Offshore wind resource assessment based on satellite wind field maps

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Abstract

The paper presents an analysis where a series of 55 wind field maps are retrieved from SAR (Synthetic Aperture Radar) images recorded by the European satellite ERS-2. The site of investigation is at Horns Rev in the North Sea where the worlds largest wind farm is in operation and where a unique meteorological time series is collected. The wind speed maps are retrieved based on the scatterometer model algorithms CMOD-4 and CMOD-IFR. The wind maps are used as input to a prototype software called RWT (Risø Wemsar Tool). The software calculates the offshore wind resource based on the spatial wind statistics from the satellite images. The calculated statistics (in form of a tab-file) can then be input to the WA^{S}P programme and used instead of observatations by instruments on masts bearing in mind the limitations of SAR in terms of its absolute accuracy and bias.

Keywords: offshore wind, satellite, synthetic aperture radar, wind resource, WA^{S}P

1. Introduction

In the early planning phase of a wind farm it is of importance to estimate the wind resource. However often there is not any representative long-term in-situ meteorological time-series available for the task especially not for offshore sites. Data from the NCEP/NCAR reanalysis (http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml) time-series with a resolution of 0.5 degrees could be used to assess wind resources or from ECMWF (http://www.ecmwf.int/) as demonstrated for the Mediterranean Basin (1). The spatial resolution of scatterometer and imaging synthetic aperture radar is higher than those of the NCEP/NCAR and ECMWF data. Therefore wind observations obtained by satellite Earth observation techniques may be an attractive alternative or supplement to other wind data, especially in regions with large spatial gradients in the wind climate.

The objective is to assess the offshore wind resource from a series of satellite Earth observation wind field maps. The scientific innovation is in the applied use of this new data source on offshore wind observations for the specific task of performing a quick offshore resource assessment. The methodology works on archived satellite images, hence there is neither a need to wait for a one-year time series to be collected, nor a necessity to cover the cost of installation and maintenance of a mast.

Ocean wind speed mapping from satellite is a well-established technique. The American defence has had a series of passive microwave sensors within the DMSP (Defence Meteorological Satellite Program) program since the early 1970'ties (2). Most notably are the global ocean wind maps from SSM/I (Special Sensor Microwave Imager) available at http://manati.wwb.noaa.gov/doc/ssmiwinds.html. The grid resolution is 50 km. Only wind speed is retrieved. Scatterometers retrieve both wind speed and wind direction with a resolution comparable to that of SMM/I. Scatterometer data are archived since the early 1990'ties. A new release of re-analysed scatterometer ocean wind data from the satellites ERS-1, ERS-2 and NSCAT for the period 1991-2001 are freely available at http://www.ifremer.fr/cersat/ as gridded weekly and monthly averages (3). Gridded daily ocean wind speed maps from QUIKSCAT since July 1999 are also freely available at the CERSAT website. The ERS-1 and -2 satellites are European whereas NSCAT and QUIKSCAT are American. In February 2003 the launch of the MIDORI-2 scatterometer was succesful. It is an American scatterometer flown on-board the Japanese ADEOS platform.

More recently ocean wind speed mapping with a higher spatial resolution is available from the SAR (Synthetic Aperture Radar) imaging sensors such as ERS-1/-2 SAR, RADARSAT-1 and ENVISAT ASAR. RADARSAT is a Canadian sensor and ENVISAT ASAR is the newest European. The SAR archives contain data from the years: ERS-1 (1991 – 1996), ERS-2 (1995- present), RADARSAT-1 (1995-present) and ENVISAT ASAR (2003-present). RADARSAT-2 is scheduled for launch in 2004.

The resolution of raw data may be as high as 12.5 m grid cells in the imaging SAR but for practical purposes grid cells of a few hundred meters is relevant for mapping winds. In the current study a resolution of 400 m grid cells is used.

The number of SAR images available for any site of interest is a critical factor. In order to estimate the mean wind speed within ±10% of the true value with a 90% confidence level, it is necessary to have around 70 wind maps that are error free and randomly selected. Satellite wind maps have error and bias on wind speed and wind direction and the observations are a function of overpass times (i.e. non-randomly). Estimation of the wind resource implies that not only the mean wind speed needs to be known but also the higher order moments, the Weibull scale (A) and shape (k) parameters. To obtain low errors on these parameters even more samples are needed. The accuracy on the wind statistics with few samples is treated in detail (4, 5). Hence the error on wind resource estimation based on SAR images is much higher than for classical wind observations due to the limited number of samples and errors inherent in SAR wind mapping. But for feasibility studies the satellite wind maps may be useful in the early planning phase.

