Spatial variability of directional misalignment between waves and wind in the Baltic Sea-model study

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Abstract

Knowledge of wave-wind misalignment is valuable for nautical activities and design of offshore structures. Wind-wave misalignment has been studied using a 41-year high-resolution hindcast in the Baltic Sea. For the first time the spatial variability of wind-wave misalignment in the entire Baltic Sea was analyzed. It is shown that wind-wave misalignment is a basin wide phenomenon. Wind-wave misalignment occurs in all sub-basins of the Baltic Sea. Average wind-wave misalignment in deep water (water depth over 50 m) shows large spatial variations, yielding from 20^0 to 40^0. However the instantaneous wind-wave misalignment during high sea states (significant wave height over 2 m and wind speed 12 m/s) reaches 80^0 in deep water. Wave-wind misalignment dependence on wind speed shows the decrease of misalignment with increasing wind speed. Main causes of misalignment in deep water are temporal changes in dynamic systems and fetch-restrictions. Further studies should concentrate also on spatial validation of directional wave characteristics in the Baltic Sea.

1. Introduction

The Baltic Sea (BS) is as a large (spans from 9^0-30^0 E and 53^0-66^0 N, total area of 435 000 km^2) seasonally ice-covered water body containing several topographically and geographically defined sub-basins (Fig. 1). The mean water depth is 55 meters and the maximum water depth reaches 459 meters in the Landsort Deep. The longest possible fetch is about 700 km in the Baltic Proper. Since the BS lies in temperate latitudes it is largely affected by the westerly airflow. This leads to a wind rose, where approximately 50 % of the time the wind blows from a 90^0 sector between 180-270^0 (S. SW, W). The wind direction in storm conditions (winds with sustained speed over 15 m s^{-1}) usually is between 180^0-360^0 due to the movement of cyclones (Jönsson et al., 2003). The yearly average wind speeds over the Baltic Sea are 6-8 m s^{-1}. During the passage of deep cyclones the 10 minute sustained wind speed has reached hurricane force winds (Suursaar et al., 2006). While the average annual significant wave height in the Baltic Sea is less than 1.25 m (Fig. 2a) and waves are short (Fig. 2c), it is appealing to see that in the fetch-limited and mostly shallow Baltic Sea the maximum significant wave heights (Fig. 2d) are up to half of what has been measured and modeled in the World Ocean (Hanafin et al., 2012).

Besides swell and heterogeneous wind field the occurrence of restricted fetches makes it possible that waves and wind might not be aligned in the deeper parts of the Baltic Sea, where the refraction is small. Pettersson et al. (2010) indeed has shown wind-wave misalignment in the central part of Gulf of Finland owing to slanting fetches. However the spatial variability of wind-wave misalignment is poorly studied in the Baltic Sea. The main aim of this paper is to study the spatial variability of wind-wave misalignment in the entire Baltic Sea. The wind-wave misalignment definition follows Van Vledder (2013) and is defined as the temporal difference between mean wave direction and mean wind direction. Therefore, peak wave directions might be even more misaligned with the wind direction.

The spatial variability of wave-wind misalignment has several practical and scientific implications in the Baltic Sea, such as:

1) Stokes drift. Oil spill calculation and search and rescue operations depend on Stokes drift, which usually is assumed to align with wind direction.
2) Navigation and route planning.
3) Structural design of offshore wind farms foundations.
4) Usage of wave prediction models. As discussed in Van Vledder (2013) the quality of wind-wave models regarding directional characteristics receives little attention. Especially in slanting fetch situations proper choice of the non-linear source term has a significant effect on directional characteristics (Ardhuin et al., 2007) & Bottema and Van Vledder (2009).
5) Wave-atmosphere interaction.

This paper is structured as follows. In the second paragraph the numerical wave model (SWAN) is described along with its setup. In the third section the results of wind-wave misalignment are presented and some general discussion follows in Chapter 4. Main conclusions are outline in the fifth paragraph.

