TALLINN UNIVERSITY OF TECHNOLOGY

Faculty of science

Chair of Oceanography

ASSESSMENT OF WIND ENERGY RESOURCE IN GULF OF RIGA

Bachelor's thesis

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Declaration

Hereby I declare that this bachelor thesis, my original investigation and achievement, submitted for the bachelor degree at Tallinn University of Technology has not been submitted for any academic degree. All content and ideas drawn directly or indirectly from external sources are indicated as such.

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LIIVI LAHE TUULEENERGIA RESSURSI HINNANG

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ABSTRACT

In this paper wind fields retrieved with different methods (*in situ* measurements, satellite imagery and operational atmospheric model) are compared. Data is collected from Gulf of Riga area and analyzed by using Wind Atlas Analysis and Application Program (WAsP), synthetic aperture radar (SAR) imagery and High Resolution Limited Area Model (HILAM) to describe wind field characteristics in the area.

Different methods have been used for calculating mean wind speeds for period 2007-2010 and for every month of the year during the four-year period. WAsP, SAR and HIRLAM methods are compared and Weibull distribution is used to describe statistical properties of wind fields. In addition, principal component analysis (PCA) is being used to describe dominant wind regime in the Gulf of Riga. Four main components are calculated to describe wind field by different methods. Also the percentages of two components for all the months in the year are calculated.

The results show that strongest winds are in the central part of Gulf of Riga, where the fetch for the prevailing wind directions (south and southwest) is the longest. There is seasonal variability in the area, as the winds are strongest in wintertime and lightest in summertime. WAsP, SAR and HIRLAM have some differences in time and space, but in general data tends to be similar. PCA confirms that largest wind variations are in the central part of the Gulf of Riga and near the coastal area.

Keywords: wind regime, Gulf of Riga, WAsP, SAR, HIRLAM

LÜHIKOKKUVÕTE

Liivi Lahe tuuleenergia ressursi hinnang

Käesolevas töös on võrreldud omavahel erinevaid tuule kiiruse andmeid: *in situ* mõõtmised, mudel ja satelliidi pildid. Tuule andmed on pärit Liivi lahelt, kasutades SARi, WAsPi ja HIRLAMi. Töö eesmärk on iseloomustada tuulerežiimi Liivi lahel.

Arvutatud on keskmised tuule kiirused kogu perioodi jaoks (2007-2010) ning 12 kuu keskmised, kasutades erinevate meetodite andmeid. Omavahel on võrreldud SARi, WAsPi ja HIRLAMi andmeid. Tuulerežiimi statistiliste omaduste kirjeldamiseks on kasutatud Weibulli jaotust ning läbi on viidud põhikomponentide analüüs.

Antud töö tulemusena on leitud, et kõige tugevamad tuuled on Liivi lahe keskosas, mis on avatud valdavatele tuule suundadele (lõuna ja edel). Lisaks on kasutatud põhikomponentide analüüsi, et kirjeldada tuulerežiimi Liivi lahes. Välja on toodud 4 peamist komponenti, et kirjeldada erinevaid meetoteid, samuti on arvutatud komponentide osakaalud. Esimese komponendi väärtused jäävad vahemikku 81.0%-97.0 %. Arvutatud on ka iga kuu kahe komponendi osakaalud, kus esimene komponent on 72.0%- 75.7%.

Võtmesõnad: tuulerežiim, Liivi laht, WAsP, SAR, HIRLAM

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INTRODUCTION

Wind energy is one of the world’s fastest and very established renewable energy resources. It is also characterized as a strongly variable form of energy. A good quality of wind speed or generation forecasting is vital to achieve high level of performance. The most important factors that determine the power output are the wind speed and wind direction, which can vary at all time scales (Landberg, L. 2011).

There are different methods for wind field analysis. One possibility is to use *in situ* measurements. With several wind measuring stations and buoys it is possible to calculate average wind speeds later for different time-scales. For example using WAsP (Wind Atlas Analysis and Application Program), which is a PC program developed by the Technical University of Denmark (DTU) in 1987 for predicting wind climates, resources and power productions from wind turbines and wind farms. WAsP is linear numerical model, which can be used to assess crucial features of a wind farm. It can analyze wind data and project it over areas of similar climate to its reference site (Ali et al., 2014). WAsP contains models for the vertical extrapolation of wind data taking into account sheltering of obstacles (Lange et al., 2001).

Second possibility is to measure wind from space, for example, it is possible to use synthetic aperture radars (SAR) or scatterometry. The main advantage of SAR retrieved wind field is high spatial resolution indirect measurement provided over the entire Gulf of Riga area. SAR imagery has been used to measure wind vectors from space (Monaldo et al., 2004, 305). SAR imagery is capable of imaging synoptic wind fields with a coverage of up to 500km×500km and a resolution as high as 100 m. Satellite images taken by space-borne radar sensors can be used to determine mesoscale wind fields and it helps in planning offshore wind farms. Compared to the other remote sensing techniques, these sensors have all-weather capability, as the radar signals penetrate clouds and in addition, SAR imagery can collect data at night. SAR imagery is especially suited for sea surface observations in coastal regions and in severe weather conditions (Lehner et al., 2001, 17-29). European remote sensing satellites ERS-1 and ERS-2, the Canadian satellite RADARSAT-1 and the European environmental satellite ENVISAT have been providing SAR images over the oceans on continuous basis since 1991. Large spatial coverage and high resolution make them a valuable tool for measuring wind fields especially in coastal areas and for comparing wind parameters for different sites located on the same SAR scene (Schneiderhan et al., 2005).