SAR data generally has not been free of charge except for certain research applications (the AO-1, AO-2 and AO-3 programmes at ESA (European Space Agency)). Currently SAR data are available cheaply within ESA EO research grants (http://projects.esa-ao.org/esa/esa). In the current study SAR images from an AO-3 (AO-153) and an EO grant (EO-1356) are analysed. The director of ESA's Earth observations Mr. Jose Achache recently has proposed to make SAR images from ESA free of charge (SpaceNews, March 2003, p 6). This may stimulate further investigation and exploitation of SAR data for offshore and coastal wind resource estimation.

In brief summary there is a great number of available satellite data useful for offshore wind speed mapping. The analysis of ERS-1/-2 SAR data into wind maps is now possible for any potential user by use of a newly developed WEMSAR Tool software. The software is a prototype tool where the wind mapping part is developed at NERSC (Nansens Environmental and Remote Sensing Center) and the wind statistical tool part is developed at RISOE.

2. Wind mapping from SAR

The imaging SAR sensor receives backscatter values from the surface of the Earth. Over the ocean the backscattered signal is a function of the instantaneous wind field due to the small-scale surface waves in the capillary and short gravity wave spectrum that are developed by the wind. The short waves efficiently reflect the C-band radar signals to the receiver of the SAR. The small-scale surface waves are correlated to the mean wind speed and the empirical relationship between backscatter values and wind speed is established in the so-called CMOD-algorithms for scatterometers with an accuracy of wind speed within ±2 m/s and wind direction within ±20º for winds in the range 2-24 m/s. CMOD algorithms are successfully applied to ERS-1/-2 SAR images to map wind speed e.g. (6-8). The wind direction can be mapped by Fast Fourier Transform (9) or wavelet analysis (10, 11). A wind direction from a meteorological mast can also be used as input to the CMOD algorithms. In the current study, the CMOD-IFR (12) and the CMOD-4 (13) are applied to the SAR scenes. The wind direction is taken from an offshore mast owned and managed by Tech-wise (14).

3. Data set

A series of 55 scenes from ERS-2 SAR recorded in the period May 1999 to October 2001 are investigated. During this period (and beyond) meteorological observations at the Horns Rev site are collected by Tech-wise for the planning and operation of the offshore wind farm (http://www.hornsrev.dk/) (15). The construction of the wind farm started in November 2001. Therefore wind speed mapping in the local area may be disturbed later on and are not included in the current analysis.

4. Analysis

WEMSAR (Wind Energy Mapping using SAR) is a EU funded project (years 2000-2003) in which NERSC (Nansen Environmental and Remote Sensing Center) in Norway developed a software that calculates wind maps from precision format ERS-1 and ERS-2 SAR PRI images through the CMOD-IFR and the CMOD-4 models. Prior to running the CMOD-algorithms, the SAR data should be calibrated by the SarToolBox or BEST software freely available from ESA (http://earth.esa.int/services/best/). Wind direction can be retrieved from the SAR images with a Fast Fourier Transform model or input from other sources of information. One header file, two files of wind maps and one file of wind direction are generated.

A separate program RWT (Risoe WEMSAR Tool) was developed to extract local winds at the site of interest by a footprint average and construct wind statistics. The user interface has three sheets:

1) satellite information (Figure 1)
2) wind statistics (Figure 2)
3) options (Figure 3)

The captions for Figures 1-3 briefly explain the functionality of the RWT tool. The wind statistical results are shown in Figure 2. The tab-file shown in the upper right panel in Figure 2 can be input into the WA^{s}P programme (16). This is demonstrated in Figure 4. For information on wind statistics of choosing only few samples e.g. 55 samples compared to several thousands, please refer to (4) and (17) and for information on interpolation techniques please see (18).