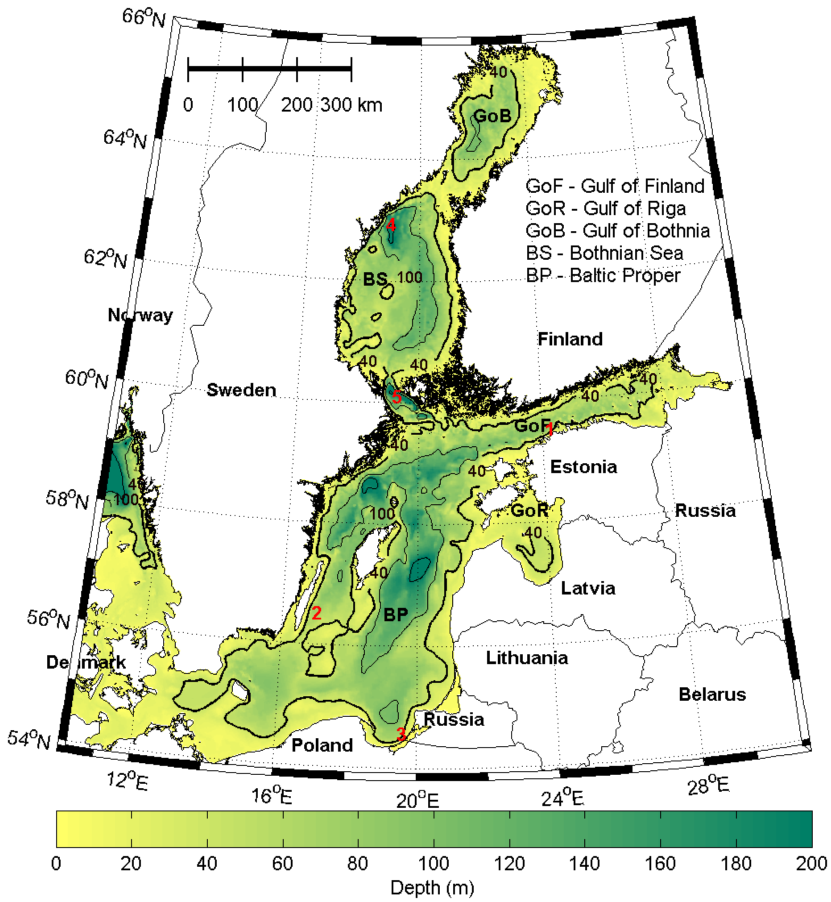


Figure 1. Baltic Sea bathymetry (Seifert et al., 1995), smoothed with 6 km filter. Red numbers corresponds to selected points, as described in Table 1. 40 m, 100 m and 200 m isobaths are also shown.

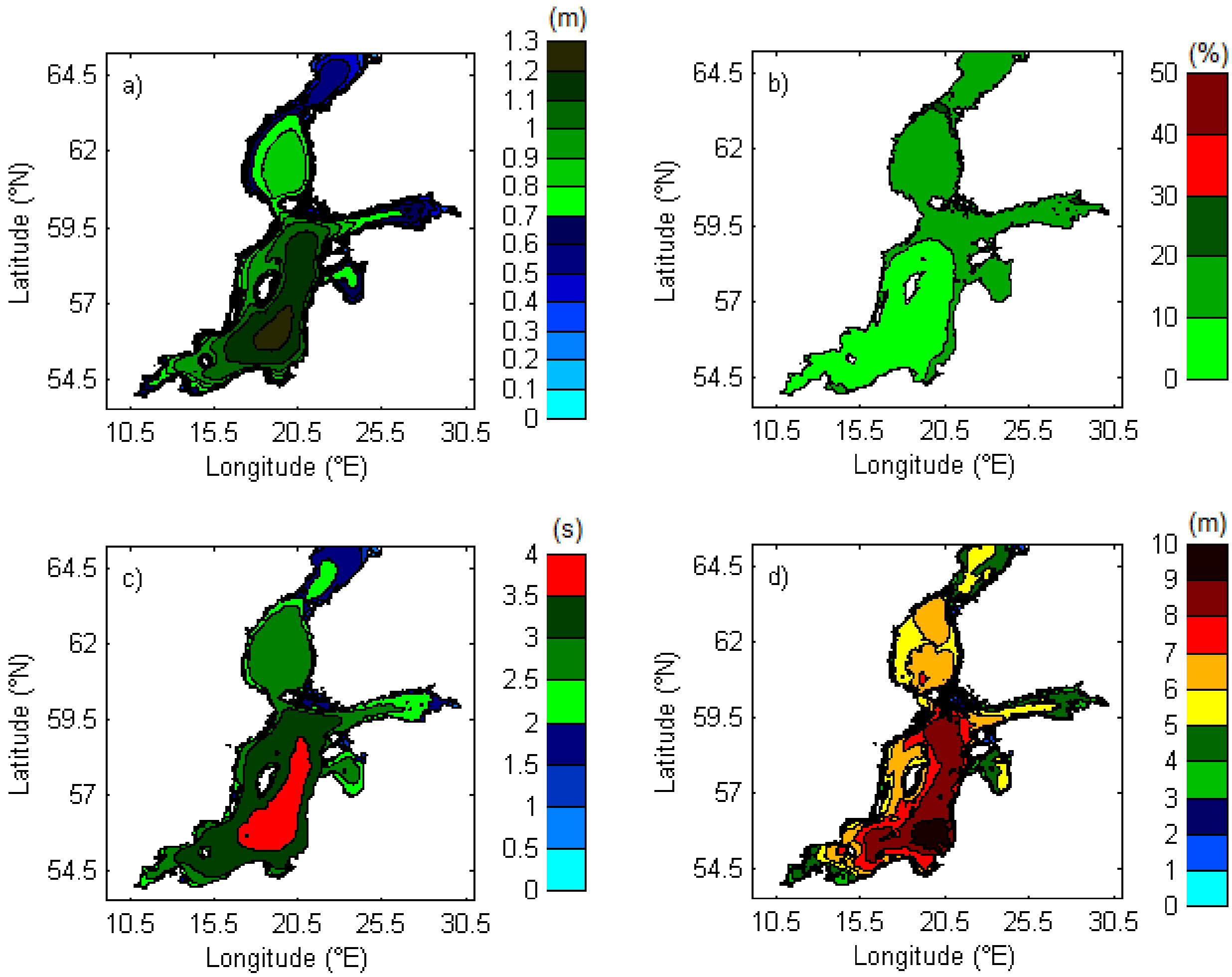


Figure 2. Modeled wave parameters in the Baltic Sea between 1965-2005. Simulated with 1 nautical mile SWAN model forced by Luhamaa et al. (2011) winds and ice fields from Rossby Centre SMHI. (a) average significant wave height; (b) standard deviation of yearly average significant wave heights divided by average significant wave height; (c) average wave period corresponding to first moment of spectrum; (d) maximum modeled significant wave height.