Third possibility is to use numerical models. For example The Weather Research and Forecasting (WRF) Model or High Resolution Limited Area Model (HIRLAM) have been used for weather forecasts (Driesenaar, 2010), but also for hindcast runs and re-analysis (Luhamaa et al., 2011). The international research program HIRLAM is a research cooperation of European meteorological institutes (Driesenaar, 2010), which serves as the main numerical weather prediction (NWP) platform for short-range (up to three days), operational weather forecasting and NWP applications in its member countries (Služenikina et al., 2011). It is a hydrostatic grid-point model, of which the dynamical core is based on a semi-implicit semi-Lagrangian discretization of the multi-level primitive equations, using a hybrid coordinate in the vertical (Driesenaar, 2009). Gulf of Riga is part of calculation domain in the HIRLAM maintained by the Estonian weather service Ilmateenistus.

Objectives of this paper are to first compare mean wind fields retrieved with different methods like *in situ* measurements, operational atmospheric model and satellite imagery. Second objective is to describe dominant marine wind field characteristics in the Gulf of Riga area.

1 THEORY

1.1 Weibull distribution for describing wind field

Weibull probability distribution is named after Swedish physicist W. Weibull, who applied the function when studying material strength in tension and fatigue in the 1930s. The Weibull distribution provides a close approximation to the probability laws of many natural phenomena including wind (Azad et al, 2013).

The Weibull distribution is defined by the classical parameters of the univariate Weibull distributions and the correlation coefficients. All of them can be easily estimated (Villanueva et al, 2013).

The Weibull distribution calculations are based on “Analysis of wind energy conversion system using Weibull distribution” from Procedia Engineering journal. The Weibull distribution function is a three-parameter function, but for wind speed, it can be expressed mathematically with two-parameter model (1):

$$f(v) = \frac{dF(v)}{dv} = (\frac{k}{a})(\frac{v}{a)}) \cdot e^{-\left(\frac{v}{a}\right)^k} \quad (1)$$

In f(v) x is wind speed in m/s, k is dimensionless Weibull shape factor and a is Weibull scale factor in m/s. The cumulative distribution function for the Weibull distribution can be expressed by equation (2):

$$F(v) = 1 - e^{-\left(\frac{v}{a}\right)^k} \quad (2)$$

Average wind speed is not enough to describe the potential energy from site. Wind distribution is important in terms of energy production. On Figure 1 actual wind speed distribution is shown with Weibull distribution.

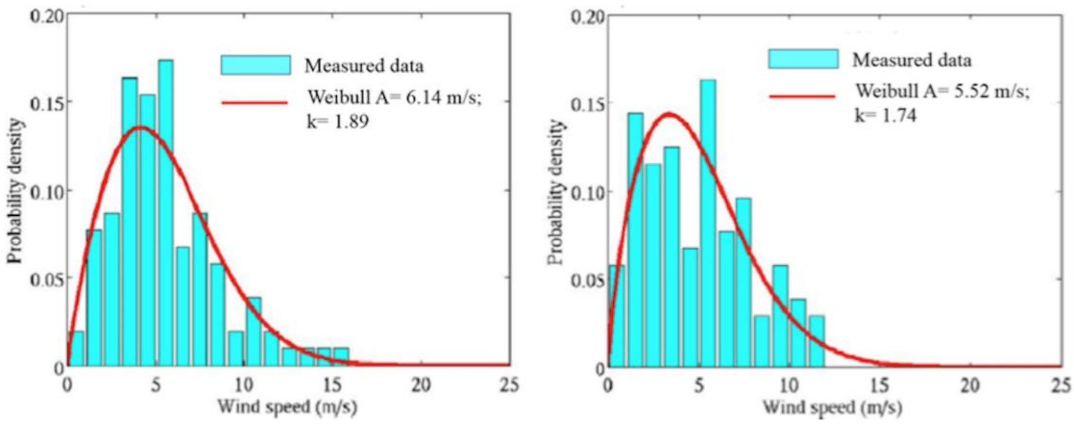

Figure 1 Example of Weibull distribution and average wind speed (Takeyama et al., 2013).

1.2 Principal Component Analysis

Main purpose of principal component analysis (PCA) is the analysis of data to identify patterns and finding them to reduce the dimensions of the dataset with minimal loss of information (Raschka, 2014).

Linear combinations of observed variables are principal components, where the first component extracts the maximum amount of information from the data and following components optimize the remaining information under the constraint of non-correlation with the other components. The transformation matrix is determined by the eigenvectors of the correlation matric of input data. In this paper, the analysis has been performed only on wind speed, finding its principal components (Davò et al., 2013).

2 MATERIALS AND METHODS

2.1 Study area

The study area is Gulf of Riga, which located in the eastern part of the Baltic Sea (Figure 2). Prevailing winds in Gulf of Riga are from south and southwest (Baltic Sea, 2007) and it has rough ice conditions during the winter (Raag et al., 2013). Wind energy is one of the important sources of renewable energy, which makes it important to study wind fields in Gulf of Riga, as it has high potential.

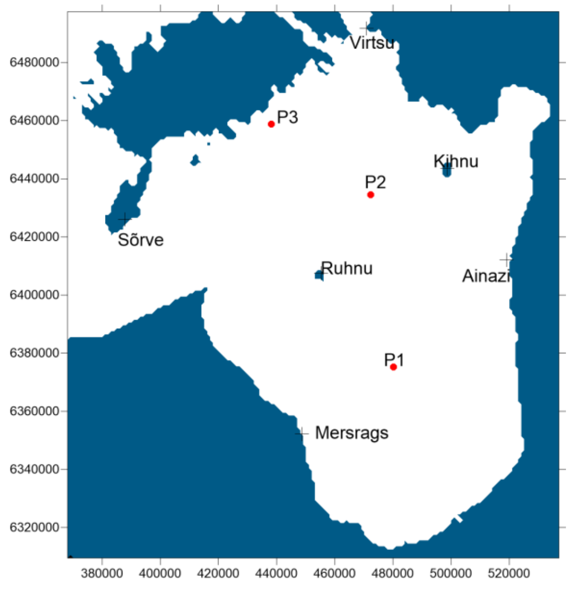

Figure 2 Gulf of Riga and *in situ* stations (black crosses), red dots represent the locations for which time series analysis was performed.

