buoy data at 16 locations (Fig. 1, Table 1) from the Swedish Meteorological and Hydrological Institute (SMHI), Finnish Meteorological Institute (FMI) and Institute for Coastal Research (ICR, now Institute of Coastal Systems), Helmholtz-Zentrum Geesthacht.

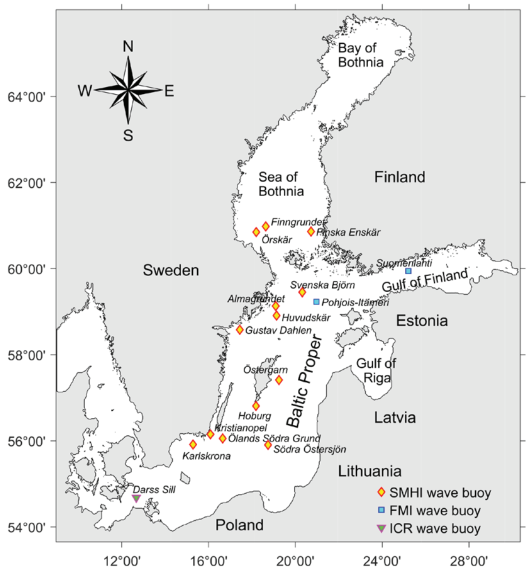

Fig 1. Locations of the SMHI, FMI and ICR instrumental wave measurement sites providing the data used in this study.

It is well known that the Baltic Sea wave fields are very intermittent and relatively short periods of intense waves are separated by much longer periods of fairly calm seas (Soomere and Eelsalu 2014). To avoid a deceptively good match between simulated and measured wave properties during calm time periods, modelled and measured wave properties are directly compared for single months chosen from relatively windy autumn and winter time.

Material and methods

Geostrophic hindcast

One set of wave properties over the Baltic Sea was simulated using the third generation spectral wave model WAM cycle 4 (Komen *et al*. 1994) for 1970–2007 and presented in a series of papers from Räämet and Soomere (2010) to Soomere and Räämet (2014). The bathymetry was based on data prepared by Seifert *et al*. (2001). The resolution of this data was 1′ along latitudes and 2′ along longitudes. The calculation was done over a regular rectangular grid (239×238 points; including 11 545 sea points) with a resolution of about 3×3 nautical miles (grid increment for latitudes 3' and for longitudes 6′). The grid covers the area from 09°36′E to 30°18′E and from 53°57′N to 65°51′N. The model was run independently from the North Sea in shallow-water mode with depth refraction but without depth-induced wave breaking. At each sea point, 1008 components of the two-dimensional (2D) wave spectrum (24 equally-spaced directions with the angular resolution of 15° and 42 frequencies ranging from 0.042 Hz with and increment of 1.1) were computed. The range of wave periods was extended to about 2 Hz to properly resolve the wave growth in low wind conditions after calm periods (Soomere 2005). The ice cover and the presence of currents were ignored.

The model was forced with the near-surface wind at 10 m level that was constructed from the SMHI geostrophic wind database. The geostrophic wind grid resolution was 1×1°. The time step was 6 h before September 1977 and 3 h after that. The geostrophic wind speed was multiplied by 0.6 and the wind direction was turned counter-clockwise by 15° as recommended by Bumke and Hasse (1989). The resulting values were interpolated to a grid with a step of about 6 nautical miles (123×107 points from 09°30′E to 30°12′E and from 53°57′N to 65°51′N) and finally into the resolution of the WAM model internally within the model. A detailed description of this model run is given in Räämet and Soomere (2010) and Soomere and Räämet (2011).

COSMO hindcast

The wave properties evaluated using geostrophic winds were compared with the results of a wave hindcast forced by COSMO winds. See the description of this model and its products in Geyer (2014). The bathymetry for the model was based on the same data set as for the model

Table 1. Instrumentally-measured wave data of the Baltic Sea. The comparisons with modelled data are only performed from the years 1977–2007.