2. Numerical model

2.1 Model description

The Simulating Waves Nearshore (SWAN) model was used to study the wave-wind misalignment in the Baltic Sea. SWAN (Booij et al., 1999) is a third generation phase averaged spectral wave model developed at Delft University of Technology. In SWAN the waves are described with the four-dimensional wave action density spectrum, whereas the evolution of the action density N is governed by the time dependent wave action balance equation, which in Cartesian coordinates reads:

$$\frac{\partial N}{\partial t} + \left(\overrightarrow{c_g} + \vec{U}\right) \cdot \nabla_{x,y} N + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma}. \qquad (1)$$

The first term represents the local rate of change of action density; the second term denotes the propagation of wave energy in two dimensional geographical space, with $\vec{c}_g$ being the group velocity and $\vec{U}$ the ambient current. The third term represents the effect of shifting of the radian frequency due to variations in depth and mean currents (in this study currents are ignored). The fourth term represents the depth-induced and current-induced refraction. The quantities c_σ and c_θ are the propagation velocities in spectral space (σ,θ), with σ and θ representing the radian frequency and propagation direction respectively. The right-hand side contains the source term S_{tot} that represents all physical processes that generate, dissipate or redistribute wave energy in SWAN. In shallow water, six processes contribute to S_{tot} :

$$S_{tot} = S_{wind} + S_{wc} + S_{nl4} + S_{nl3} + S_{bot} + S_{db}. \qquad (2)$$

These terms denote the energy input by wind (S_{wind}), the nonlinear transfer of wave energy through three-wave (S_{nl3}) and four-wave interactions (S_{nl4}), and the dissipation of waves due to whitecapping (S_{wc}), bottom friction (S_{bot}) and depth-induced wave breaking (S_{db}), respectively.

2.2 Model setup

Model resolutions

The model (SWAN cycle III, version 40.91) was run in a non-stationary mode with a 15 min integration time step. The modeling period was from 1965-2005. Structured grid with spherical coordinates and resolution of 1' along latitudes and 2' along longitudes was used. The grid extended from 9.5167^{0}E to 30.4834^{0}E and 53.7583^{0}N to 65.9916^{0}N, which gave 629 meshes along longitudes and 734 along latitudes. The grid included 106,082 sea points. Only at these points the calculations were performed (so-called wet grid points) and four output parameters were generated. The parameters are: significant wave height H_{m0}, average wave direction θ_0 , peak wave period T_p and wave period T_{m01} corresponding to first moment of the spectrum. The wave spectrum was described with 32 frequencies distributed logarithmically (with 10% increase) on frequency range from 0.05-1 Hz and with 24 equally spaced directions in the 360^0 rose.

Physical processes

Third-generation formulations with respect to wave-wave interactions (triad and quadruplet), whitecapping, wind input, bottom friction and depth-induced breaking were used. The whitecapping was due to Westhuysen et al. (2007) and combined with the wind input by Yan (1987). Linear growth term for wind growth was also activated. The quadruplet interactions were approximated using the Discrete Interaction Approximation (DIA) by Hasselmann et al., 1985 with default settings and triad interactions were approximated with Lumped Triad Approximation (LTA) by Eldeberky (1996). The depth-induced breaking was due to Battjes and Janssen (1978) with the breaker parameter set to 0.73. JONSWAP (Hasselmann et al., 1973) form of bottom friction with the bottom friction coefficient of 0.067 m^2s^{-3} was used.

Input fields

The wind used in this wave study was from the Baltic Sea regional reanalysis database BaltAn65+ (Luhamaa et al., 2011). Basically it is a regional refinement of the ERA-40 dataset with a horizontal grid resolution of 0.1 degrees (approximately 11 km). The period of the reanalysis covers 01.01.1965-31.12.2005. High Resolution Limited Area Model (HIRLAM) was used for the reanalysis (Luhamaa et al., 2011). Wind velocity components (and other meteorological parameters) were saved every 6th hour. Velocity components were interpolated to model integration time steps internally in SWAN and the interpolation was strictly energy conservative.

The ice concentrations used in this wave study were calculated at the Swedish Meteorological and Hydrological Institute (SMHI) by using a coupled ice-ocean model. The Rossby Centre Ocean (RCO) model and Helsinki Multicategory Sea Ice Model (HELMI) were run for the period 01.01.1965-31.12.2005 with a 2 nautical mile horizontal grid step. The coupled ice-ocean model was forced with the downscaled ERA-40 dataset (with 25 km resolution). The temporal recording interval of the ice concentration was 2 days. As SWAN has no special treatment of ice the ice was introduced to wave model with the water level switch. When the ice concentration was over 50 % then that grid point was assigned as a dry point by subtracting 500 m from the water depth, as SWAN considers water depth as positive values. Kriezi and Broman (2008) and Cieślikiewicz and Paplińska-Swerpel (2008) used also 50 % threshold value for ice concentration, while Tuomi et al. (2011) used 30 %.

The digital topography covering the entire Baltic Sea with a resolution of 1 nautical mile (Seifert et al., 1995) was used in this study (See Figure 1)

3. Results

3.1 Average spatial variability

Though the entire dataset of modeled waves (see last section) covers 41 years, we selected for data analysis only the year 2005. This is quite representative year in terms of annual average parameters, but the winter average wave heights were one of the highest in the 41 year dataset. The maximum ice extent in this year was reached in March (Fig. 3), when the Gulf of Finland, Gulf of Bothnia and Gulf of Riga were ice-covered. The average wind-wave misalignment for year 2005 is shown on Fig. 4. Points are displayed for every 11 km (due to wind field resolution) and also, points which are closer to the coast than 11 km and points which are in shallower water than 50 m are excluded. This leaves total of 1667 points. In each spatial point 1456 temporal points (every 6th hour) are averaged to obtain the yearly average.

The yearly average absolute misalignment in water deeper than 50 m stays between 19^0-42^0 and the overall average is 27^0. This indicates that wind-wave misalignment is a basin wide phenomenon in the Baltic Sea. Several areas can be distinguished, where the misalignment is above the average. These include the coastal zone of Estonia in the Gulf of Finland, coastal zone of Sweden in the Bothnia Sea and Bay of Bothnia, east coast of Öland Island and Aland Sea in Sweden and the Gdansk Bay, Poland. This is important information for the design of foundations of offshore wind farms and nautical activities in these coastal regions.

