ENERGY, ENVIRONMENT AND SUSTAINABLE DEVELOPMENT

**ENERGY, ENVIRONMENT AND SUSTAINABLE DEVELOPMENT**

**Programme for Research, Technological Development and Demonstration under the Fifth Framework Programme 1998 – 2002**

# WEMSAR

## Wind Energy Mapping using Synthetic Aperture Radar

***Key Action 5: Cleaner Energy Systems, Including Renewable Energies***

**NERSC Technical Report No. 237**

**WEMSAR Final Report**

**(01 March 2000 – 28. February 2003)**

**Scientific Results**

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# Contents

# 1 Executive Summary

**Main achievements**

The main result from the project is a prototype satellite SAR wind retrieval and statistical analysis tool. The tool is an add-on the widely used WAsP micrositing model for wind turbine siting. The specific milestone achievements are:

1. SAR wind retrieval algorithms have been reviewed.
2. SAR images from the test sites in Norway, Denmark and Italy have been analysed to derive wind speed using, whenever possible, SAR retrieved wind direction.
3. New model simulations of the wind fields in the test sites have been carried out.
4. Model results and in situ data have been compared with SAR retrieved wind fields.
5. Definition and development of the WEMSAR tool.
6. Validation of WEMSAR tool.
7. Marketing of WEMSAR tool.

## 2. Background

The Earth's population is facing an increasing demand for electrical power. After the Koyoto meeting which clearly signalled the need to reduce the $CO_2$ emission to the atmosphere, it is clear that new alternative sources of power must be considered to meet those needs. In this context it has been focused on possibilities for increasing the utilization of converting wind energy into electrical power by use of wind turbines. With the technical improvement of wind power turbines in recent years, operating wind power-plants have become more economically efficient, and is today a full-worthy source for complementing other types of energy. As an example, 7% of the Danish power consumption supplying about 200.000 households are wind generated.

In planning for wind turbine park installations it is of fundamental importance to have sufficient information about the wind characteristics for different weather situations. Standard wind measurements are available from ground-mounted instruments, such as cup- or sonic anemometers which usually provides time series of averaged 1 or 10 minutes intervals. Such measurements are very local and will not properly resolve the spatial variations in the wind field, and it is thus generally difficult to estimate wind conditions at a nearby site. Since it is known from atmospheric boundary layer meteorology that the surface wind field will have large spatial variations, mapping of the wind field with high spatial resolution will be of great importance for wind turbine siting, and thus, for cost-effective use of wind energy.

High resolution SAR (C-band) measurements are today available from the European ERS-2 and ENVISAT satellites and the Canadian RADARSAT-1. The radar instruments have their clear advantages in being able to operate under all atmospheric conditions and are independent of daylight and clouds. The SAR derived wind speed data has a spatial resolution of 400 m. This is more than sufficient for the application presented here, as is the improving temporal coverage of potential wind turbine park sites.

Wind turbine parks can also be important to the meet energy demands in developing countries. In these areas where the infrastructure is limited regarding power distribution systems, local wind turbine parks can be an efficient way to provide sustainable power. In these regions, high resolution SAR derived wind data can play a very important role for planning installations regardless of lacking field observations and difficult accessible areas.

An important aspect of wind turbine siting is including the potential for offshore wind turbine parks. Several parks are already constructed, e.g. Vindeby and Tunø Knob in Denmark, and more are in the planning phase. Many countries lack suitable land-based wind turbine sites, and moving the wind-turbines off shore is therefore more appropriate. Just as important is the fact that wind speeds are often higher offshore than onshore, differences of 20% within a small area on/offshore are not uncommon. An important aspect in mapping coastal wind-energy areas from satellite is the advantage of combining the continuous spatial coverage with equally spatial continuous data sets of ocean bathymetry, i.e. ocean depth. Obviously offshore wind installations will need to be located in relatively shallow areas to keep the construction costs as low as possible.

The methods developed in the WEMSAR project can prove valuable for mapping coastal wind energy potential on a global scale. A cost-efficient method for mapping this valuable renewable energy source has the potential to be adopted by international organizations, foreign governments as well as private companies.

# 3. Project objectives

The overall objective was to develop, validate, and demonstrate the potential of satellite-based Synthetic Aperture Radar (SAR), scatterometer and altimeter to map wind energy in offshore and near-coastal regions for potential wind turbine siting.

**The specific objectives of the WEMSAR project were:**

1. Identify, streamline and evaluate the state-of-the-art algorithms for wind retrieval from satellite radars.

   It is essential to have available the state-of-the-art algorithms which can take full advantage of the SAR, scatterometer and altimeter data. These will be implemented and streamlined for optimal performance in a wind turbine siting tool.

2. Investigate and streamline mesoscale and micro-siting models for use in wind turbine siting system.

   An important task is to calculate the off-shore and near-shore atmospheric flow patterns at a resolution of 1 km using the KAMM meso-scale model. Then produce local wind resource maps from a WAsP micro-siting programme based on field observations of the wind climatology and the local terrain effects. It will be essential to test the use of radar data on wind speed and direction for the wind climatology analysis to be used in WAsP.

3) Develop and test an integrated tool for maximum site selection efficiency.

   A major task will involve development of an integrated tool for wind turbine siting. This new WEMSAR tool can only be developed and tested through cooperation with potential customers who need this information in their decision-making process. NEG Micon is one such potential customer, and will be involved both in development and testing of the final tool.

4) Identify gaps between currently available wind speed data, and user requirements for wind turbine siting.

   The requirements for WEMSAR information, necessary for better siting of future wind turbines, will be obtained from potential customers. These requirements will then be used as a guideline for developing and improving data products for the WEMSAR tool.

5) Present WEMSAR for potential customers.

   The WEMSAR tool and its products will be presented for potential customers. Such a presentation will include costs and benefits of the products.

6) Assess and recommend future product development and integration.

   The possibilities of integrating the WEMSAR tool with computer models covering land and topography will be assessed, as will integration in Marine Information Systems (MGIS).

The results from the WEMSAR project are described in the following sections. The SAR wind retrieval algorithms, data, models, comparison between SAR, in situ and model results, the WEMSAR tool, validation and marketing results are described.

# 4. SAR and wind retrieval algorithms

Satellite SAR provides images of the backscatter coefficients $\sigma^0$, (normalised radar cross section, NRCS). The backscatter depends on the short wind generated surface waves, and can therefore be used to calculate wind speed and direction (Figure 1). Several empirical models exist, relating the radar backscatter signal to the wind at the sea surface, e.g. the CMOD4 wind retrieval algorithm (Stoffelen and Anderson, 1993), the CMOD-IFR2 (Quilfen et al., 1998), VIERS of University of Hamburg and the NORUT algorithm (Engen and Johnsen, 1995). The WEMSAR project has focused on the CMOD algorithms.