Station	Lon	Lat	Time Period
Finngrundet (SMHI)	61.00	18.67	02.06.2006–19.08.2016
Finska Enskär (SMHI)	60.88	20.75	08.08.1989–19.12.1989
Örskär (SMHI)	60.87	18.23	21.07.1989–12.12.1989
Svenska Björn (SMHI)	59.47	20.35	01.11.1982–03.01.1987
Almagrundet (SMHI)	59.15	19.13	27.10.1978–04.09.2003
Huvudskär (SMHI)	58.93	19.17	10.05.2001–19.08.2016
Gustav Dahlen (SMHI)	58.60	17.47	07.07.1983–16.10.1987
Östergarn (SMHI)	57.43	19.28	01.05.1986–21.11.1986
Hoburg (SMHI)	56.83	18.22	24.06.1981–24.01.1982
Kristianopel (SMHI)	56.17	16.12	19.04.1990–13.03.1991
Ölands Södra Grund (SMHI)	56.07	16.68	19.10.1978–26.03.2004
Karlskrona (SMHI)	55.93	15.32	14.11.1985–15.01.1986
Södra Östersjön (SMHI)	55.92	18.78	15.06.2005–16.04.2011
Suomenlahti (FMI)	59.96	25.24	18.10.2000–02.11.2015
Darss Sill (ICR)	54.70	12.70	29.01.1991–05.07.2011
Pohjois-Itämeri (FMI)	59.25	21.00	01.01.1996–02.11.2015

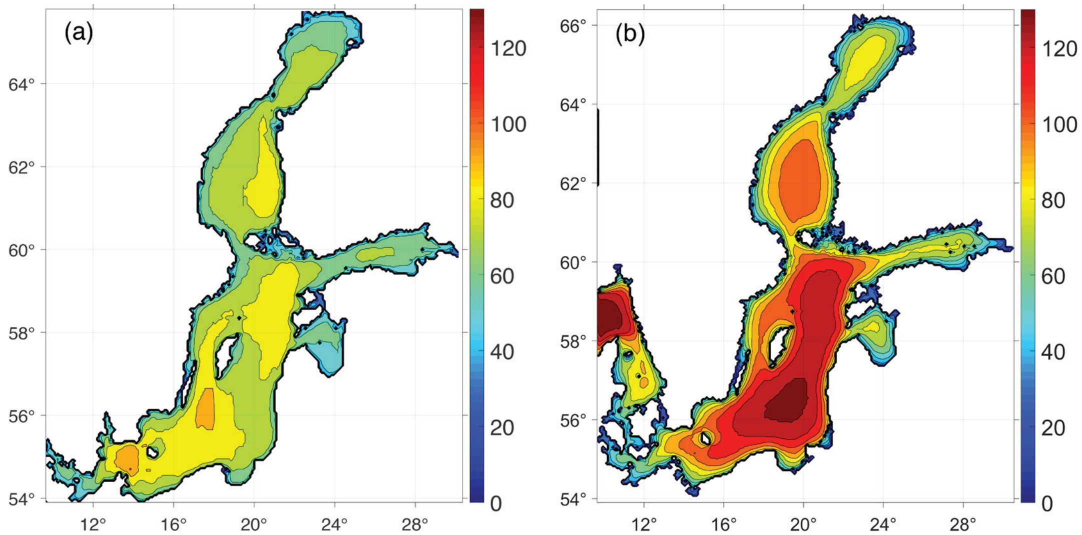

Fig 2. Long-term average significant wave height (cm) in the Baltic Sea from 1970–2007 from the WAM model forced by (**a**) geostrophic winds (adapted from Räämet and Soomere 2010) and (**b**) COSMO winds.

forced with geostrophic winds. The regular rectangular grid with the same resolution covers a slightly larger area from 09°00´E to 31°30´E and from 53°30´N to 66°00´N. The grid contains 226×251 points (including 13 396 sea points). The wave hindcast was run in shallow-water spherical mode with depth-induced wave breaking and depth refraction accounted for. Similarly to the geostrophic hindcast, the ice cover, the presence of currents and the wave energy flux from the North Sea were ignored. The directional structure of the wave spectrum was approximated by 24 equally spaced directions on a rotated grid (from 7.5° to 352.5°). The energy of wave components was approximated using 35 frequencies (from 0.042 Hz to 1.07 Hz) arranged in a geometrical progression with an increment of 1.1.