2.2 Data and methods

Wind fields were obtained by using 3 different methods: *in situ* measurements, SAR and HIRLAM.

Firstly, *in situ* measurements from six stations located in the GoR (Virtsu, Kihnu, Ruhnu, Sõrve, Mersrags, Ainasi, see Figure 2) were used. Data from different stations collected during 2007-2010 was interpolated over the Gulf of Riga area using WAsP model.

Secondly, 800 images form 2007-2010 were used to outline monthly wind field variation (Figure 3b). The SAR imagery originating from ENVISAT/ASAR sensor was used in this paper. SAR image has pixel spacing of 75 m and the temporal coverage of Gulf of Riga area is approximately 1-2 images per two days. In order to calculate wind speeds from images, CMOD5 algorithm was implemented (Uiboupin et al., 2013, Hersbach et al., 2007).

HIRLAM results cover years 2007-2010 and were calculated using forecast data from HIRLAM model. HIRLAM has temporal resolution of 3 h and spatial resolution of 11 km (Männik et al., 2007), which was interpolated to 1 km to compare them with SAR and *in situ* data.

Average wind speed for the four-year period and monthly mean wind speed maps were calculated for the three different data sets. Also, monthly mean maps of Weibull distribution parameters *a* and *k* were calculated.

2.3 Comparison methods

In this paper two comparison techniques were used.

Differences between methods were calculated in order to compare them and find out how much they vary. All the calculations were made with Surfer software (Golden Software, 2009).

PCA was also used in this paper. Singular value decomposition (SVD) was used in PCA calculations, whereas all calculations were made in Python programming language using numpy module (Numpy developers, 2013).

SVD factorizes data matrix with:

$$M = U \cdot S \cdot V \, , \tag{3}$$

where U and V are singular matrices, S is a diagonal matrix of eigenvalues.

Singular matrices are including orthogonal vectors of unit length in the rows and columns correspondingly. Diagonal matrix includes the singular values of M, which are squared divided by the number of observations will give the variance explained by each PC (Vogt, 2001).

PCA is calculated by using two different inputs:

1. different methods separately (Table 1);
2. entire time period month averages by all methods together (Table 2).

3 RESULTS AND DISCUSSION

3.1 Mean monthly wind speed maps

In order to characterize monthly wind field variations from *in situ* observations (Figure 3a) mean monthly wind speed from WAsP results was calculated. On the mean monthly wind speed map, created based on WAsP data, large seasonal variations are seen. The strongest mean wind speed can be seen in winter season and quite strong wind in autumn. Mean wind speed is the strongest in October, November, December and January (7-10 m/s). During the summer months mean wind speed is lower (4-6 m/s). Impact from fetching in the central part of Gulf of Riga is also standing out because of average west and southwest wind.

On SAR imagery based mean monthly wind speed map, seasonal variability is noticeable. From Figure 3b it is seen that during the summer mean wind speed is lower (4-7 m/s), except in August (6-9 m/s). The strongest mean wind speed is observed during January, August, September and November (6-10 m/s). Although it has to be considered maps calculated for the winter months could be affected by lack of satellite data due to ice conditions. It can also be seen that the strongest mean wind speed is in central part of Gulf of Riga.

Results from HIRLAM are similar with WAsP mean monthly wind speed. Strong seasonal variability of mean wind speed is seen in the Gulf of Riga (Figure 3c). The strongest winds are during the winter - December and January (6-10 m/s), but relatively high values are also seen in autumn - October, November (6-10 m/s). Very low wind conditions are during spring and summer months (April, May, June and July), about 4-6 m/s. The HIRLAM results also indicate that in central part winds are stronger due to fetch. In coastal areas, mean wind speeds are much lower.