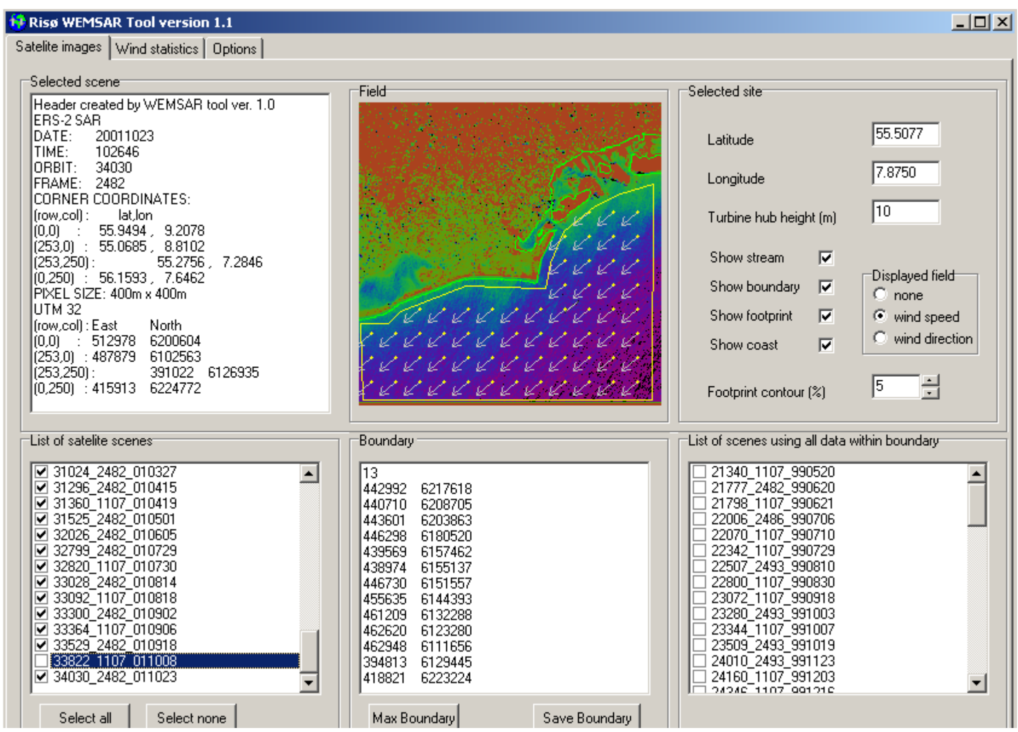

Figure 1. RWT satellite image information. The upper left shows the header information of the selected image. The image is displayed in the middle upper panel with the coastline is green and the selected polygon drawn in yellow. The corresponding polygon coordinates are displayed below. The list of selected satellite scenes (orbit_frame_date) is shown in the other two panels.

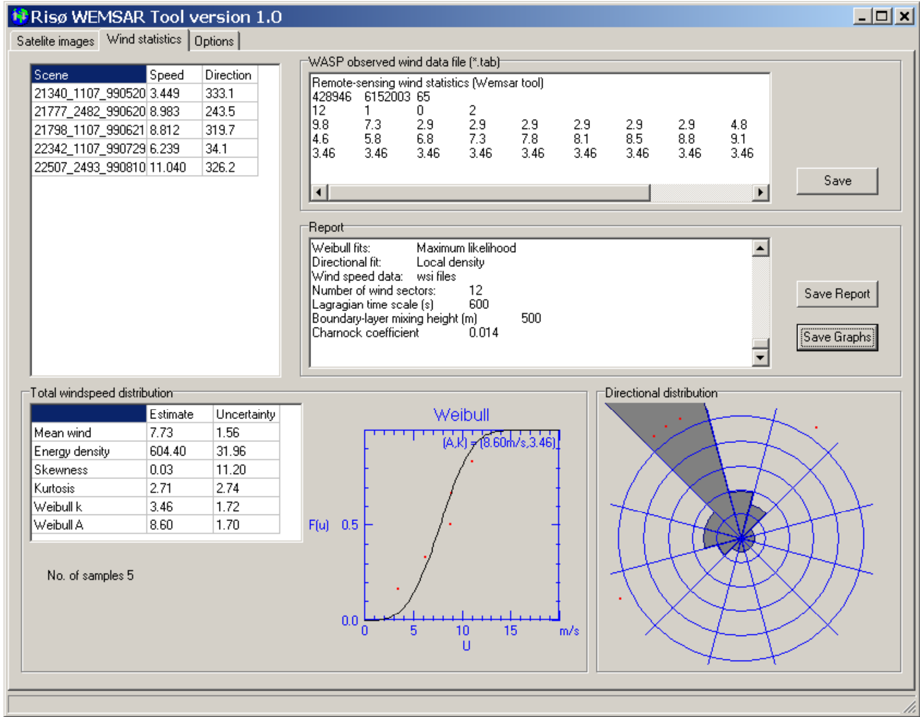

Figure 2 RWT wind statistical sheet. The results from the calculations are displayed with the wind speed and wind direction per scene in the upper left panel. The energy density and Weibull A and k are shown below. The tab-file information is the Weibull A and k values per wind sector in the upper right panel.