For this run, the WAM model v.4.5.3.2 was forced by winds from the meso-scale meteorological model COSMO-CLM 4.8 (Rockel *et al*. 2008) performed for 1948–2012. The wave model was run from the for 1970–2007. As the COSMO model is widely used in atmospheric modelling (Geyer 2014) and in a number of applications (Hermans *et al*. 2012, Geyer *et al*. 2015), we only present here a very brief overview of the wind data. The COSMO model is a non-hydrostatic operational weather prediction model that is developed by the several European national weather services organized in the "COnsortium for Small-scale MOdelling". The wind information from this model has a horizontal resolution 0.22° that corresponds to a grid spacing of about 24 km. The COSMO simulation has a regular rectangular grid in rotated coordinates where 40 vertical levels up to a height of 27 km are used. The time step of the data used was 1 h.

Results

The comparison of the output of the hindcasts was performed for the years 1970–2007. Both hindcasts agree that the most intensive wave fields occur in the central and south-eastern Baltic proper to the south and south-east of the island of Gotland (Fig. 2). The long-term average wave height reaches 1.3 m according to the run forced with COSMO winds. The second area of high wave activity appears in the Sea of Bothnia where the average wave height reaches 1.1 m according to COSMO winds. Semi-enclosed areas like the Gulf of Finland, the Gulf of Riga and the Gulf of Bothnia host much lower wave activity, with the long-term average wave heights approximately 0.8 m. The described pattern matches well the outcome of Tuomi

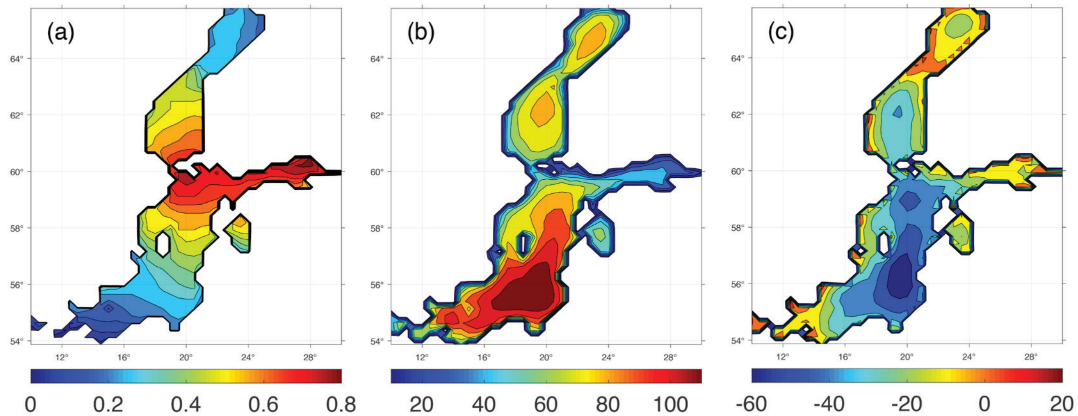

Fig 3. (**a**) Correlation, (**b**) root mean square deviation and (**c**) bias (cm) between modelled wave data produced by models forced using geostrophic winds and COSMO winds. Negative bias means that the model forced by COSMO winds gives higher waves than the model driven by geostrophic winds.

et al. (2011), which was performed using the WAM model and wind data from the HIRLAM model. A similar pattern was found also in Jönsson *et al*. (2003). A 41 year long hindcast for 1965–2005 (Björkqvist *et al*. 2018) performed using the SWAN model and BaltAn65+ winds revealed a spatial distribution of wave heights very close to the results presented here, with the mean wave heights in the Baltic proper almost the same as those evaluated using COSMO winds. The consistency with previous validated hindcasts suggests that the hindcast based on COSMO winds replicates well wave properties in the study area.