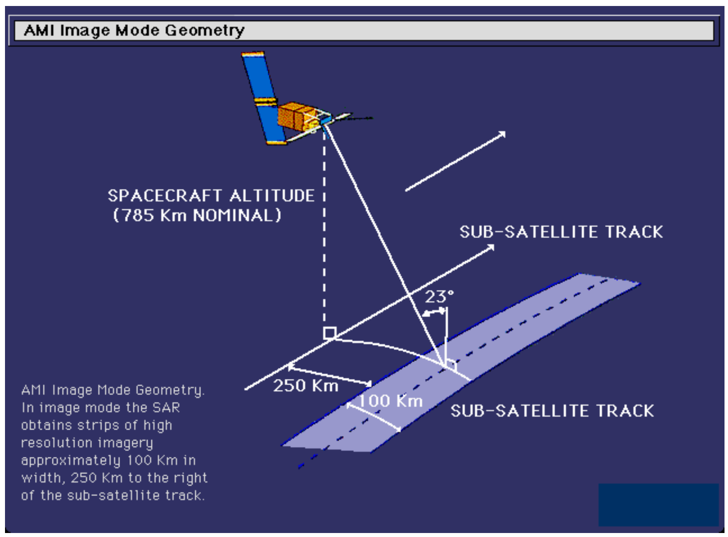



Figure 1. ERS SAR imaging geometry. The ERS swath is 100km wide.

## 4.1 The CMOD-4 and CMOD-IFR2 algorithm

The CMOD-4 (Stoffelen and Anderson, 1993) and CMOD-IFR2 (Quilfen et al., 1998) wind retrieval models are developed for the ERS-1 C-band scatterometer but it is also shown to give good estimates of wind speed when applied to ERS SAR images (Johannessen et al., 1994; Vachon and Dobson, 1996; Vachon et al., 1995, Furevik and Korsbakken 2000). The model was developed for deep sea conditions, and is running operationally at several meteorological centres. CMOD-4 is empirically tuned to ECMWF wind fields, while CMOD-IFR2 is tuned to buoy data.
The C-band algorithm CMOD-4 gives a theoretical $\sigma^0$ value as a function of relative wind direction $\phi$ ($\phi$ = 0 for a wind blowing against the radar), and local incident angle ($\alpha$) of the illuminated area expressed as

$$\sigma^0 = B_0[1+B_1\cos\phi + B_2\cos(2\phi)].$$

The coefficients $B_0$, $B_1$ and $B_2$ depend on the radar beam incidence angle ($\alpha$) and wind speed. The accuracy in the model is given to 20° in wind direction relative to the radar look direction, and 2 m/s in wind speed. The CMOD-4 model is derived for a neutral stratification. In order to compute the wind speed ($U_{10}$) from the radar backscatter accounting for the stratification ($\Delta T$) in the atmospheric boundary layer (ABL) the CMOD-4 derived wind speed must be modified. A correction for this can be derived from expressions relating unstable and stable stratification to neutral stratification as suggested by Wu (1993) The saturation effect of the analogue to digital

conversion (ADC) in the satellite is described by Laur et al. (1993), Meadows and Willis (1995) and Scoon (1995). The effect is strongest over ocean in the near range and increases with radar backscatter intensity (i.e. at high winds). It leads to an underestimation of $\sigma^0$ and has to be compensated in order to properly estimate the absolute value of the radar backscatter. The absolute calibrated $\sigma^0$ is derived in accordance with a comprehensive calibration scheme provided by ESA (Laur et al., 1996) except for correction for variance in the replica pulse power.
The effect of saturation is much less severe for the ERS-2 images due to different gain settings (Lehner et al., 1996). In the future ASAR, an advanced version of the ERS SAR to be mounted on ENVISAT, the 5 bit AD-converter is replaced by an 8 bit version to avoid saturation problems completely.

## 4.2 Wind speed and direction estimated from SAR

To estimate wind direction, it is best to use wind streaks, if any are visible (Johannessen et al., 1994, 1996; Korsbakken et al., 1998; Rosenthal et al., 1996). Vachon and Dobson (1996) automated this procedure by determining the wind direction from the low wave number part of the SAR spectrum ( $\lambda > 2.5$ km). They found they could retrieve the wind speed and direction with an accuracy of 1.5 m/s and 24°, respectively, for winds between 3 and 12 $ms^{-1}$ (with a 180° ambiguity).

The wind direction can also be estimated from the CMOD-4 model for different incidence angles provided the wind speed, derived from the SWA method, can be associated with the corresponding measured radar backscatter ($\sigma^0$) (Kerbaol and Chapron 1996; Korsbakken 1996). In such cases four solutions, i.e. two pairs, each with 180° ambiguity can be found, except in the cases when the direction is close to directly upwind or downwind, for which only one pair is found. (Note that for the three beam scatterometer on ERS-1/2 the number of solutions is reduced to a single pair with a 180° ambiguity).

The wind speed accuracy is generally of the order of ±2 $ms^{-1}$ for both *in situ* measured and SAR derived wind speeds. It is generally seen that the SWA, CMOD-4 and combined wind speeds are in good agreement. In particular, the SWA wind speeds in SAR images containing a fully developed wave system (no fetch limitation) are in agreement with the *in situ* observations, whereas for fetch-limited seas and high wind cases the SWA method seems to underestimate the wind speed compared with the CMOD-4 and the *in situ* wind speeds. The latter suggests that the performance of the SWA method is limited to SAR images containing clear wave modulation from which the azimuth cut-off can be derived. On the other hand, the typical range of incidence angles of ERS-1/2 SAR images places no apparent constraint on the SWA method. Moreover, the estimated wind directions inverted from CMOD-4 (based on input of the SWA wind speeds and corresponding incidence angles and radar backscatter) gives relatively good results (wind direction accuracy of about ±20°) in those cases when the performance of SWA is good. This suggests that this combination of the SWA and the CMOD-4 methods may provide a promising system for quantitative wind speed and wind direction retrievals from SAR images at high spatial resolution of 6 to 10 km.

For near-coastal applications the method often fails. The short fetch and interaction of different wave fields can explain this (Korsbakken et al., 1998). Fetch limited seas can lead to underestimation of the local SWA wind retrievals since the sea state has not reached equilibrium with the local wind speed. This effect can be compensated for provided the wind direction and fetch distance can be determined. The azimuth cut off wavelength decays as a function of the wind speed at different fetch compared to a fully developed sea. The corresponding underestimation of wind speed in SWA becomes significant at 10 $ms^{-1}$ if the seas are not fully developed. In contrast, incoming swell generated by surface winds outside the region will, of course, introduce a surface wave field that is not, again, directly in equilibrium with the local wind field. Hence, the SWA method might overestimate the local wind speed due to increased smearing.