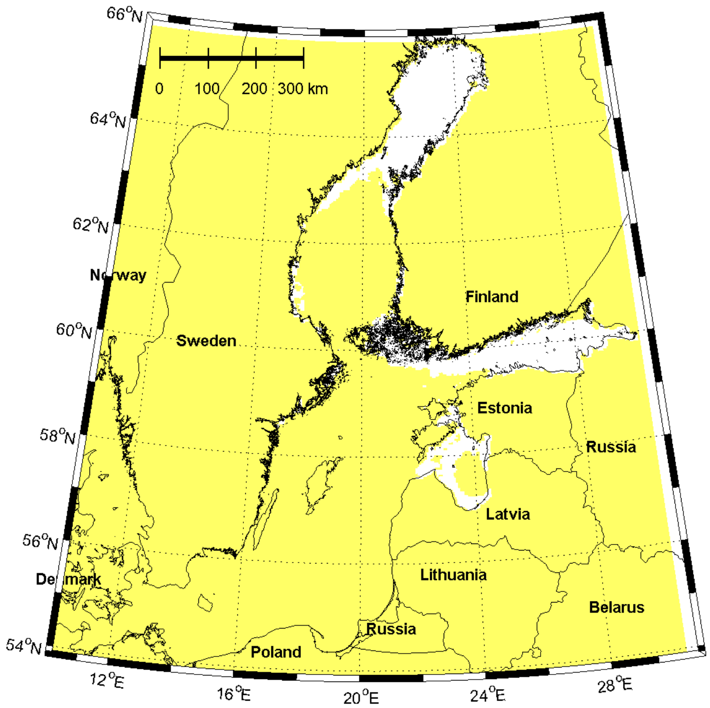


Figure 3. Maximum ice extent in 2005. Ice is indicated white.

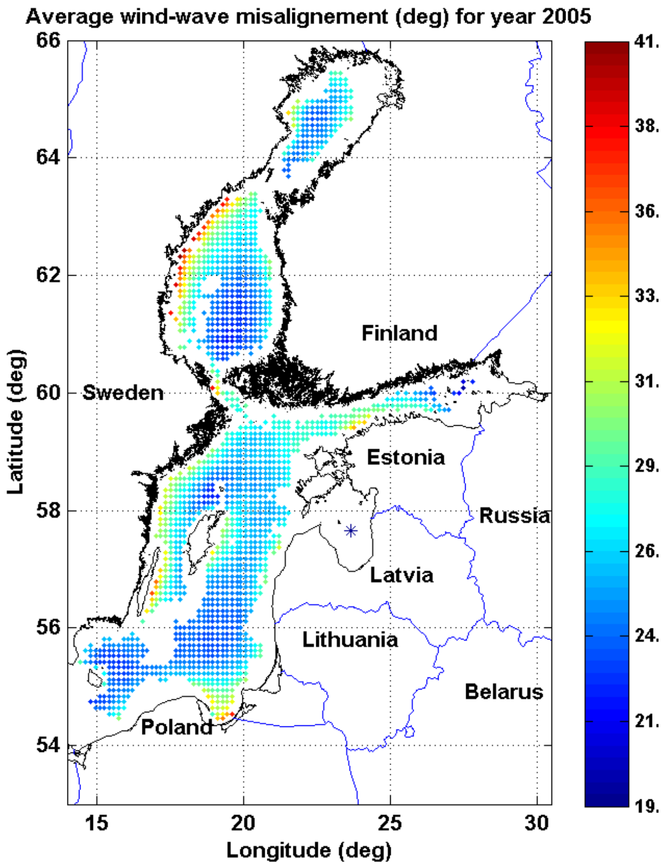


Figure 4. Spatial variability of yearly average wind-wave misalignment (^{o}).

3.2 Misalignment as a function of wind speed

From the zones mentioned above we picked representative points (as described in Table 1; locations on Fig. 1) and studied the wave-wind misalignment dependence on wind speed (Fig. 5). The general trend is the decrease of misalignment with increasing wind speed, consistent with Van Vledder (2013). For all the 1677 points it stabilizes around 13^0, whereas for the selected five points it is twice as large. However, even the five selected locations display different behavior in wind speeds above 10 m/s. In the Gulf of Finland the difference is over 30^0 in quite strong wind conditions, but as the water depth there is 90 m, the refraction is deemed small. In the Gdansk Bay the difference grows up to 40^0 in winds over 16 m/s. Note that only 3 days in a year was the wind speed over 16 m/s.

Table 1.

Nr	Location	Linear index	Lon	Lat	Water depth (m)	Mean misalignment (^{0})
1	Gulf of Finland	1617	24,1014	59,5083	89,2	34
2	East coast of Öland	131	16,8755	56,4915	71,6	34
3	Gdansk Bay	725	19,4396	54,5414	72,8	35
4	Bothnia Sea west coast	519	18,8069	62,9085	170,4	36
5	Aland Sea	626	19,1066	60,0917	172,9	33