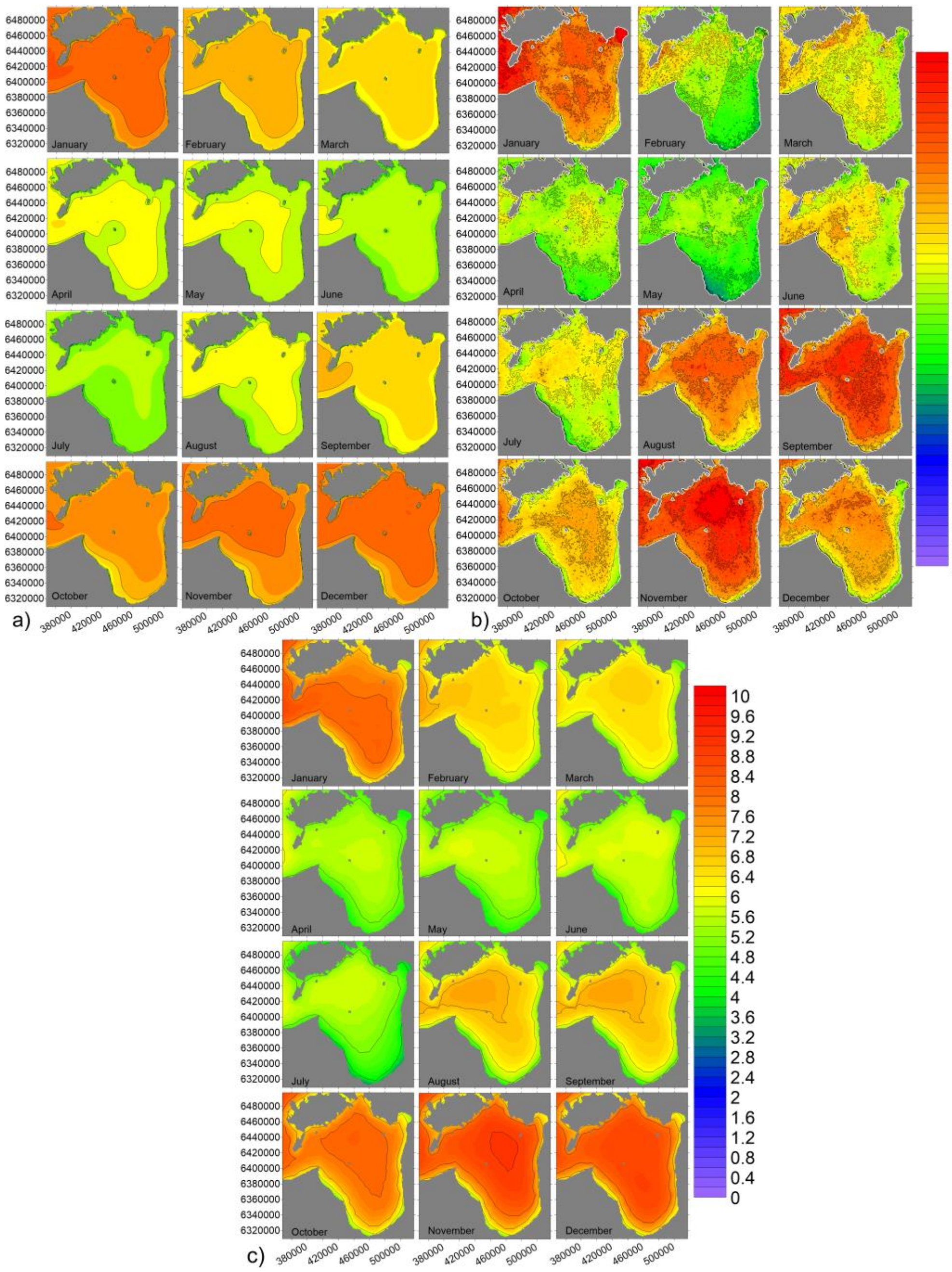

Figure 3 WAsP (a), SAR (b) and HIRLAM (c) mean monthly wind speed (m/s).

Some differences between methods are seen, but in general methods cover the seasonal variability of monthly mean wind speed. There are some differences in time and space. For example, SAR is underestimating mean wind speed in February, but this can be caused by ice conditions. Generally, wind is stronger in wintertime and also in central area of Gulf of Riga. On Figure 4 we can see that HIRLAM is underestimating wind speed in location P3 (Figure 2) that is in coastal area and could be caused of its spatial resolution of 11 km, which is interpolated to 1 km. In the central part of Gulf of Riga P2 results are quite similar, but SAR is slightly overestimating. During the winter, mean wind speed is 6-8 m/s, although in November SAR results are 10.5 m/s while WAsP and HIRLAM are around 8 m/s. In the location P1 results are the most similar, mean wind speed is lower May to July (4.5- 6.2 m/s) and stronger from August to January (6-8 m/s).

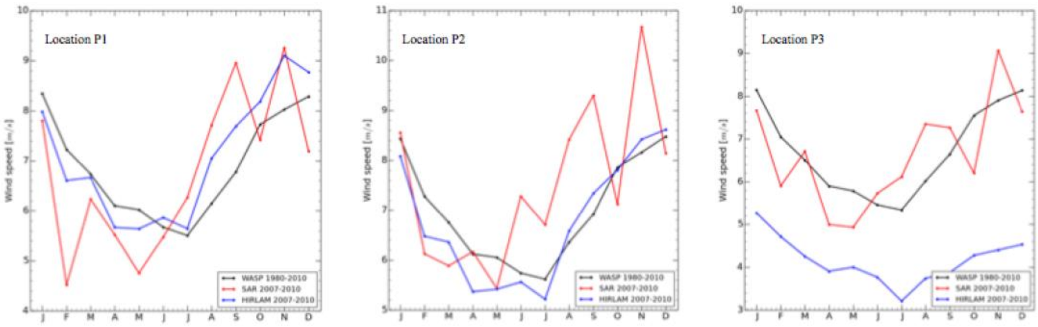

Figure 4 Comparison of three methods in different locations.

3.2 Comparison of Weibull parameters

Weibull parameters *k* and *a* are calculated from WAsP, SAR and HIRLAM on Figure 5 and Figure 6.

Weibull parameters *k* and *a* calculated from WAsP results show seasonal variability (Figure 5a and Figure 6a). The dimensionless shape parameter *k* varies between 1 and 2.5. In the summer, wind is more widely distributed and parameter *k* is lower (1.3- 2.2), but in the winter *k* is bigger (1.3-3) and there are stronger winds in more certain range. Weibull *a* increases from 2 m/s to 10 m/s, while the values are larger in the winter and also in the central part of Gulf of Riga.

Weibull parameters *k* and *a* from SAR images are shown on Figure 5b and Figure 6b. Compared to the WasP and HIRLAM results, seasonal variability is not well observed in SAR results. Although parameter *a* has larger values for winter months, the high values occur in coastal areas compared to the HIRLAM and WAsP. However data in February is inadequate due to ice conditions. Most likely, ice conditions influence the statistics in wintertime. In addition, parameter *k* has large spatial variability within each month.