While image calibration is required for the CMOD-4 method it is not needed for the SWA method since the first method uses radar backscatter values while the latter uses spectral characteristics. For the different ERS-1/2 SAR modes, only the low resolution images constrain the SWA method since typical wavelengths of swell are not properly resolved in such images.

In comparison, the six different operating modes on ENVISAT ASAR (to be launched in 2001) contain no apparent limitations for the CMOD-4, except for the possibility to conduct absolute calibration of the Wave Mode products, while the SWA method undergoes the same degradation (as for the ERS-1,2 cases) when the image resolution is reduced for the wide swath and global modes. The SWA performance for the far range sector of the full image mode and the wave mode for incidence angles of about 25-40$^{\circ}$ is unclear.

The ERS wave mode data has limited analog-to-digital conversion (ADC) precision. This limits the usefulness of this mode for wind retrieval using CMOD-4 (or equivalent). In comparison it can be mentioned that this problem will not exist for ENVISAT wave mode products.

The CMOD-4 wind speed estimates appear not to be affected by fetch-limited seas. Quite differently, on the other hand, this method is affected by surface boundary layer conditions such as the stratification and presence of surface films. While the former effect can be corrected for via a boundary layer model for stable or unstable stratification, the effect of the latter will always dampen the surface roughness and hence reduce the wind speed. At the same time, increased presence of surface films will attenuate $\sigma^0$ and lead to an underestimation in the CMOD4 wind speed. Quantification of the effect is difficult because the attenuation of $\sigma^0$ depends on the unknown physical parameters of the surface films. An uncertainty factor in applying the CMOD4 model to SAR data is local variations in the surface wind direction and, in turn, our assumption of a local in situ measurement to be valid in all sub-images in the imaged area. The only confidence in this assumption applies to cases where windrows confirm the homogeneity of the wind direction.

The largest errors in wind directional asymmetry in the CMOD-4 model occur if the used wind direction has positive deviations from 45$^{\circ}$. The error estimate does not vary significantly in the range of ERS SAR incidence angles of about 19$^{\circ}$ to 26$^{\circ}$. For the relative high wind speeds observed in most of the cases studied by Korsbakken et al., (1998) the wind direction used to derive the CMOD4 wind speed becomes a significant error source and may cause errors up to 2 $ms^{-1}$ in the derived wind speed, if the wind direction estimate is no better than ±20$^{\circ}$. The CMOD-4 method may also be sensitive to rain showers affecting the radar backscatter.

A better spatial resolution than discussed before (10 x10 km) can be obtained for CMOD-4 wind speed estimates. The dependency in CMOD-4 wind speed and the $\sigma^0$ of the spatial resolution is illustrated in Figure 10 which shows the variability in $\sigma^0$ and the corresponding CMOD-4 wind speed as a function of increasing the sub-image size from 100 m to 10 km, using in situ wind data as reference.

The CMOD-4and CMOD-IFR2 algorithms were evaluated to be the most practical basis for WEMSAR use. It is very important that correct calibration information is always easily accessible so that absolute backscatter coefficients can be derived.

Further details on SAR wind retrieval algorithms can be found in deliverable D2 “Rieview of Wind Retrieval Algorithms” of the WEMSAR project.

# 5. Data

The project focused on three test sites: Hellisøy on the western coast of Norway, Horns Rev in Denmark and Maddalena in Italy (Figure 2).

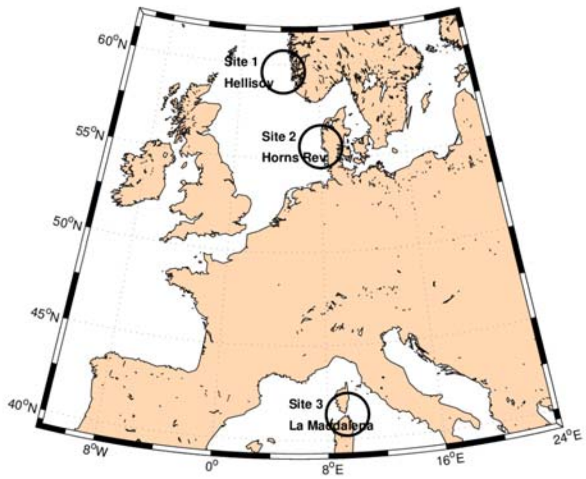



Figure 2. Location of the sites for study and validation in Norway, Denmark and Italy.

The following data were available:

*Table 1. Data and model results available in the WEMSAR project.*

| Location | Nbre. of SAR scenes | In situ data | Model output |
|---|---|---|---|
| Norway, Hellisøy | 53 | Time series from the Hellisøy light house. | WasP and KAMM |
| Denmark, Horns Rev | 20 + 47 | Time series from a meteorological tower. | WasP and KAMM |
| Italy, Maddalena | 9 | Time series from the offshore Mezzo-Passo anemometer. | WasP and KAMM |

The additional SAR scenes covering Horns Rev (47 scenes) were acquired for use in the WEMSAR tool validation phase.

# 6. Models

Three models have been used in WEMSAR, KAMM, WasP and LINCON. These are further described below.

## 6.1 KAMM

Numerical simulations have been done with the non-hydrostatic Karlsruhe Amospheric Mesoscale Model KAMM [Adrian, 1994, 1998]. The model is initialized with a hydrostatic and geostrophic basic state. This large-scale pressure gradient and the daily cycle of radiation represent the external forcing of the model. The model has a vertical with 30 levels from the surface to 5000 m height with the first 2 levels above the surface approximately at 21 m and 53 m. The soil and surface temperatures need to be known. The roughness may be taken from a land-use category in a database or from classified satellite imagery. Every land-use class will be assigned a roughness value and the roughness at each grid point is derived by logarithmically averaging the neighboring roughness. For each situation 6 h real time can be simulated. The geostrophic wind is constant and uniform throughout the model domain. Wind speed, surface stress and surface heat flux are averaged from 3 h to 6 h representation g stationary, adapted conditions. The wind climate is constructed from the different simulations by calculating the weighted mean of the simulated wind at each grid point. The weights are the frequencies assigned to the geostrophic wind classes.

## 6.2 The micrositing model WAsP

WAsP (Wind Atlas Analysis and Application Program**)** is a software program for predicting wind climate and power production from wind turbines (Troen and Petersen, 1989, Mortensen et al. 1993). The predictions are based on wind data measured at stations in the same region. The program includes a complex terrain flow model, a roughness and a sheltering obstacle model. It is developed and distributed by Wind Energy Department at Risø National Laboratory, Denmark. The analysis part is based on wind data, whether in the form of a timeseries or a climatological table, can be transformed into regional wind atlases. Such data may be the users own data or general climatological data. The complex terrain flow model of WAsP is a sophisticated 3-dimensional flow model capable of handling flow over hills and moderately complex terrain. The model employs a "zooming" grid with resolution concentrated at the site of interest.