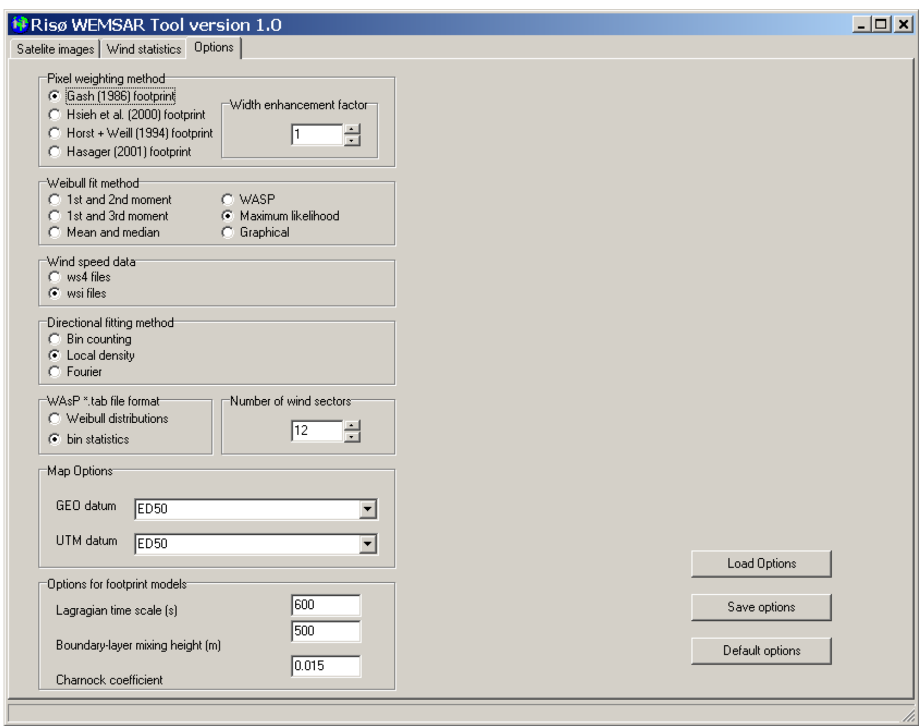

Figure 3. The RWT option sheet shows the different footprint and Weibull fitting methods that can be chosen. Concerning wind speed data, it is possible to select between the ws4 (CMOD-4) and wsi (CMOD-IFR) wind maps.