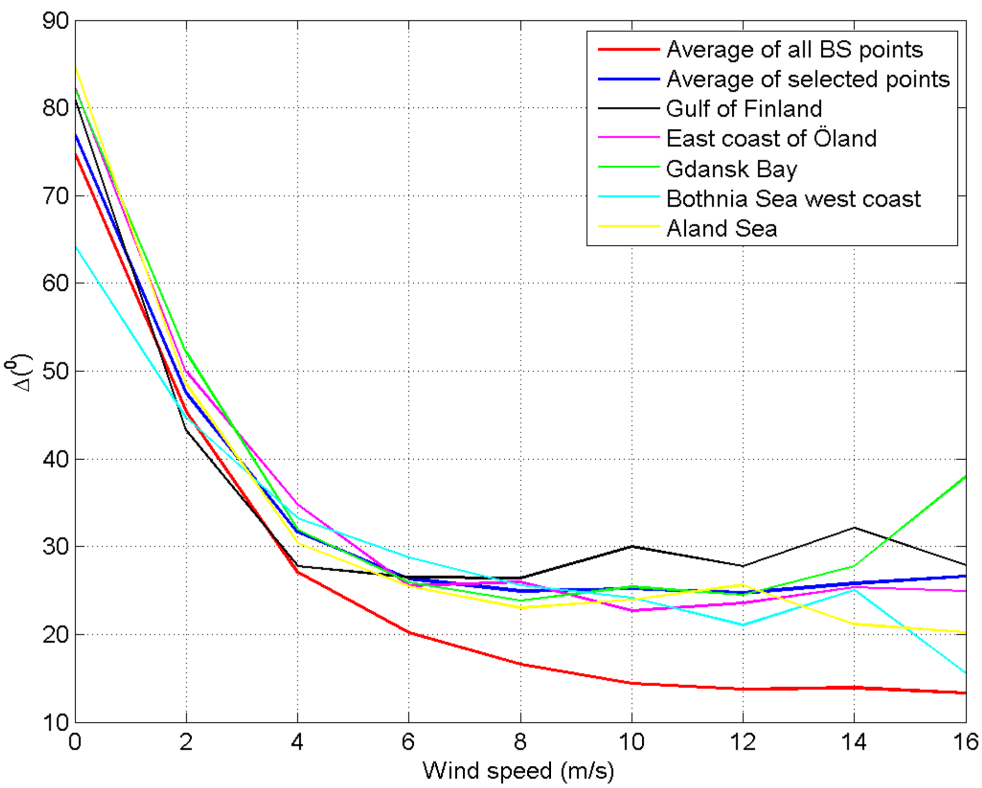


Figure 5. Wave-wind misalignment dependence on wind speed at 10 m height.

3.3 Cyclone Gudrun

A snapshot of wave and wind field (Fig. 6) during cyclone Gudrun, which passed the Baltic on January 9th, 2005, shows the complex pattern of wave and wind direction. As the centre of cyclone was above Finland, the dominant wind direction was from west in the Baltic Proper, while the waves preferably came from the SW. There might be two explanations for that. Firstly, the wind direction 6 h before was also more to SW (the classic pattern of wind veering, where the wind direction turns from SW to NW eventually, when the cyclone centre passes from north) and the waves have not yet turned. As discussed in Van Vledder and Holthuijsen (1993) the speed of the directional response depends on the sea state, which may partly explain the misalignment. The second explanation would be slanting fetch, since the fetch component from SW is much longer compared to that of W. The second explanations sounds more plausible here, since indeed the waves in southern part of Baltic Sea (attacking Lithuania) are coming from west (as wind) and also from the longest fetch. But in the northern Baltic Proper the waves are coming from SW, which also have the longest fetch. By inspecting Fig. 4 once more it is clear that the average directional misalignment is greater in the northern Baltic Proper than in the southern Baltic Proper. This coincides with Fig. 6 suggesting that the waves in the northern part of Baltic Proper are under the influence of slanting fetch and or/ have greater share of swell, thus contributing to the misalignment. It should be noted that in swell affected/dominated systems the mean wave direction is partly independent of wind direction.