Non-uniform surface roughness conditions - around meteorological stations and points of interest - are also taken into account. The roughness description can be obtained from standard topographical maps by digitizing roughness change lines, i.e. lines separating areas of constant roughness. For micrositing, a detailed site-specific roughness description may be employed. Terrain roughness is given directly as roughness length values. The reduction of wind speeds behind three-dimensional obstacles as e.g. buildings and shelter belts is treated by a special obstacle model. Wake effect from nearby wind turbines and wind farms is also calculated in the WASP program. The wake effect is the lee-effect from one wind turbine to the next and much further downstream of the order of 5 km. In the wake, the mean wind is reduced, hence the wind power potential is reduced (up to 60%) and the turbulence intensity is increased. Wake effects from large offshore wind farms is poorly described and poses an increasing planning problem. It is for logistics (use of infrastructure) practical to space offshore farms closely, but this is at the same time at the cost of less wind potential. A very detailed analysis of wake effects therefore gains much attention in the future development of offshore wind farms.

Predictions for wind climate and power output may be performed for single sites, entire wind farms and for so-called resource grids. In the latter case the predictions are performed for a number of grid points evenly spaced within a specified rectangular area.

## 6.3 The micrositing model LINCON

LINCOM (Astrup et al., 1996; Astrup and Larsen, 1999; Astrup et al., 1999) is a model for the wind flow over slightly complex terrain. LINCOM is an acronym for LINearized COMputational model. Based on the actual area orography and roughness pattern, it calculates the perturbations these surface parameters induce in a background flow that is otherwise in equilibrium with a flat area with uniform roughness. The sum of the perturbations and the background flow gives the final LINCOM flow field.

For the calculation of relatively small perturbations to a known background wind, the Navier-Stokes equation can with no great error be linearized, and a further simplification can be obtained by formulating the equations in a horizontally Fourier transformed space, the z-dimension remaining in real space. Analytical solutions are obtainable for the Fourier coefficients of the velocity components as functions of wave numbers and of z, but surface boundary conditions have also to be applied in Fourier space.

In the actual version of LINCOM two types of flow distortions are modelled, those due to hills, and those due to an uneven surface roughness over the calculational area. The corresponding boundary conditions can be formulated as: Near the ground the flow shall

1) be parallel to the ground, and
2) be in equilibrium with the local roughness.

With the Fourier coefficients found analytically at a given height, a Fast Fourier Transform quickly gives the corresponding real space velocity field.

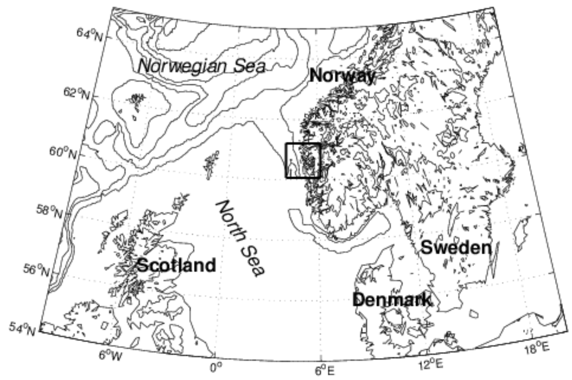
The orography and the roughness pattern for the calculational area are normally input to LINCOM, but sea surface roughness is a function of the wind, and should therefore correspond to the LINCOM output. In order to obtain a realistic response for the wind over sea, LINCOM has been interfaced with a model for sea surface roughness (Astrup et al., 1999; Astrup and Larsen, 1999), and an iterative procedure leads to a wind field and a sea roughness field in mutual equilibrium.

LINCOM can fulfill a single wind speed/direction requirement, i.e. by iteration it can find the field that in a given point has a specified speed and direction. In order to allow specification of speed/direction pairs at more than one site, it is implemented so that a weighted sum of x- and y-components of the velocities calculated by LINCOM for a number of specified positions match the weighted sum of the components of the velocities specified for these positions. This also works for offshore sites.

# 7 Comparison between SAR, in situ and model results

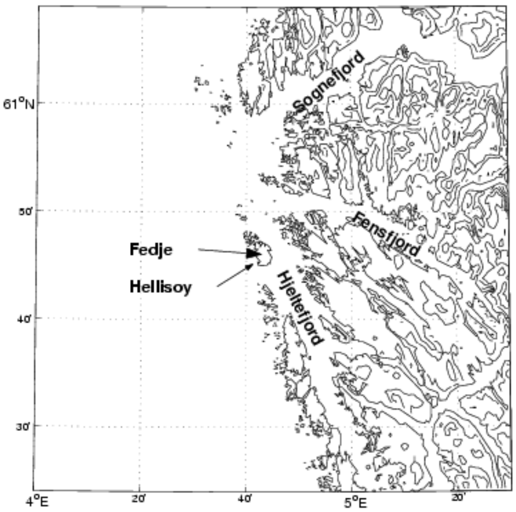
## 7.1 The Norwegian test site

The weather station on Hellisøy is situated on top of a 10 m high mast mounted in connection with a house, and is further surrounded by several other masts and buildings and a very rough terrain which all have impact on the wind climate (Figure 3). The anemometer measures wind at 33 m above sea level and records the average wind speed over ten minutes every hour. The speed-up effect caused by the terrain will vary for the different wind directions and may be considerable under certain conditions (Jackson and Hunt, 1975). Presently we have no models available to correct for these conditions in the Hellisøy data, and therefore we cannot expect that a comparison between the ocean wind measurements provided by the SAR and the *in situ* measurements will show very good agreement. However, in a preliminary study, the main characteristics of the wind field will be represented by the *in situ* data.




a)

b)

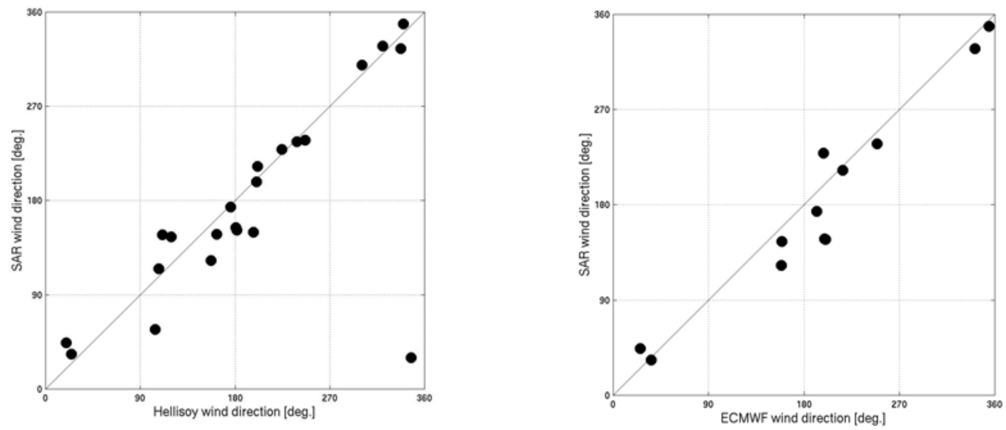



c)

Figure 3. a) Map of the North Sea region showing the study area on the west coast of Norway. b) The geographical position of Hellisøy where in situ wind measurements were taken. c) Photograph of Hellisøy (from east) showing the position of the mast from which the wind data were obtained (arrow).