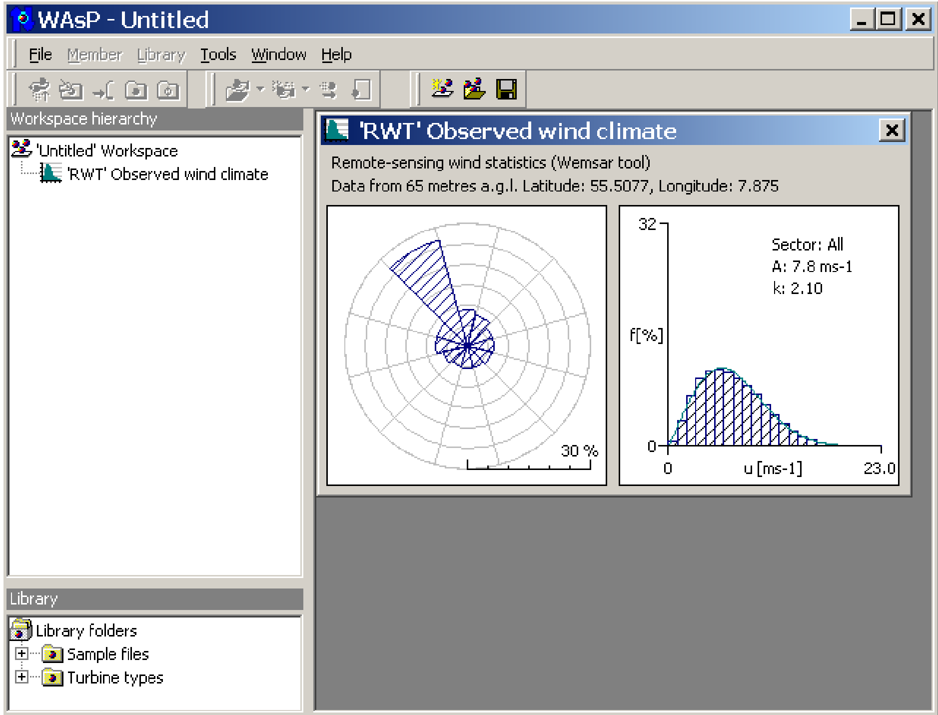

Figure 4. The resulting statistics from the RWT software is here shown in WA^{s}P.

5. Results

A series of 55 ERS-2 SAR satellite scenes are analysed by the new WEMSAR Tool developed by NERSC and RISOE. The wind maps are compared to in-situ meteorological observations.

In-situ observations from the mast are collected at 62 m, 55 m, 45 m and 15 m height above standard normal zero (DNN). From these observations, the wind speed at 10 m is calculated by the logarithmic wind profile method. The 10-m level is chosen for direct comparison to the SAR wind maps that are valid at 10 m above sea level. The mast data are corrected for sea level changes due to tidal variation.

The SAR wind maps are snap-shots in time collected within seconds. The meteorological data are stored as 10-minute averages but here calculated into hourly averages centered around the time of the satellite passes. The data are graphed in Fig. 5. A good correspondence is seen. The results from the wind maps are calculated by a simple footprint method (19). It weighs equally the wind speed in all cells contained within an ellipse-shaped area located upwind to mast. In this way a satellite wind representative for the mast observations is obtained. Around 26 cells are area-averaged. The averaging reduces noise.

Results from a linear regression analysis between the winds from in-situ and satellite data are listed in Table 1 and graphed in Figure 6. It is seen that the CMOD-4 wind speed results correlate slightly better than the CMOD-IFR wind speed as the adjusted R^2 is higher and the standard error and bias are lower.

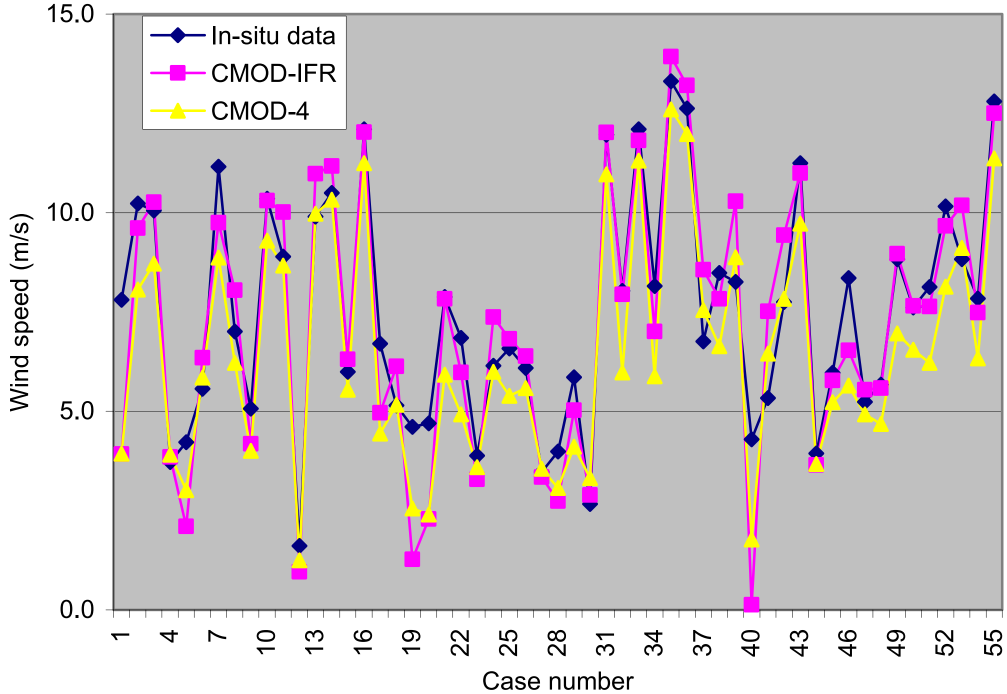

Figure 5. Wind speeds from the Horns Rev mast in the North Sea. The SAR wind speed values are from the CMOD-IFR and CMOD-4 algorithms with the wind direction taken from the meteorological mast.