Seasonal variations in the Weibull parameters from HIRLAM are noticeable (Figure 5c and Figure 6c). Parameter *k* varies from 1.8 to 3. The value is larger in wintertime, more specifically in October, November and December. Parameter *a* is in the range of 5-10 m/s and it has also larger values in winter. This means that during winter there are stronger winds. In the summer wind is more widely distributed and wind speed is lower. Both parameters have larger values in central part of Gulf of Riga, where wind is more stable.

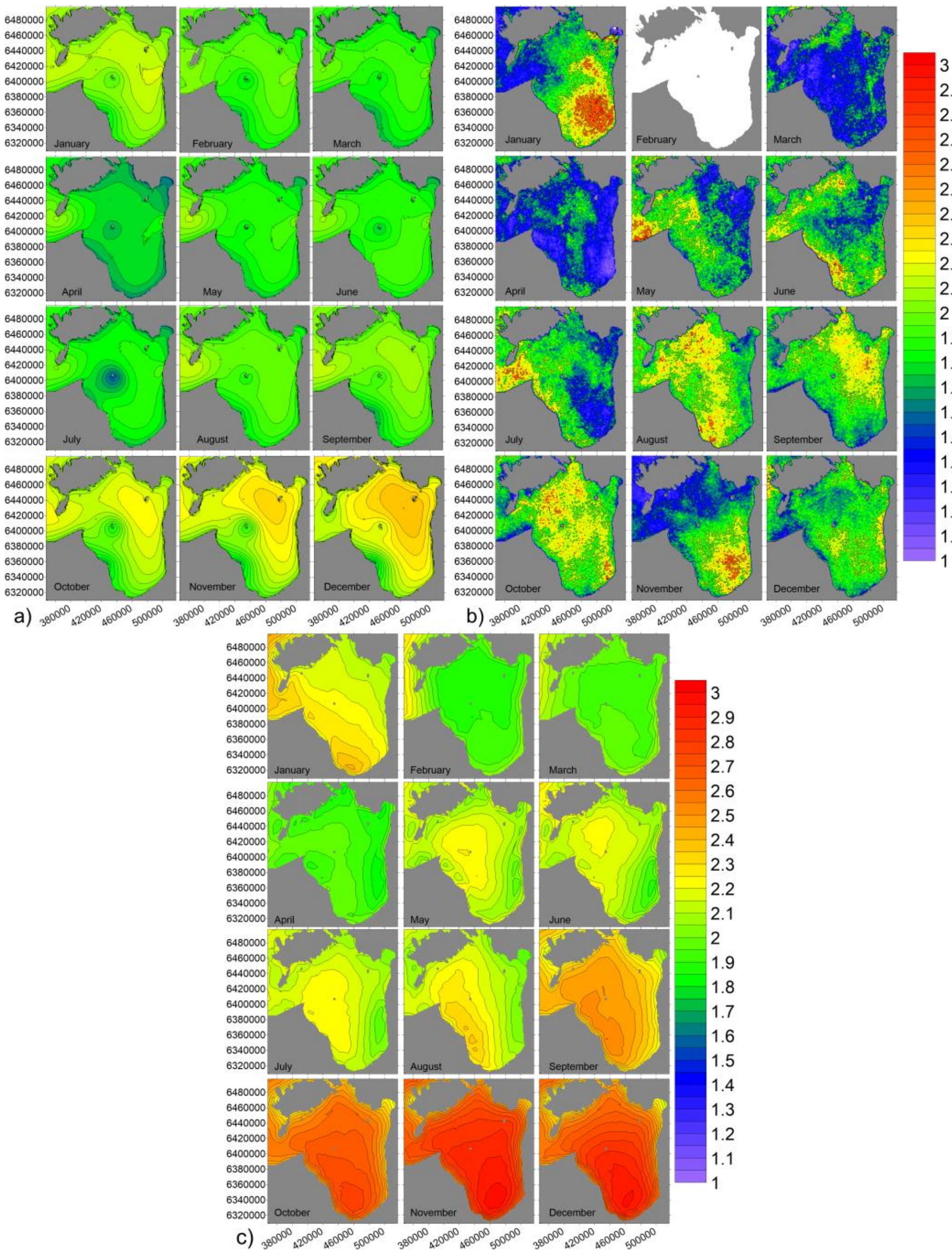

Figure 5 WAsP (a), SAR (b) and HIRLAM (c) Weibull parameter *k*.