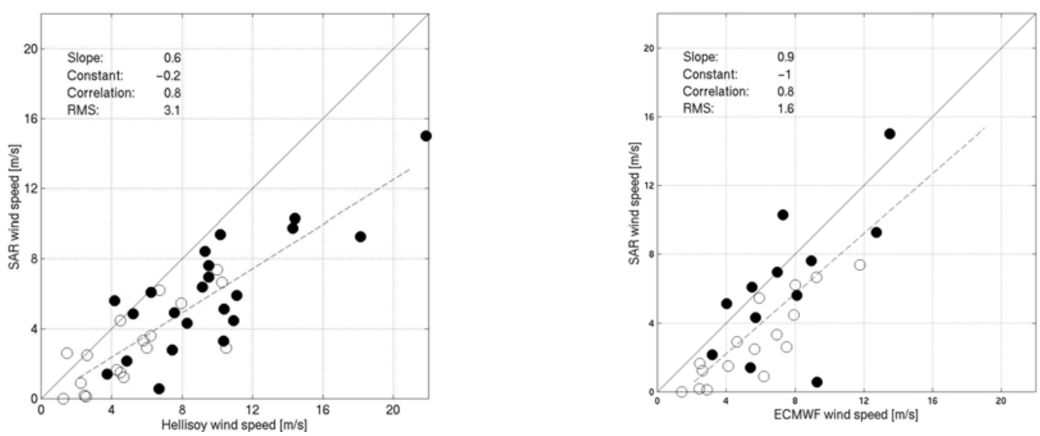
The wind extracted from the SAR scenes are averaged over a 10 km × 10 km region (white box, Plate 6) and compared with measurements from Hellisøy and the ECMWF data for all available days. It was possible to derive wind directions from 22 of the 50 scenes and these agree very well with the directions observed at Hellisøy and from the ECMWF (Figure 4). The wind speed values are somewhat scattered and underestimate for high wind speeds compared to the in situ data (Figure 5a, 40 data points). We interpret this as being mainly due to a speed-up effect over the island, as discussed earlier. The SAR retrieved wind speed values are found to agree better with the wind from the ECMWF analysis (10 m above sea level) extracted offshore at 60.5ºN × 4.5ºE (Figure 5b, 28 data points). This may confirm the hypothesis of a speed-up effect at the Hellisøy lighthouse station.

There is one data point where the SAR retrieved wind is very low (1.2 m/s) while both Hellisøy and ECMWF data indicates relatively high winds of 6.6 m/s and 9.2 m/s, respectively. This point refers to a situation from early summer with offshore winds. As the warm air (about +18ºC) from land moves offshore over the relatively cold sea surface, an internal boundary layer seems to develop which keeps the air flow from interacting with the sea surface (Kaimal and Finnigan, 1994). This gives low wind conditions in the wind field retrieved from SAR.




(a) (b)

Figure 4. a) Comparison of SAR derived wind directions (averaged within a 10km × 10km region) against wind direction from Hellisøy lighthouse (10min. average). b) Comparison of SAR wind direction against ECMWF wind direction.

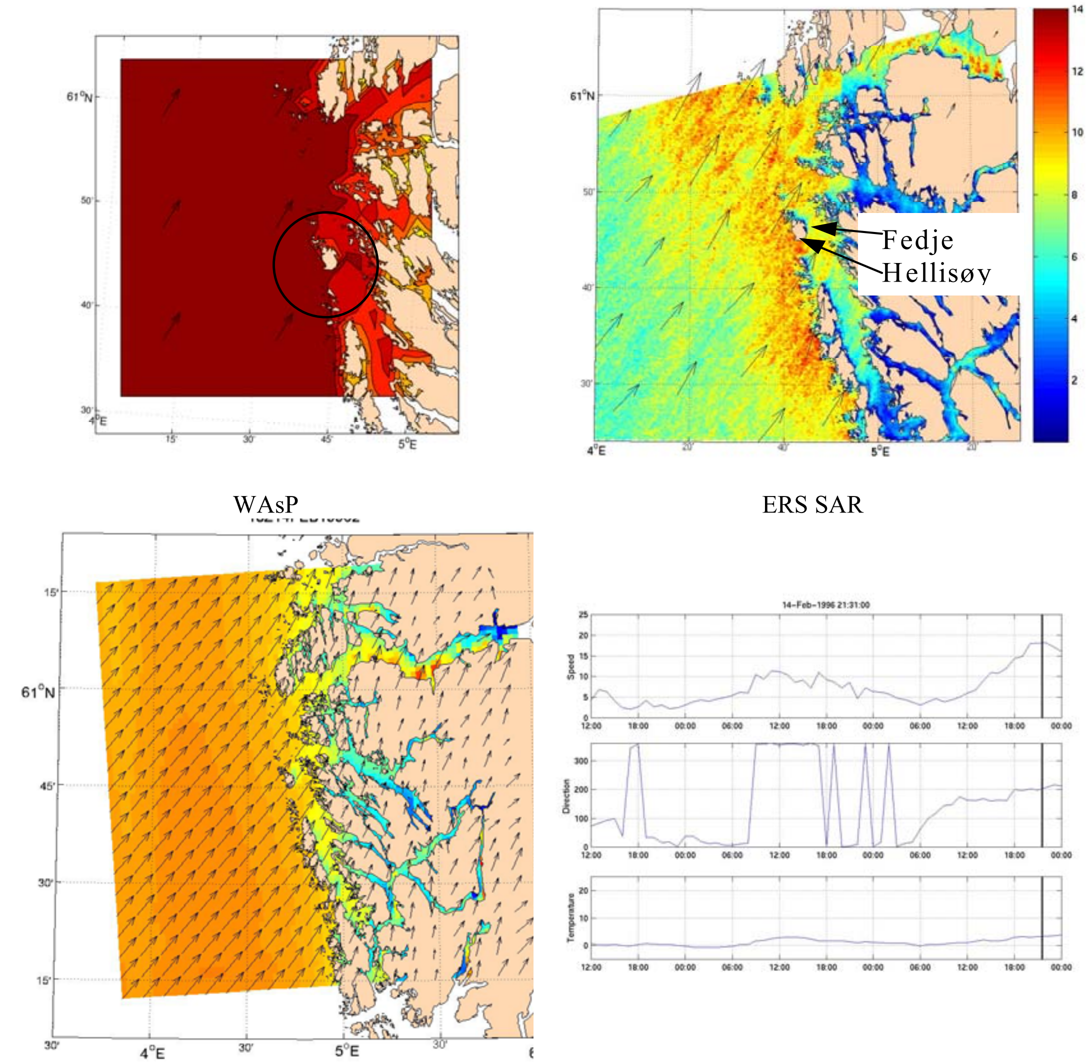



(a) (b)

Figure 5. (a) Comparison between SAR derived wind speed against in-situ (40 data points), and (b) ECMWF (28 data points) wind speed. When possible, input wind direction was taken from SAR (Black dots). For the remaining cases, Hellisøy wind direction was used (white dots).