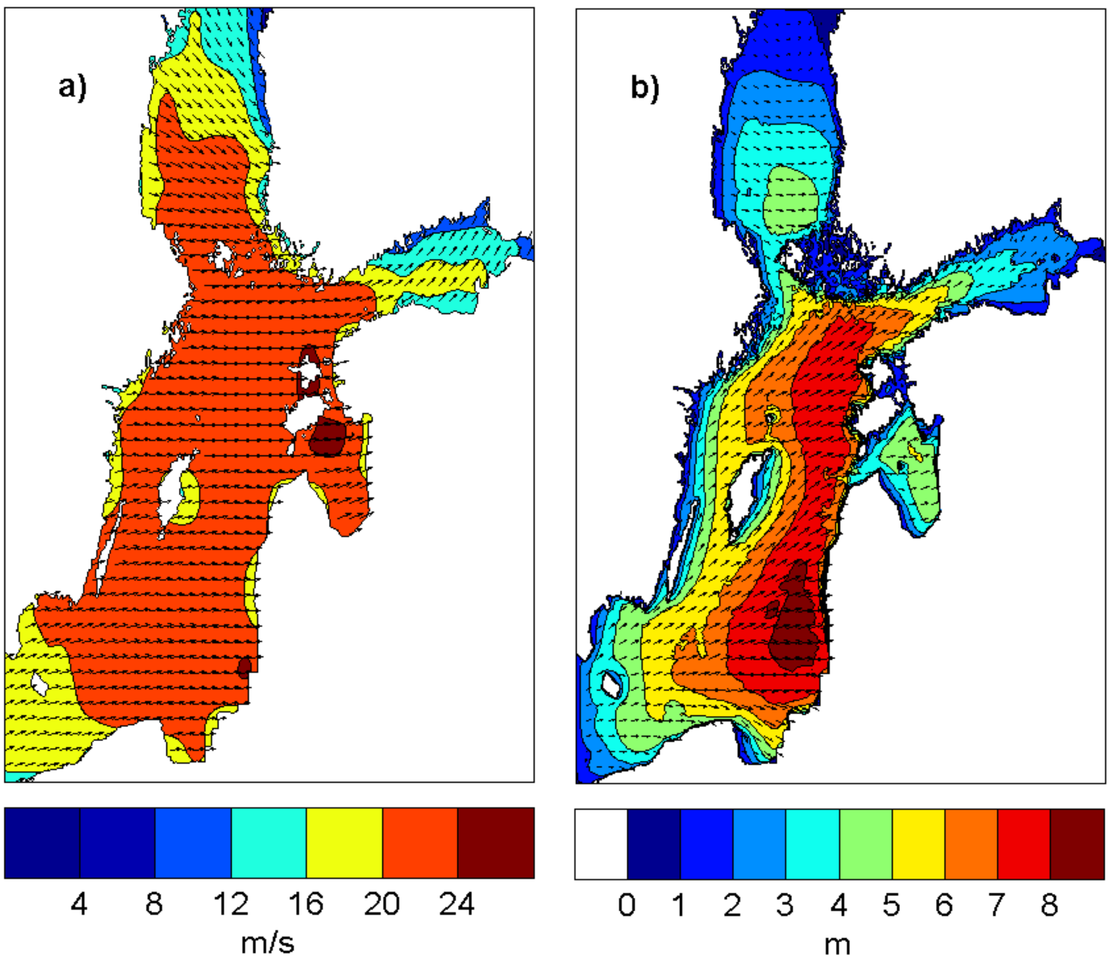


Figure 6. Snapshots (06:00 UTC, 09.01.2005) of modeled wind speed and direction (left) and significant wave height and mean wave direction (right) during cyclone Gudrun in the Baltic Sea.

3.4 Temporal course

Temporal courses of wave-wind misalignment, corresponding sea states and directions in selected locations (Figs. 7 and 8) further point out the importance of wave-wind misalignment during storms. Especially in rapidly turning wind situations the mean wave direction significantly lags behind the wind direction (Van Vledder and Holthuijsen, 1993). In the Gulf of Finland during cyclone Gudrun, when wave height reached 4 m, the directional misalignment was up to 40^0 and up to 70^0 in case of 1.5 m significant wave height. It can be said that the wave direction in the Gulf of Finland is quite frozen and oriented in the longest possible westward fetch. Indeed, while the variability of wind direction was 150^0, it was only 55^0 for waves.

In the Gdansk Bay significant wave height reached also 4 m during cyclone Gudrun and again, the wave-wind misalignment was 40^0. The wind speed at that certain time-instance was 20 m/s. This might become an important feature, since oil extraction platforms are planned to be installed in the Gdansk Bay in future. One of the most persistent large misalignments (over 40^0) in seas higher than 2 m occurs in east coast of Öland. When the wind direction tends to be W the wave direction is SW.

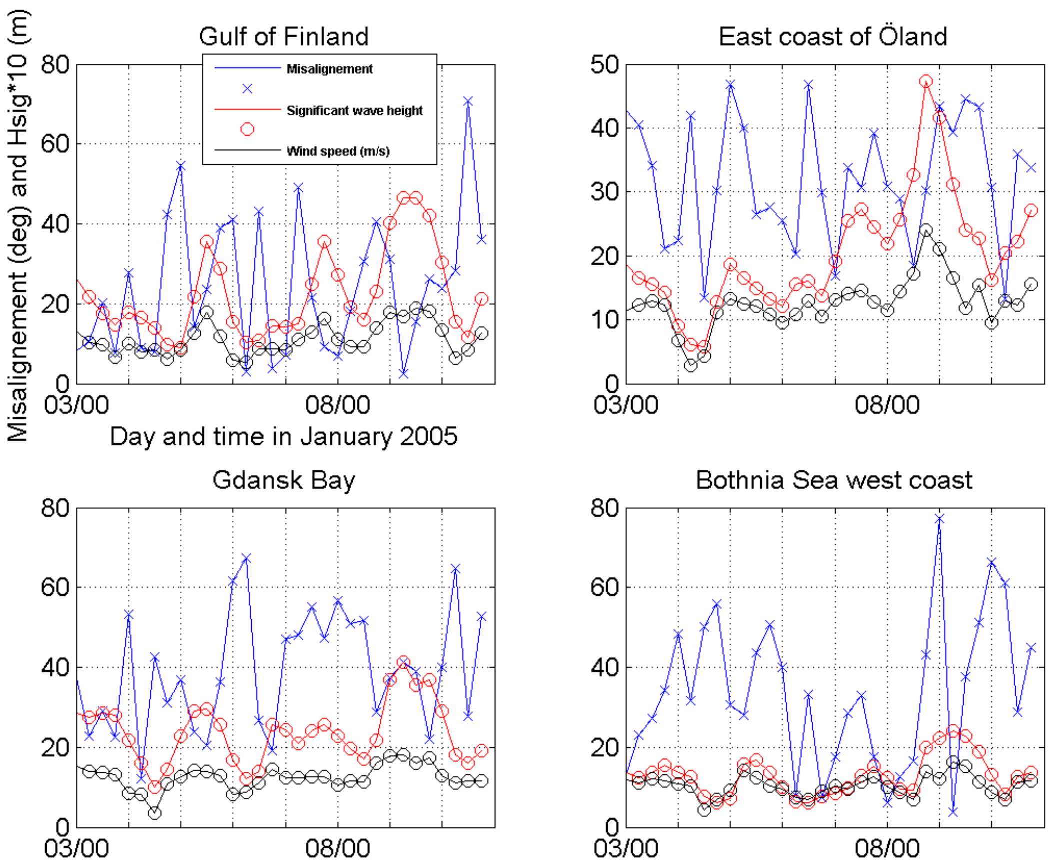


Figure 7. Temporal behavior (one stormy week in January 2005) of directional misalignment (blue), significant wave height (red) and wind speed (black) in some selected locations (see

Table 1 and Fig. 1). Notice that to obtain real significant wave height, one has to divide by 10. Also the y-scale is varying.