The hindcast that used geostrophic winds showed systematically lower average wave heights than simulations using COSMO winds (Fig. 2). A previous comparison with instrumental measurements and visual observations indicates that the model forced by geostrophic winds underestimates wave heights by about 15–20% (Soomere and Räämet 2011, pp. 345 and 359). The spatial pattern of long-term average wave heights is generally similar to that established using COSMO winds. The largest wave heights are in the southern Baltic proper, the northern Baltic proper and the Sea of Bothnia. The patterns based on COSMO winds are more symmetric in the east-west direction whereas the results based on geostrophic winds indicate larger wave heights in the western part of the southern Baltic proper and in the eastern part of the Sea of Bothnia.

The largest average wave heights are found in the northern and southern Baltic proper. In contrast to results obtained using COSMO winds, the wave activity evaluated using geostrophic winds is quite low in the south-eastern part of the Baltic proper near the coasts of Lithuania and the Kaliningrad district. The maximum average wave height (0.87 m in the Baltic proper) is lower than in simulations with the COSMO winds and appears in an area southwest of Gotland. Similarly to simulations with COSMO winds, wave heights in semi-closed areas such as the Gulf of Finland and the Gulf of Riga are noticeably lower (0.6–0.7 m) than in the Baltic proper. Simulations using geostrophic winds give the same maximum average wave height in the Sea of Bothnia as in the Baltic proper (0.86 m).

Different from the simulations with the COSMO wind, the hindcast based on geostrophic winds indicates strong east-west asymmetry of average wave heights in the Sea of Bothnia, where the eastern part of the sea hosts much larger waves. Also, simulations forced with geostrophic winds indicate a distinct wave height maximum (0.93 m) in the Arkona basin. This anomaly is present neither in the COSMO hindcast nor in the earlier studies (Jönsson *et al*. 2003, Tuomi *et al*. 2011, Siewert *et al*. 2015, Björkqvist *et al*. 2018). This peak apparently stems from the inability of geostrophic winds to follow different roughness of sea and land in this region.

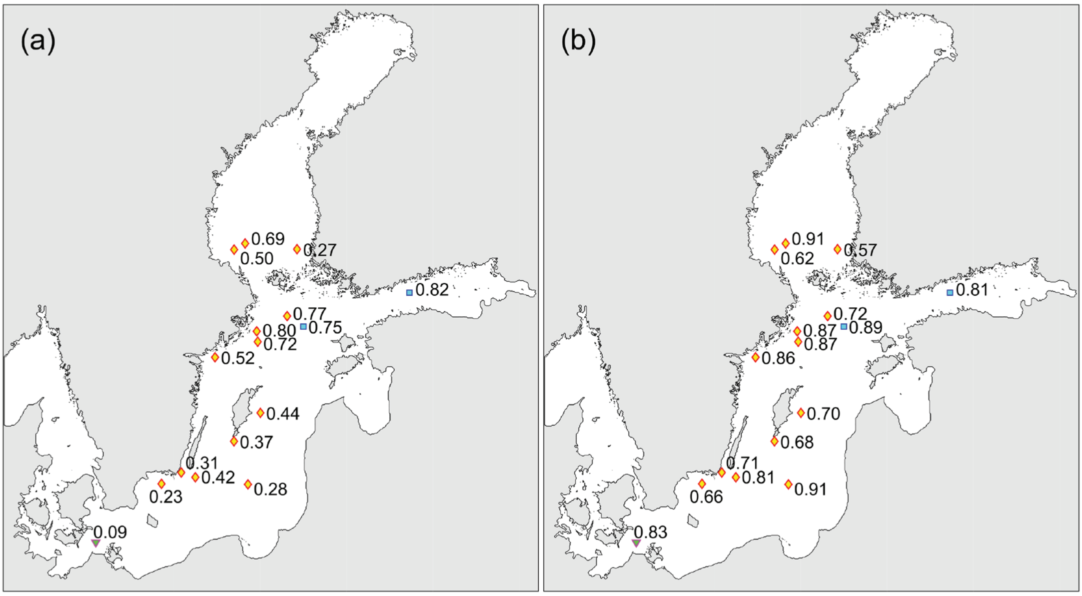

Fig 4. Correlation coefficients between measured wave properties at the locations of the SMHI, FMI and ICR measurement sites and wave heights simulated using (**a**) geostrophic winds and (**b**) COSMO winds.