*Comparison – spatial features*

The analysis of the model data for this site is still ongoing. However, in Figure 6 an example comparison between WAsP output and the SAR retrieved wind from February 14 1996. WAsP is run using the wind speed and direction from Hellisøy weather mast at the time closest to the satellite passage. The model predicts 14m/s wind offshore while the SAR wind speed is lower at between 8-12 m/s. An increase in wind speed towards the coast is seen in the SAR wind field which may be due to the case not being stationary. From the time series in Figure 6 it is seen that the wind is steadily increasing during that day. The KAMM model predicts 9-10 m/s offshore, which agree well with the SAR. All three captures a decrease in wind speed of 2-4 m/s in lee of Fedje (and Hellisøy) island.




WAsP ERS SAR

KAMM Hellisøy weather station

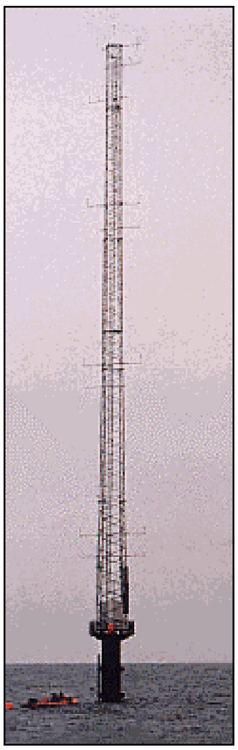
Figure 6. Spatial comparison between model output from WAsP and KAMM and SAR retrieved wind field on February 14 1996 at the Norwegian site. The same colour scale is used for plots of model and SAR results. Below is shown the plots of wind speed, wind direction and temperature at Hellisøy weather station. The vertical bar indicates the time of the SAR passage. Please note that the WAsP results are only valid in a distance of about 5-10km from Hellisøy weather station.

## 7.2 The Danish test site

The validation at the Danish test site includes analysis of SAR wind speed maps to in-situ observations from a tall offshore mast, LINCOM model results and KAMM model results. The offshore meteorological mast is owned and maintained by Tech-wise. We acknowledge the access to these unique observations for the validation phase for this site.

Horns Rev is located west of the Jutlandia North Sea coast in Denmark. At distance of 14 km from the Jutlandic shoreline, a tall meteorological tower is erected, see the map in Figure 7. From the tower a long-term data series of atmospheric observation of wind speed, wind direction and air temperatures has been collected by ELSAM/ELTRA (Neckelmann, 2000). The data series from 16-5-1999 to 31-5-2000 is studied in the WEMSAR project.


*Figure 7. Map of the Horns Rev site in the North Sea, Denmark. From https://www.elsam.com/default_ie.htm.*



The geographic coordinates of the meteorological tower is 55E30’27.82’’ N, 7E52’30.05’’ E (in UTM32/WGS84 Easting 428.946, Northing 6.152.003). The data are collected for the planning of a large offshore wind turbine farm (https://www.elsam.com/default_ie.htm). A photo in Figure 8 shows the mast.

The wind data from the Horns Rev meteorological tower is measured at four levels. For the three lower levels identical cup anemometers are placed at booms in two directions. One boom is pointing to the southwest at 225 degrees and the other boom to the northeast at 45 degrees. So for the sector 135-315 degrees the southwest data are analyzed, and for the 315-135 sector the northeast data are analyzed. The reason for two booms in opposite directions is to avoid flow distortion from the tower itself in the dataset. The wind speeds are measured at 15 m, 30 m, 45 m and 62 m above DNN (Dansk Normal Nul), the temperatures are measured at 13 m and 55 m, and the wind direction is measured at 60 m.

*Figure 8. Meteorological mast at Horns Rev. From https://www.elsam.com/default_ie.htm.*

**Satellite scenes from ERS-2 SAR**

ERS-2 SAR scenes in the PRI format has been calibrated by the SAR Tool Box software and processed into maps of offshore wind speed using the CMOD-IFR2 algorithm at the Nansen Environmental and Remote Sensing Centre (NERSC) (Johannessen, 2001). The wind speed maps each cover an area of 100 km * 100 km with a cell size of 400 m * 400 m.

There are 32 available ERS-2 SAR scenes in the study period from the Horns Rev site, i.e. the ERS-2 SAR sensor observed the site approximately three times per month. From the ESA archives a subset of these satellite scenes have been selected and ordered. The scenes are granted free of cost through the ESA AO3-153 project (Principal Investigator: C. Hasager).

In order to study the physical relations between SAR backscatter signals and the wind speed a special series of satellite scenes are retrieved. The ERS SAR satellite scenes series are selected from a set of ideal criteria:

- ❖ 1. Wind speed regimes (low 5-9 m/s, medium 9-13 m/s, high > 13m/s)
- ❖ 2. Wind direction (on-shore 270°, along-shore 0°/180°, off-shore 90°)
- ❖ 3. Stability (stable typical spring, unstable typical autumn).

The SAR scenes are selected from the in situ wind speed observations at 62 m level. Wind speeds lower than 5 m $s^{-1}$ adds only little to the wind power potential. The 16 days from which scenes are ordered are listed in Table 2.