The largest misalignment (Fig. 7 lower right panel) of 77^0 occurs in the west coast of Bothnia Sea at midnight of 9^{th} January, when wind speed was 12 m/s and wave height 2.5 m. The corresponding wind direction was 249^0 and wave direction 172^0 (Fig. 8).

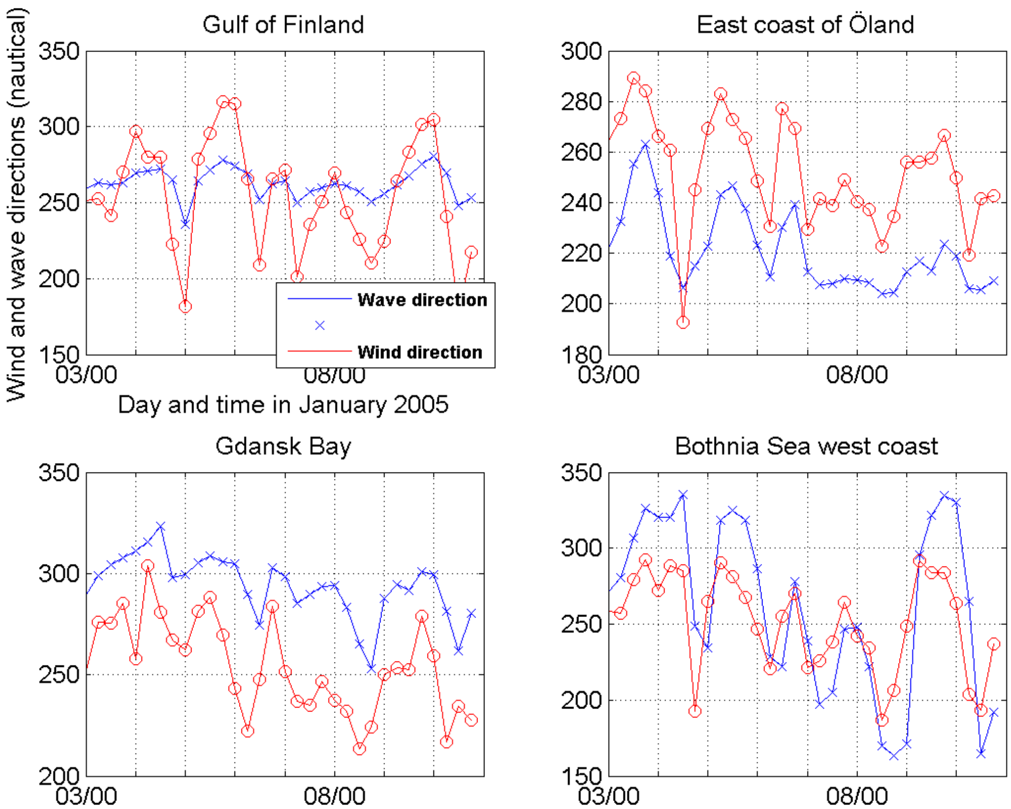
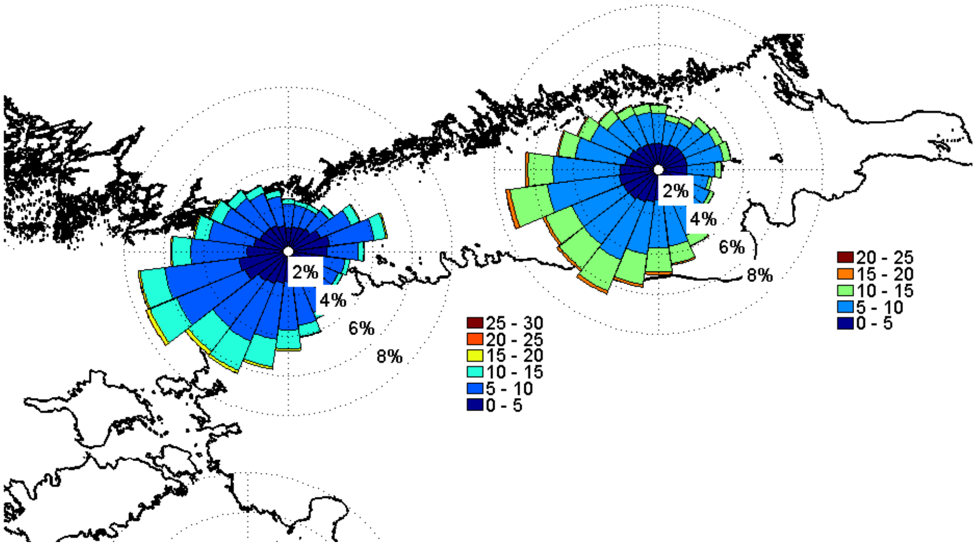


Figure 8. Same as Fig. 7 but of wave and wind directions.

4. Discussion

The 41 year dataset for some locations in the Gulf of Finland (Fig. 9) indicate that the wave rose is much more anisotropic compared to that of wind. We could make similar plots for other parts of the Baltic Sea and come to similar conclusions. From Fig. 9 it is clear that the waves in Gulf of Finland are preferably propagating along the Gulf's longest axis, i.e WSW and its opposite. This illustrates that the wind-wave misalignment is a persistent phenomena and needs to be taken into account, when planning offshore structures. However in the Baltic Proper it is possible, due to cyclone trajectories, that wave directions in high sea states vary as much as 180^0 over few hundred km (Fig. 10).