The wave heights calculated using geostrophic and COSMO winds best match each other in the northern Baltic proper, in the southern part of the Sea of Bothnia and in the Gulf of Finland (Fig. 3). The maximum correlation coefficient (up to 0.8) was found in the eastern Gulf of Finland. To the north and south of the latitudes of the Gulf of Finland the correlation between the two simulated wave data sets decreases rapidly. A remarkable mismatch between wave heights calculated using geostrophic and COSMO winds appears in the south-western Baltic Sea and in the Bay of Bothnia where the correlation is almost zero.

The pattern of root mean square deviation (RMSD, Fig. 3) between the two wave simulations to a large extent mirrors the spatial distribution of the correlation coefficient. It is fairly small, at a level of 0.1–0.2 m in the Gulf of Finland and around latitude 60°N in the Baltic proper. This match is very good in the light of a comparison of modelled data with the outcome of simulations (Björkqvist *et al*. 2018). The difference is much larger, at a level of about 0.5 m in the entire Sea of Bothnia, including the Bay of Bothnia where wave heights are basically the same as in the Gulf of Finland. Therefore, a good match of the two simulations at the latitudes of the Gulf of Finland does not stem from simply low wave activity in this area and apparently reflects the acceptable quality of the geostrophic winds in this region.

Consistently with the spatial distribution of the correlation coefficient, the RMSD is very large, over 1 m in the southern Baltic proper, thus at the level of the average wave height in this basin. This large difference does not necessarily mean that one of the simulations is useless. It may easily stem from a difference in the timing of strong wind events in COSMO and geostrophic winds.

The spatial patterns of bias (Fig. 3) between the outcome of the two models first demonstrates the feature noted in discussions of the wave climate replicated using geostrophic winds (Soomere and Räämet 2011, 2014, Soomere *et al*. 2012): that such simulations systematically underestimated the wave height. Consistent with this feature, simulations using COSMO winds give higher waves in almost the entire sea compared to the hindcast forced by geostrophic winds. There are only some small areas near the coasts where the situation is different. This pattern also apparently reflects the inability of geostrophic winds to take into account the different roughness of sea and land. Wave heights calculated using COSMO winds substantially exceed wave heights obtained with the use of geostrophic winds in the southern part of Baltic proper where the bias is almost 60 cm. On such occasions it is apparent that the simulations using the geostrophic winds are not reliable. In the northern Baltic proper where the correlation is higher the bias was in the range of 30–40 cm. As expected, the main features of the spatial distribution of bias and RMSD follow long term mean wave heights calculated using COSMO winds.

To avoid a deceptively good match between simulated and measured wave properties during calm time periods, we calculated correlation coefficients for one, two or three month periods depending on the availability of measured wave data (Fig. 4). The months for comparisons were chosen from the relatively windy autumn and winter time.

Not surprisingly, the time series of wave heights replicated using COSMO winds shows much better correlation (the relevant correlation coefficient usually in the range of 0.7–0.9 and only in a few places below 0.7) with measurements than those retrieved from simulations forced by geostrophic winds. This correlation between measurements and wave properties obtained with the use of geostrophic winds changes over a wide range. In the northern Baltic proper and in the Gulf of Finland the correlation coefficient is about 0.7–0.8. To the north and south of this region it decreases rapidly. In the Sea of Bothnia and in the southern Baltic proper it falls to 0.2–0.3 and in the south-western Baltic Sea the correlation is almost zero. This pattern follows the spatial distribution of correlation coefficients between the two hindcasts (Fig. 3).

To quantitatively compare the modelled and instrumentally measured wave heights, we calculated average significant wave heights at the available SMHI, FMI and ICR wave measurement sites for all available measured wave data (Table 2). The wave heights calculated using geostrophic winds are, in almost all locations, significantly lower than the measured wave heights. The biggest difference (about 0.5 m) is at Huvudskär. Interestingly, simulations forced with geostrophic winds give higher than measured average wave height at the Gustav Dahlen and Kristianopel locations near the Swedish coast.