*Table 2. Meteorological observations at the Horns Rev site: wind speed (U), wind direction and standard deviation, air temperature ($T_a$) and sea temperature ($T_{sea}$) averaged to one hour mean values. Measured by TECH-WISE.* * *estimated value.*

| Case | Date | Hour (UTC) | *U* at 62 m (m/s) | Dir. at 60 m (º) | Std.dev. at 60 m (º) | $T_a$ at 55 m (ºC) | $T_a$ at 13 m (ºC) | $T_{sea}$ at – 4 m (ºC) |
|---|---|---|---|---|---|---|---|---|
| 1 | 20051999 | 21:30 | 8,2 | 122,3 | 1,6 | 15.2 | 13.4 | 10.9 |
| 2 | 21061999 | 21:24 | 11,2 | 313,9 | 3,9 | 11.4 | 12.3 | 14.6 |
| 3 | 10071999 | 20:57 | 7,3 | 71,8 | 2,0 | 21.3 | 20.3 | 17.1 |
| 4 | 29071999 | 21:30 | 7,6 | 34,9 | 10,6 | 17.8 | 18.3 | 17.7 |
| 5 | 10081999 | 10:30 | 12,2 | 328,8 | 2,6 | 16.3 | 17.8 | 19.5 |
| 6 | 30081999 | 21:24 | 8,1 | 291,8 | 4,3 | 14.8 | 15.7 | 17.3 |
| 7 | 03101999 | 10:30 | 13,8 | 240,8 | 4,8 | 13.7 | 14.6 | 16.2 |
| 8 | 07101999 | 21:30 | 12,3 | 274,4 | 3,2 | 13.8 | 14.7 | 15.4 |
| 9 | 19101999 | 10:30 | 9.4* | 88,8 | 4,8 | 7.8 | 8.8 | 12.5 |
| 10 | 23111999 | 10:30 | 3,0 | 233,3 | 4,3 | 8.9 | 9.4 | - |
| 11 | 16121999 | 21:30 | 13,5 | 244,3 | 2,9 | 7.0 | - | - |
| 12 | 16012000 | 10:30 | 11,5 | 305,6 | 3,4 | 6.0 | 6.6 | - |
| 13 | 01022000 | 10:30 | 15,6 | 235,1 | 2,6 | 6.6 | 6.8 | - |
| 14 | 07032000 | 10.28 | 17,6 | 256,3 | 2,8 | 6.3 | 6.7 | - |
| 15 | 26032000 | 10.31 | 4.8 | 125.6 | 3.8 | 16.3 | 17.1 | - |
| 16 | 16052000 | 10.28 | 8,3 | 182,3 | 1,3 | 11.2 | 11.9 | - |

The criteria on different wind speed regimes are covered well by the chosen scenes. The scenes are graphed as a function of wind direction and wind speed in

Figure 9. However, only for low wind speeds are all wind directions represented. For wind speeds > 10 m $s^{-1}$ the wind direction was always between southwest and northwest.

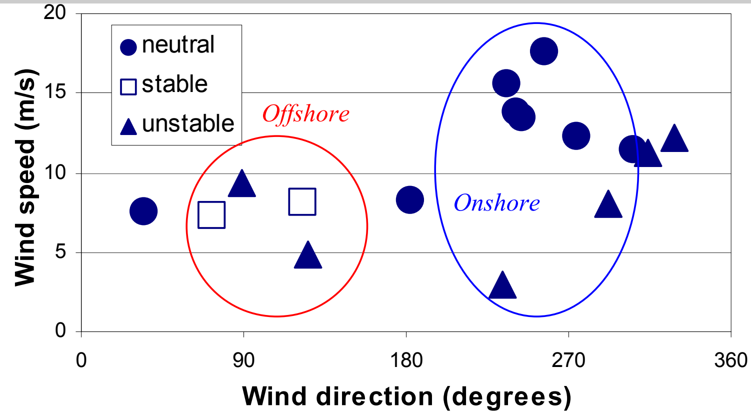
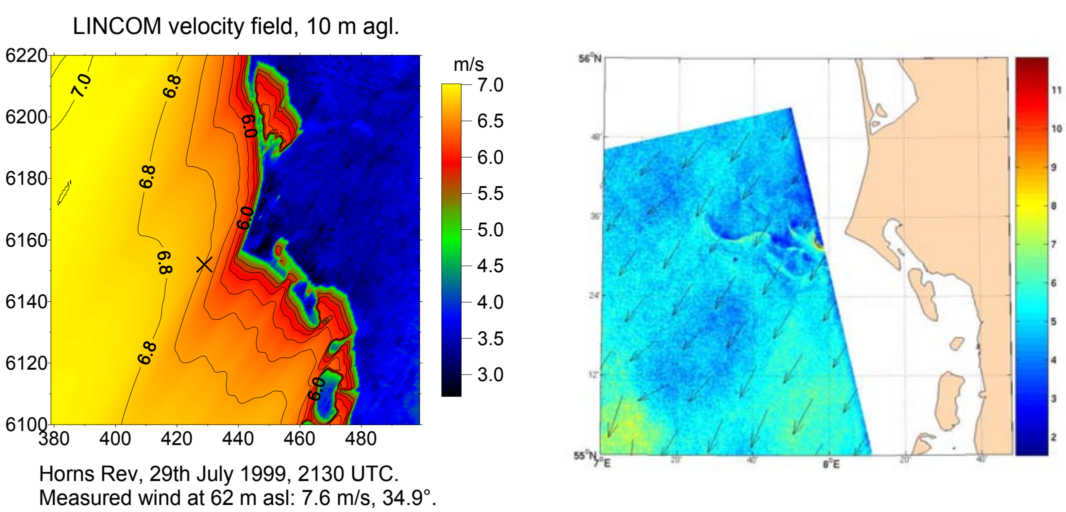



*Figure 9. Wind speed, wind direction and stability for the cases at Horns Rev. Offshore and onshore cases are indicate.*

The atmospheric static stability is assumed to be mainly stable in spring and unstable in autumn. In spring cold air from land may be advected over the relatively warm ocean. In autumn warm air from land may be advected over the relatively cool ocean. The two cases of stable conditions occur in spring and summer. The unstable conditions occur during all times of the year. For the cases of strong winds the atmospheric stability is near- neutral from autumn to early spring.

The LINCOM model has been run for all 16 cases and the KAMM model for only a selected number of cases. All of these are reported in Hasager et al. 2002a. As an example the case of July 1999 is shown below (Figure 10) with the LINCOM wind map, the ERS-2 SAR wind map and the KAMM wind map.



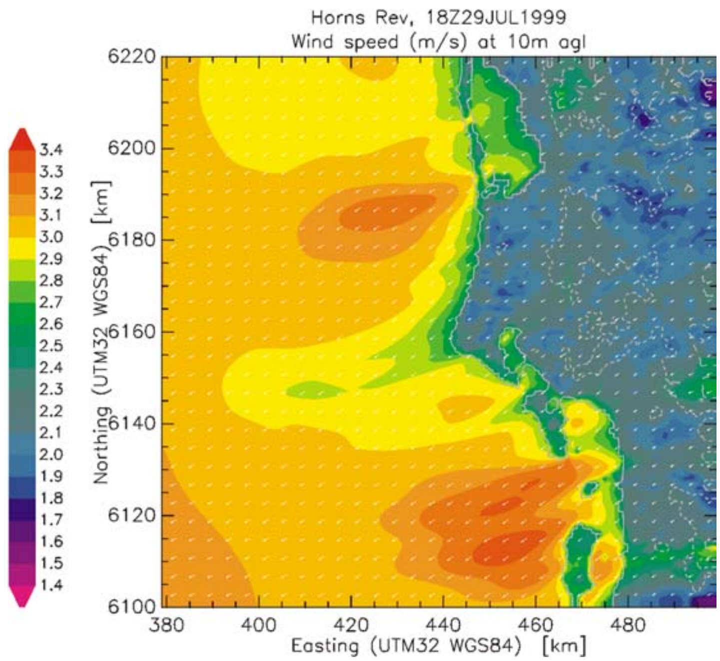



*Figure 10. The LINCOM wind map, the ERS-2 SAR wind map and the KAMM mesoscale model wind map for July 29, 1999. From Hasager et al. 2002a.*

**Comparison LINCOM and ERS-2 SAR**

The main results for the comparison between LINCOM and ERS-2 SAR wind speed maps is the finding that the near-coastal wind of a distance of around 1 km is severely biased.