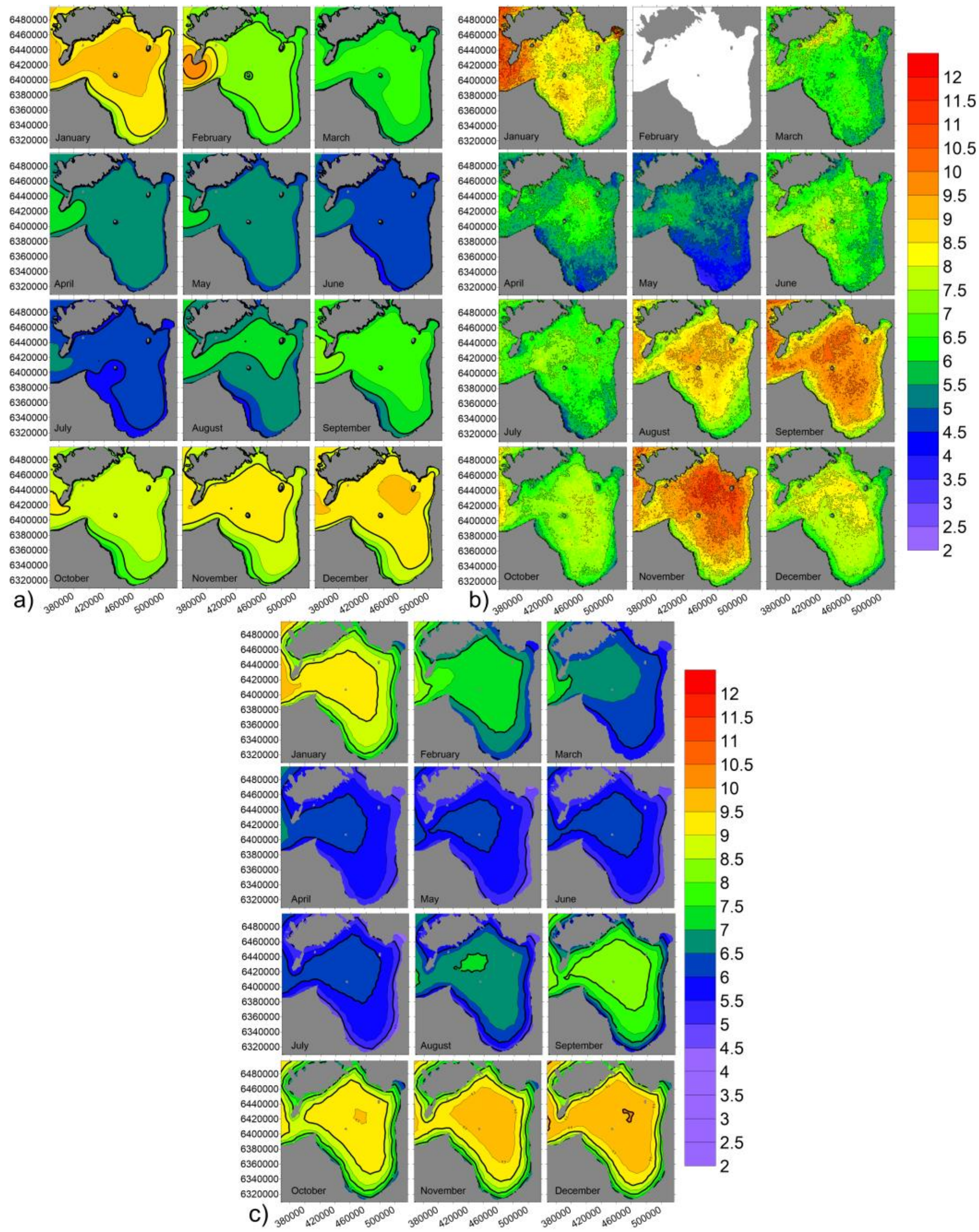

Figure 6 WAsP (a), SAR (b) and HIRLAM (c) Weibull parameter *a* (m/s).

3.3 Comparison of different methods

In this paper, wind conditions in the Gulf of Riga based on WAsP, SAR and HIRLAM are used. The mean wind speeds (2007-2010) in Gulf of Riga from different methods are shown on Figure 7.

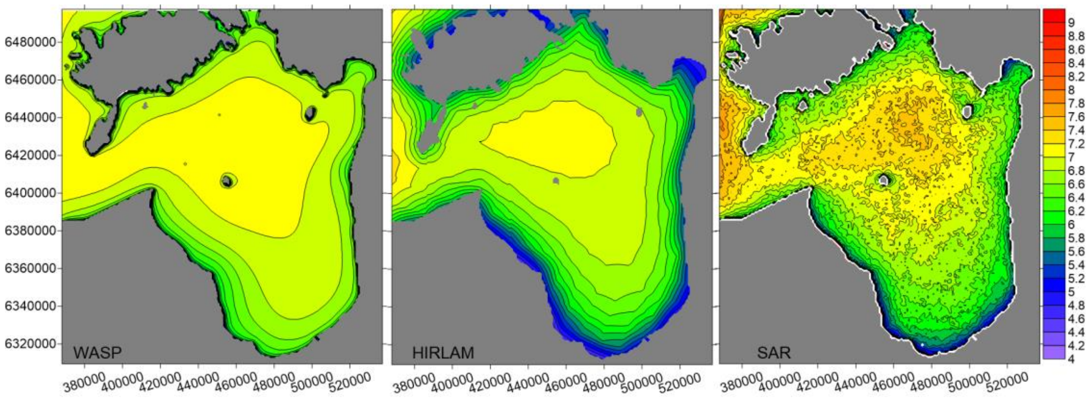

Figure 7 WasP, HIRLAM and SAR average wind speed for entire period (m/s).

HIRLAM and SAR results are more similar, while WasP differs more, for example in coastal areas according to WAsP mean wind speed is about 6 m/s but from HIRLAM and SAR results are around 4.6- 5.6 m/s. WasP results would be probably better if there were more measurement stations. WasP was using only 6 wind measuring stations, which are: Virtsu, Kihnu, Ruhnu, Sõrve, Mersrags, Ainasi (Figure 2) and due to that, spatial coverage is not as good as SARs and HIRLAMs.

SAR has large spatial coverage and high resolution and it seems to be very accurate in space. However there can be some influence from lack of data due to ice cover during winter.

From the HIRLAM and SAR data, the impact of land is very noticeable, specifically in Pärnu Bay and south part of Gulf of Riga, where winds are lighter. The winds are strongest in the central part of Gulf of Riga (Figure 7). This is due to the fact that prevailing wind direction in the Gulf of Riga is from South to Southwest and in the central part the southwesterly winds are coming from fetching.