On the contrary, the hindcast forced with COSMO winds gave systematically higher average wave heights than the measurements. The difference is smaller than that between the measured data and the outcome of modelling using geostrophic winds. The largest mismatch (22 cm) is at Södra Östersjön in the southern Baltic Sea. Similar to the above, the hindcast based on COSMO winds underestimated average wave heights at two stations (Finska Enskär

Table 2. Comparison of the average significant wave height at the locations of SMHI, FMI and ICR wave buoys, cm.

Station	Buoy	Geostr	COSMO	G–Buoy	C–Buoy
Finngrundet	84	76	99	–8	15
Finska Enskär	123	82	109	–41	–14
Örskär	79	74	89	–6	10
Svenska Björn	112	80	119	–32	7
Almagrundet	88	71	100	–17	12
Huvudskär	121	73	106	–48	–14
Gustav Dahlen	69	75	78	5	9
Östergarn	83	73	92	–1	9
Hoburg	92	84	109	–8	17
Kristianopel	64	68	78	4	14
Ölands Södra Grund	103	84	117	–19	14
Karlskrona	95	73	103	–23	8
Södra Östersjön	104	82	126	–22	22
Suomenlahti	84	68	77	–16	–7
Darss Sill	75	81	82	5	7
Pohjois-Itämeri	124	82	119	–4	–5