Table 1. Linear regression results between in-situ wind speed and ERS-2 SAR wind speed calculated by the CMOD-IFR and CMOD-4 algorithms. b is slope and a is intercept.

	a (m/s)	Standard deviation on a (m/s)	b (-)	Standard deviation on b (-)	Adjusted R^2	Standard error (m/s)
CMOD-IFR	-0.85	0.46	1.09	0.057	0.87	1.20
CMOD-4	-0.38	0.36	0.92	0.045	0.89	0.94

Table 2. Wind statistics calculated maps of wind speed calculated by the CMOD-4 and CMOD-IFR algorithms.

		CMOD-IFR		CMOD-4	
		estimate	uncertainty	estimate	uncertainty
Mean	m/s	7.16	0.65	6.47	0.53
Energy density	m3/s3	639.9	32.31	427	15.23
Skewness	-	0.51	12.39	0.36	11.64
Kurtosis	-	3.04	1.49	2.86	1.19
Weibull scale A	m/s	8.08	0.76	7.29	0.6
Weibull shape k	-	2.21	0.34	2.5	0.38
Covariance cov(A,k)	m/s	1.15		1.31	

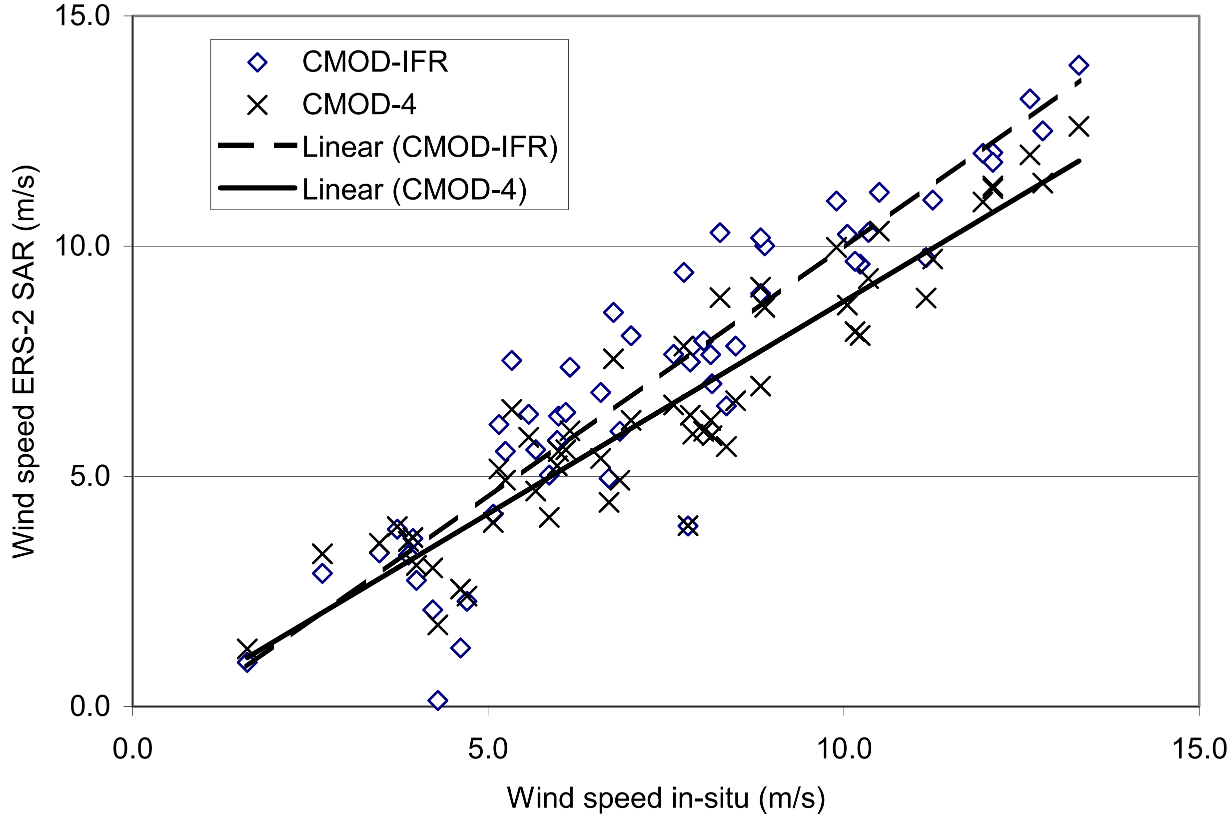

Figure 6. Scatterplot of in-situ wind speed from the Horns Rev mast and from ERS-2 SAR satellite wind maps. Linear regression lines are also shown.