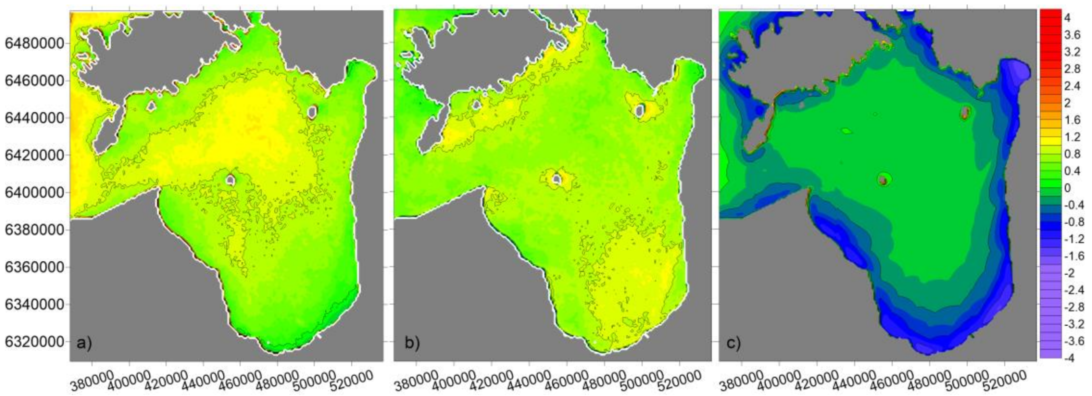

Figure 8 Differences between mean wind speed maps: a) HIRLAM-SAR b) SAR-WasP c) HIRLAM-WasP (m/s).

The differences between the methods for mean wind speeds are shown on Figure 8. The differences between HIRLAM and SAR are relatively low (Figure 8a), whereas in coastal areas they are almost zero. Largest values are 0.8-1.2 m/s, which are in the central part of Gulf of Riga.

Relatively small differences are also between SAR and WasP, but compared to the HIRLAM, the SAR values are higher from WasP values in the northern and southern parts of the gulf (Figure 8b). Most likely this is due to the fact that for the southern part of the Gulf data from only one wind station was used for the interpolation.

Noticeable differences between WasP and HIRLAM mean wind speeds are seen in the coastal areas (Figure 8c), while in the central part differences are the smallest compared to the SAR, which means that there are not enough SAR images for characterizing mean wind speeds. Largest differences are seen in the Pärnu Bay, where the interpolation of *in situ* measurements might be overestimated.

3.4 Dominant wind regime description in Gulf of Riga (based on PCA)

Four components of PCA in WasP are shown in Figure 9a. Largest spatial variations are due to the impact of the land, specifically in places, where land blocks westerly and southwesterly winds. South part of Sõrve Säär variation is large, due to fetch. Also the fluctuations between Kihnu and Ruhnu islands are larger. First component describes 97.0 % of variability and are caused by the land. From second component land impact in south part of Gulf of Riga is seen. Second, third and fourth component show the impact of wind spatial variations in measuring stations.

SAR PCA four components are shown on Figure 9b. The first component shows that the highest spatial variations are caused by the land, which describes 81.0 % of variability. Very large variation is also in the central part of Gulf of Riga, where the fetch for the prevailing wind directions (south and southwest) is the longest. First PCA component corresponds to the spatial changes of wind. In Pärnu Bay the data is insufficient, which is seen from other three components. The number of suitable SAR images for Pärnu was lower compared to the other areas and this has an overall impact to the statistics.

Four components of PCA in HIRLAM are shown on Figure 9c. Largest spatial variations are due to the impact of the land and fetching. Similarly with SAR, somewhat larger variations in central parts are visible as well, which is seen from image of component one. Second component is 4.2 % and land impact is still seen.