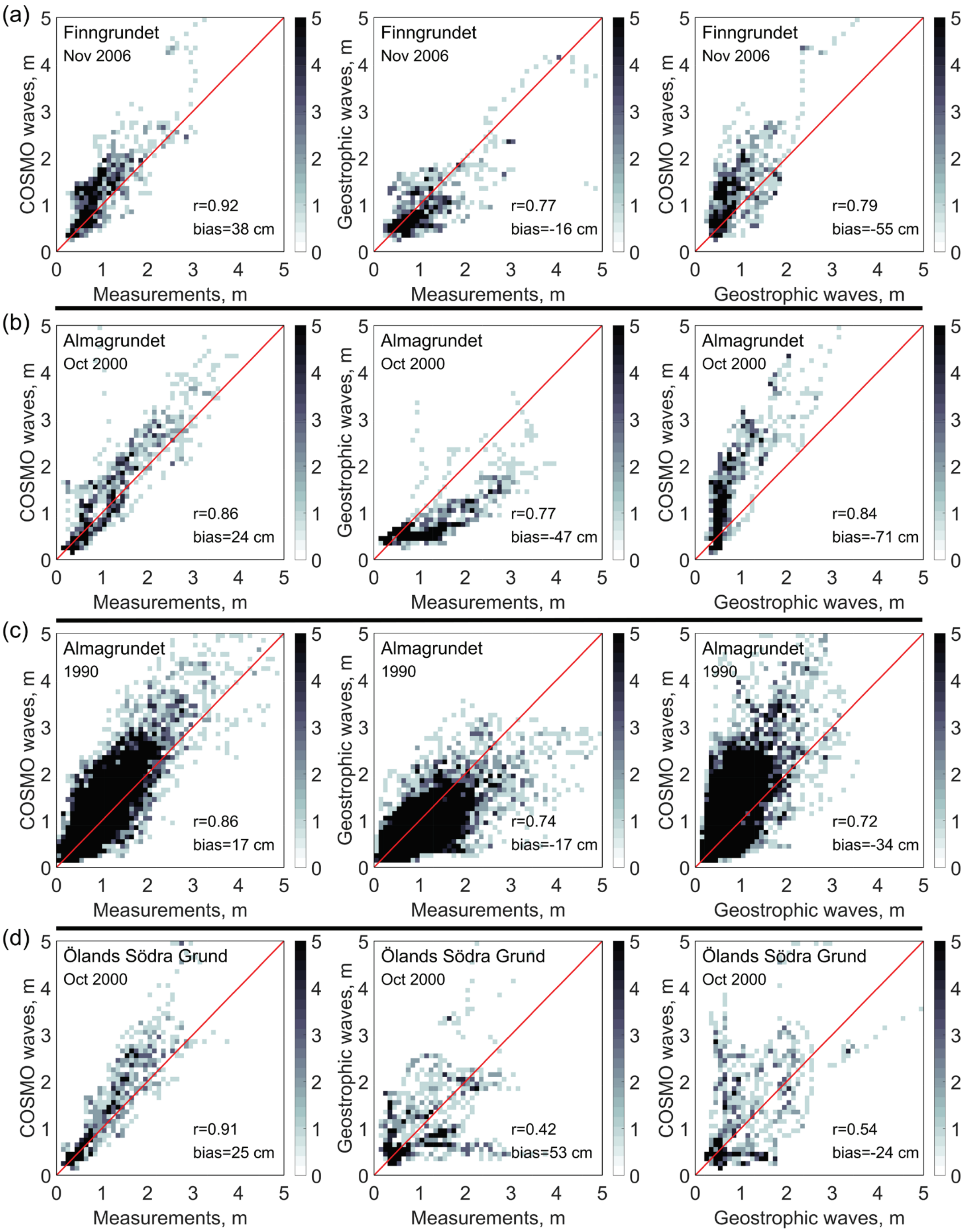

Fig 5. Scatter plot of measured and modelled significant wave heights at the locations of the SMHI wave buoys. The brightness scale shows the number of wave events in pixels with dimensions of 10×10 cm. Panels (**a**), (**b**) and (**d**) represent single windy months whereas panel (**c**) represents one year.

in the Sea of Bothnia and Huvudskär in the northern Baltic proper) in the northern part of the sea. At these stations the mismatch of measured data with the simulations using geostrophic winds was the largest (Table 2).

Further information about the (mis)match of modelled and hindcast data can be obtained using scatter plots of single overlapping data entries (Fig. 5). As the Baltic Sea wave fields are very intermittent, we present scatter plots for single months from the relatively windy autumn and winter time. The pattern of similarities and differences of modelled and measured wave heights is highly different in different locations. The outcome of both simulations match the measurements relatively well in the northern Baltic proper at Almagrundet (Fig. 5b). The simulations forced by COSMO winds give a quite good match with measured data (but slightly overestimate wave heights) in most locations. The nature and level of scatter is similar for the Sea of Bothnia (Finngrundet, Fig. 5a), the northern Baltic proper (Almagrundet, Fig. 5b) and the southern Baltic proper (Ölands Södra Grund, Fig. 5d).

As expected, scatter plots for longer time periods (one year in Fig. 5c) lead to point clouds that present much fewer features and where the average match of measured and hindcast wave data seems reasonable. This kind of match is mostly supported by data points that correspond to relatively low wind and wave conditions. As the number of such data points is comparatively large in the intermittent wave climate of the Baltic Sea, the presence of many such points to some extents masks the mismatch of wave properties under higher winds.

Consistent with the above, the simulation forced by geostrophic winds reasonably replicates wave heights in the Sea of Bothnia (Finngrundet), systematically and severely underestimates wave heights in some parts of the northern Baltic proper (Almagrundet) and unsatisfactorily follows actual wave heights in the southern Baltic proper (Ölands Södra Grund). In particular, this hindcast completely fails to replicate a set of strong wave events with heights of 2–4 m at Ölands Södra Grund.

The described pattern of differences is also evident in scatter plots of the outcome of simulations with COSMO winds and geostrophic winds. The relevant bias between the measured and hindcast data for the compared data subsets is again considerably higher for simulations based on geostrophic winds than for those forced by COSMO winds (cf. Fig. 4). The described features again confirm that simulations with COSMO winds have consistently the same level of quality over the entire sea but simulations forced with geostrophic wind have very low quality in the southern areas of the sea.

Discussion

The presented material gives an insight into the accuracy (and thus the reliability) of an older hindcast of wave properties in the Baltic Sea for 1970–2007 in comparison with contemporary simulations of the wave climate. The results of two discussed hindcasts (performed using geostrophic winds and COSMO winds, respectively) are compared with available instrumental wave measurements.

The core message is a well-known conjecture that the quality of historical simulations of wave climate substantially varies in different regions and that most of these (often great) differences stem from the different replications of the wind field that are used to force the wave model.