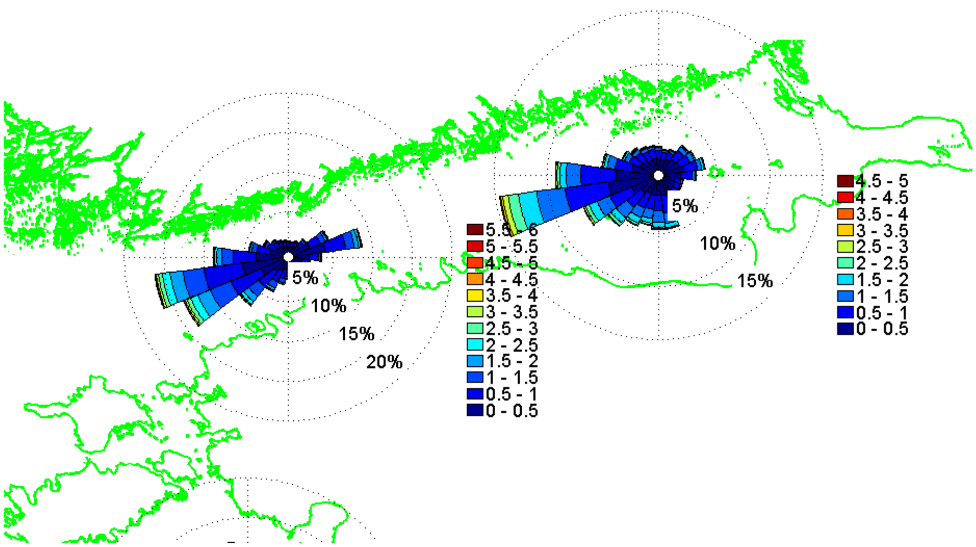


Figure 9. Wind (upper panel) and wave (lower panel) “roses” at 2 locations in the Gulf of Finland for the years 1965-2005. Colors are in [m] for wave height and [m/s] for wind speed.

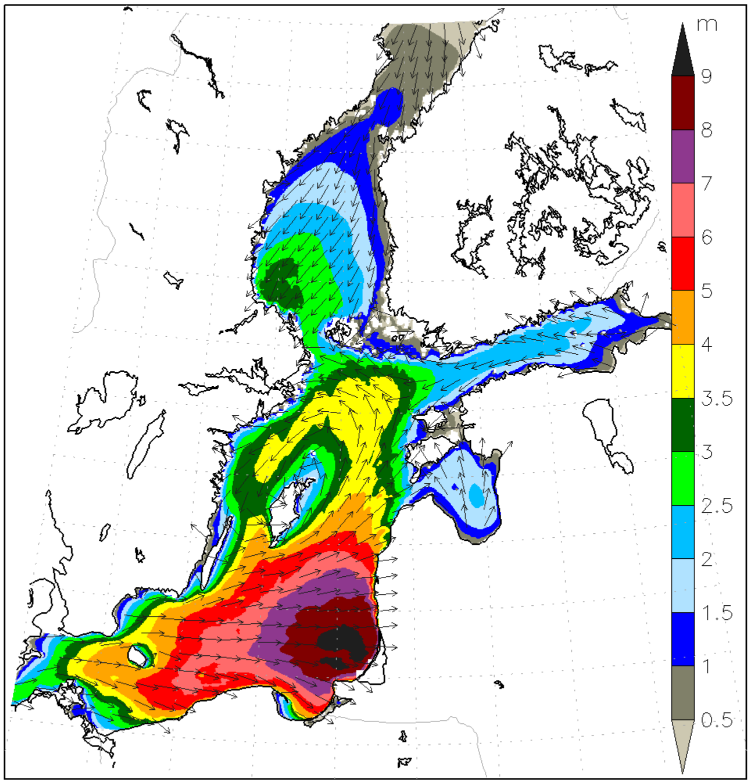


Figure 10. Significant wave heights and mean wave directions in a cyclone, which produced the highest waves in the modeled dataset between 1965-2005. The figure is a snapshot for 09:00 UTC on 4th December 1999.

In situations (in time and space) with a high amount of directional misalignment, the 2D wave spectra will be directionally asymmetric and often double peaked. Especially in slanting fetch situation this poses requirements to the modeling of quadruplet interactions and whitecapping (Ardhuin et al., 2007; Bottema and Van Vledder, 2009). This leads to a question of validating directional properties of wave prediction models.

A common method would be validating wave properties with directional wave buoys in certain areas of interest. However, in order to validate the spatial variability of wave parameters (Fig. 10) remote sensing data would be beneficial. Consecutive images of the TerraSAR-X satellite allow mapping the wave parameters over large scale (100 km) with a pixel resolution of 1.25 m. For the Baltic Proper, Gulf of Finland and Gulf of Riga we have already acquired nearly hundred of wave field images, which will be used to validate the 2-dimensional wave spectra in the continuation of this study.

5. Conclusions

Wind-wave misalignment has been studied using a 41-year high-resolution hindcast in the Baltic Sea. For the first time the spatial variability of wind-wave misalignment in the entire Baltic Sea was analyzed. Several conclusions can be drawn:

- Wind-wave misalignment occurs in all sub-basins of the Baltic Sea.
- Average wind-wave misalignment in deep water (water depth over 50 m) shows large spatial variations, yielding from 20^0 to 40^0.
- Instantaneous wind-wave misalignment during high sea states (significant wave height over 2 m and wind speed 12 m/s) reaches 80^0 in deep water.
- Wave-wind misalignment dependence on wind speed shows the decrease of misalignment with increasing wind speed.
- Main causes of misalignment in deep water are temporal changes in dynamic systems and fetch-restriction.

Knowledge of wave-wind misalignment is valuable for nautical activities and design of offshore structures. Further studies should concentrate also on spatial validation of predicted directional wave characteristics in the Baltic Sea.

Acknowledgments

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