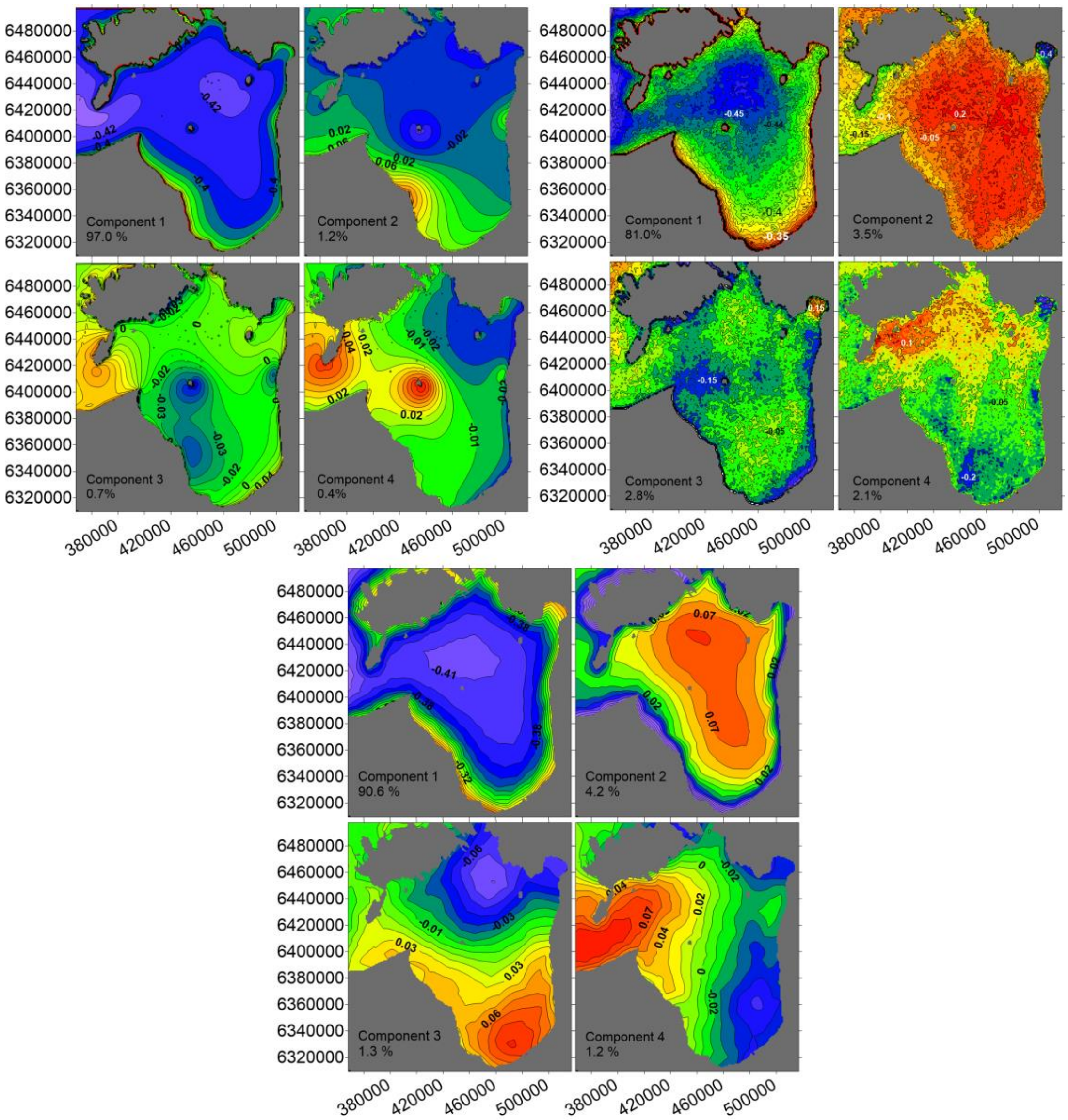

Figure 9 PCA four components from WAsP (a), SAR (b) and HIRLAM (c).

SAR, WasP and HIRLAM four components percentages are shown in Table 1. First component tends to be quite high, ranging from 81.0% to 97.0%. High values show that the first PCA component characterizes the largest part of data variations. Other three components have much smaller values (0.4%- 4.2%). SAR and HIRLAM seem to be more similar than WAsP, which has smaller values due to the fact that the impact of the land and fetching was considered during the interpolation. SAR data is the most accurate in space. From all three methods impact of the land is large, but also winds from offing (the Baltic proper) are affecting the results.

Table 1 SAR, WasP and HIRLAM PCA four components.

	SAR	WasP	HIRLAM
Component 1	81.0%	97.0%	90.2%
Component 2	3.5%	1.2%	4.2%
Component 3	2.8%	0.7%	1.3%
Component 4	2.1%	0.4%	1.2%

Percentages of two components of each month are shown in Table 2. First components are in range from 72.0% to 75.7%. First component is highest in December and lowest in April, but it does not vary much. Component 2 is in range from 16.0% to 19.0%. It is lowest in December and highest in April.

Table 2 Every month two PCA components for entire time period.

	Component 1	Component 2
January	73.5%	18.0%
February	73.4%	17.6%
March	73.3%	18.1%
April	72.0%	19.0%

May	72.4%	18.5%
June	72.4%	18.9%
July	73.5%	17.8%
August	74.5%	17.5%
September	75.2%	17.0%
October	75.6%	16.1%
November	75.1%	17.0%
December	75.7%	16.0%

SUMMARY AND CONCLUSIONS

In this paper, wind fields retrieved with different methods like *in situ* measurements, operational atmospheric model and satellite imagery were compared. Measurements were taken over the Gulf of Riga: SAR, WAsP and HIRLAM data was used.

Some differences between methods were seen, but in general methods covered the seasonal variability. There were also some differences in time and space. Impact of the land is very noticeable from the HIRLAM and SAR data, specifically in Pärnu Bay and south part of Gulf of Riga. In WAsP interpolation land impact was considered. During winter, ice affected SAR data availability near the land. Wind was strongest in the central part of Gulf of Riga, which is open for southwest winds, one of the prevailing wind directions in the area.

Different months were also compared by different methods. All in all, winds were stronger in wintertime and the lightest until April to July. In general winds are getting stronger already in autumn (September, October, November) and are lighter in spring and summer (April, May, June, July).

Weibull distribution was also used for describing wind fields. Seasonal variations in the Weibull parameters from HIRLAM and WAsP were noticeable, however in SAR results they were not. In general, Weibull distribution showed that during winter winds are stronger and in the summer wind is more widely distributed and conditions are lighter. SAR Weibull distribution results differed from WAsPs and HIRLAMs.

Differences between methods were calculated to compare methods and find out how much they vary. Calculations were made with using Surfer program. The differences between HIRLAM and SAR were relatively low. Small differences were also between SAR and WAsP, but compared to the HIRLAM, the SAR values are higher from WAsP values in the northern and southern parts of the gulf. In the coastal areas there were noticeable differences between WAsP and HIRLAM mean wind speeds.

Principal Component Analysis was used to describe dominant wind regime in Gulf of Riga. Firstly, images for four components were made by each method and their percentages were calculated to describe wind field. First component was the highest (81.0%- 97.0%) and the large variability was in the central part of Gulf of Riga, where the fetching for the prevailing wind directions (south and southwest) is the longest. Largest spatial variations were caused by the impact of the land and fetching. High values show that the first PCA component characterizes the largest part of data variations. Other three components had much smaller values (0.4%- 4.2%). In all three methods, impact of the land was large, but also winds from fetching (the Baltic proper) were affecting results. Secondly, for each month, two components percentage was calculated by using all methods together. First component tended to be highest in December (75.7%) and lowest in April (72.0%). Second component was lowest in December (16.0%) and highest in April (19.0%).

In conclusion, strongest winds are in central part of Gulf of Riga, where the fetching for the prevailing wind directions (south and southwest) is the longest. There are seasonal variations in the area, where winds are stronger in wintertime and lightest in summertime. Three methods, which were used in this paper, had some differences in time and space, but in general data tends to be similar. PCA confirmed that largest wind variations are in the central part of Gulf of Riga and near the coastal area.

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