There are some features for which all the recent and historical wave simulations agree. For example, the eastern part of the Baltic Sea has the most severe wave climate. The wave intensity is, on average, somewhat lower in the Sea of Bothnia and considerably lower in the smaller sub-basins of the sea such as the Bay of Bothnia, the Gulf of Finland, the Gulf of Riga or the Arkona basin.

There remain differences and inconsistencies that seem to be an intrinsic part of wave modelling in the Baltic Sea. For example, the locations of hindcast long-term wave height maxima differ considerably. The models do not even agree as to whether the highest waves appear in the north-eastern (Tuomi *et al*. 2011) or south-eastern (Nikolkina *et al*. 2014, Björkqvist *et al*. 2018) areas of the Baltic proper or to the south of Gotland in the south-western Baltic proper (Soomere and Räämet 2011). In essence, it is a reflection of a common feature in wave modelling today, that a significant difference between measurements and modelling often occurs (Bonaduce *et al.* 2019).

It is highly unlikely that small differences in bathymetry, model parameters or model type can cause such large differences in simulation results. Even ignoring sea ice cannot cause these differences, in particular, to the south of the Gulf of Finland latitudes. The most likely source of mismatches is thus hidden in the wind information. The use of geostrophic winds evidently suppresses wave heights in the sea area between Gotland and Lithuania and Poland (Fig. 3). This feature may easily relocate the actual area of maximum wave intensity at these latitudes to the west. Also, subtle changes in the wind patterns such as possible changes in the directional structure of winds (highlighted in the analysis of satellite information in Kudryavtseva and Soomere 2017), may cause "relocation" of the maxima of wave intensity in simulations performed over different time intervals.

Another important message is that older wave modelling efforts evidently have very different quality in different parts of the Baltic Sea. The match with newer simulations is better in nearshore areas and in some of the semi-enclosed sub-basins (Soomere *et al.* 2012) where the bias in terms of wave heights is relatively low. This bias probably does not play a great role in applications such as wave-driven alongshore sediment transport that only use certain long-term properties of the wave climate. For example, specification of the closure depth only requires the wave heights that occur, on average, 12 hours a year and estimates of wave-driven alongshore sediment transport and simple models of shoreline evolution rely on the frequency of occurrence of waves with different heights, periods and propagation directions, often under the assumption that the wave climate is statistically stationary (e.g., Deng *et al.* 2015). It is, however, critical in applications that require an adequate timing of wave events such as evaluation of the contribution of wave set-up to the total water level (Pindsoo and Soomere 2015). On such occasions it is strongly suggested that contemporary numerically simulated wind information is used.

The hindcast forced by an even relatively old version of COSMO winds (performed in 2013 for the years 1948–2012, Geyer 2014) seems to produce fairly consistent results over the entire sea. The correlation between modelled and measured wave heights remains generally the same over the entire sea. The relevant correlation coefficient is about 0.8 and in some places even above 0.9. Scatter plots of modelled and measured wave heights also reveal that wave heights are reasonably replicated in the largest basins of the sea.

In contrast, the adequacy of the wave climate restored using geostrophic winds varies greatly in different parts of the sea. In the northern Baltic proper and Gulf of Finland the outcome gives results that match the hindcast using COSMO winds. However, away from this region, the accuracy of replication of wave properties using geostrophic winds rapidly drops. This feature becomes evident in all components of our analysis. The replication of the main statistical properties of the wave climate (e.g., the mean wave height) may still be acceptable in some sheltered and/or nearshore regions as shown in (Viška and Soomere 2012) in terms of the hindcast of sediment transport along the Curonian Spit. We once more note that historical wave hindcasts using geostrophic winds systematically underestimate wave heights in the open sea areas whereas simulations using COSMO winds tend to overestimate the wave heights.

In conclusion, offshore wave properties simulated using geostrophic winds provide an acceptable replication of long-term wave height only in the northern Baltic proper and the Gulf of Finland. The simulations using COSMO winds acceptably replicate the past wave climate in most areas of the Baltic Sea in terms of the wave height. The outcome of the hindcast using COSMO winds is close to the one that used BaltAn65+ winds (Björkqvist *et al.* 2018) whereas simulations using geostrophic winds provide results that diverge significantly from both of these studies.

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