The Weibull A and k parameters, mean wind and energy density and uncertainty is calculated based on 55 CMOD-4 and CMOD-IFR wind maps. The results are listed in Table 2.

6. Discussion

The results from the analysis of 55 ERS-2 SAR images converted into wind speed maps through the CMOD-4 and CMOD-IFR algorithms, show good comparison to the in-situ observations from the mast. The mast is located 14 km offshore. Therefore the footprints are useful, i.e. cover sea surface only, for all wind directions for a height of 10 m. Close to the mast however, there is a long reef with shallow water (on which the wind farm is constructed after the satellite scenes where recorded). The combination of tidal currents and changes in sea level between +1.7 m and –0.6 m DNN within the study gives an effect (noise) to the wind speed mapping near the reef in some cases. An in-depth study of sea current, water depth and wind speed has not been carried out yet; hence the results obtained so far are preliminary.

For the calculation of offshore wind resources, it is recommended to select an area at a few kilometers distance (say 3 km) from the reef to avoid error in the wind speed caused by sea current structures. It should also be noted that the wind speed maps close to the shoreline typically have a negative bias (20). Hence the selected site should be far enough offshore that the footprint does not include wind speed mapped within the nearest 1.5 km off the coast (or include any land surface where wind mapping by SAR is not possible). Therefore the polygones should be drawn such that these areas are discarded in the footprint averaging proces.

The wind resource results reported here are from near the reef and calculated for a 10 m height and without a correction for low- and high-wind samples that have had to be discarded due to limitations of the CMOD algorithms valid in the range 2 to 25 m/s. It is important for the Weibull fitting functions to have this information to calculate the best fitting parameters (even though cases of wind speeds below 2 m/s do not add to the potential wind resource and the turbines typically may be stopped at higher wind speeds). The Weibull statistics compare reasonably to the in-situ results from the period May 1999 to November 2002 (15)where the Weibull A of 8.46 and k of 2.2 are here extrapolated by the log-wind profile to 10 m level. The mean wind speed at Horns Rev at 10 m was 7.36 m/s during these 3.5 years.

Wind directions used as input in the present study are all taken from the in-situ mast. It is however also possible to retrieve the wind direction directly from wind streaks in most of the satellite images. Work is in progress on comparing wind direction retrieved from SAR and in-situ observations, and on using this wind direction instead of the in-situ wind direction in the CMOD-4 and CMOD-IFR algorithms for wind resource calculation.

7. Conclusion

A set of prototype software called the WEMSAR Tool has been developed jointly be NERSC and RISOE. The satellite part of the tool calculates wind speed from calibrated ERS-1/-2 SAR PRI scenes by use of the CMOD-4 and CMOD-IFR algorithms. Within the programme wind direction can be retrieved through Fast Fourier Transforms mapping the dominant direction of the wind streaks. This wind direction information can be used as input to the CMOD algorithms. Alternatively a wind direction from other sources can be input.

A series of 55 ERS-2 SAR satellite wind maps from the Horns Rev site are compared to in-situ observations with good results. The bias between in-situ and satellite wind speeds is around 0.5 m/s and the standard error around 1 m/s. The results from CMOD-4 are better than from CMOD-IFR but a more thorough analysis is needed prior to drawing firm conclusions on the advantage of either of the algorithms.

It is demonstrated how the series of wind speed maps can be area-averaged by a footprint methodology and calculated into wind statistics such as the Weibull scale (A) and shape (k) parameters. The uncertainty is higher than on classical in-situ data. The methodology may however be useful in feasibility studies for offshore or coastal sites where no other observations are available.

The WEMSAR Tool prototype is developed and ready for use by any potential user. A new market for satellite Earth observation may soon appear within the wind energy industry especially so if the cost of SAR scenes is being reduced.

Acknowledgements

We gratefully acknowledge funding from EC for the WEMSAR project (ERK6-CT1999-00017), the in-situ data from the Horns Rev mast from Tech-wise, the tidal data from Danish Meteorological Institute/Farvandsvæsenet and the satellite scenes from ESA AO-153 and ESA EO-1356.

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