From Figure 11 showing a horizontal transect of ERS-2 SAR wind speeds near the coast, it is clear that SAR wind speeds decreases dramatically near the coast. It is true for all wind speeds. The coast is positioned at 59.5 km, i.e. the data further east are over land for which the SAR algorithm is not applicable. Near the coast sub-pixel contamination for mixed pixels containing land and sea are most likely to prevail. The geometrical rectification is only accurate to around one pixel. It means that wind speeds from distances closer than 400 m to the coastline are unreliable.

The SAR wind speeds start decreasing 1.0 to 1.5 km offshore. It is most clear for the high wind speeds. The LINCOM model also show a decrease in wind speed near the coast (not graphed here but in Hasager et al. 2002a), however at a smaller rate. It is anticipated that the LINCOM model results are closer to the truth as this model has been extensively verified against in-situ observations.

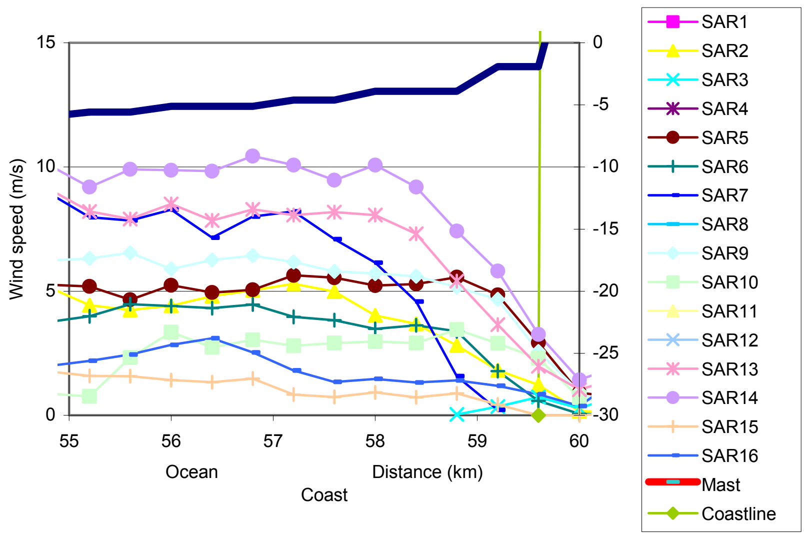



*Figure 11. Latitudinal horizontal transect of the SAR wind speeds and the water depth at Horns Rev 5 km offshore and to the coast. For SAR case numbers please refer to Table 2.*

**Comparison KAMM mesoscale model and SAR**

The comparison between KAMM mesoscale model results and SAR shows good agreement. The main finding is that the driving variables taken from an independent data set (NCEP reanalysis data) in some cases deviate from the locally observed weather. As an example the comparison between the observations from the offshore in-situ mast and the NCEP grid cell is shown in Figure 12. Only if the two observations are approximately similar is it feasible to compare the KAMM and ERS-2 SAR results. This has been done successfully for the Danish and Italian site (Hasager et al. 2002a, Jørgensen, 2001 and 2002). For the Danish site where the terrain is very flat no significant mesoscale effects are found. In contrast, the Italian site showed significant mesoscale effects of the island Corsica just north of the area of interest.

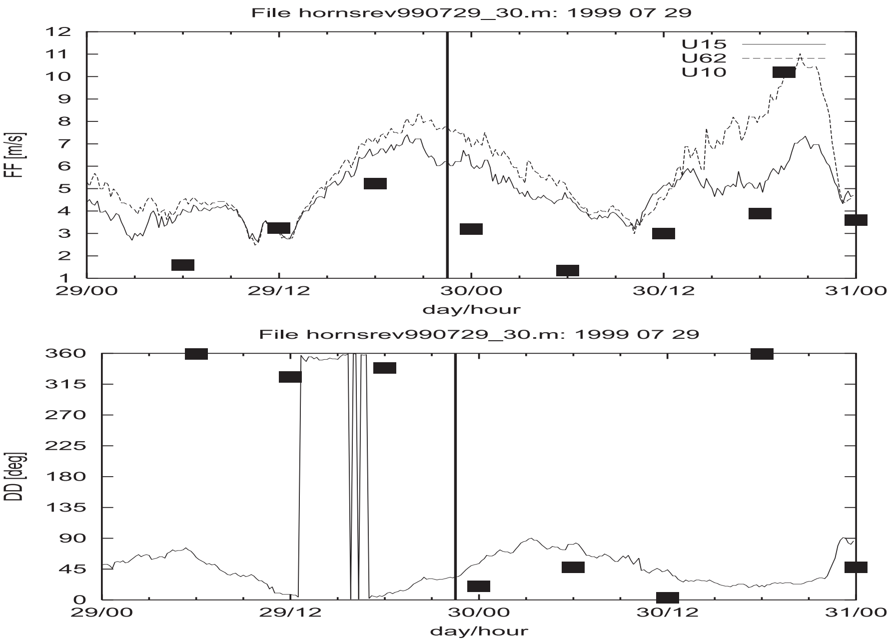



*Figure 12. Wind speed (above) and wind direction (below) measured at the mast at Horns Rev is compared to the surface wind at 10m height from the reanalysis data (filled boxes). The satellite overpassing is indicated with a vertical line.*

## 7.3 The Italian test site

The Meteorological station Mezzo Passo is a 10m offshore tower situated in the narrow strait between Sardinia main-land and the Maddalena Island (Figure 13). Wind measurements are available as 10-min. mean speeds for the period January 1997 – June 1999. Comparison between SAR retrieved wind speed and direction for the 9 SAR images obtained for this test site thus far, are shown in Figure 14.

The two points in Figure 14b, which are near 360° in wind direction, should have been plotted as 0°. The wind directions from SAR are in fairly good agreement with in situ measurements from Mezzo Passo. The SAR wind speed values differ somewhat from in situ measurements. This can be explained by the location of the in situ measurement station (in between some islands, Figure 13).

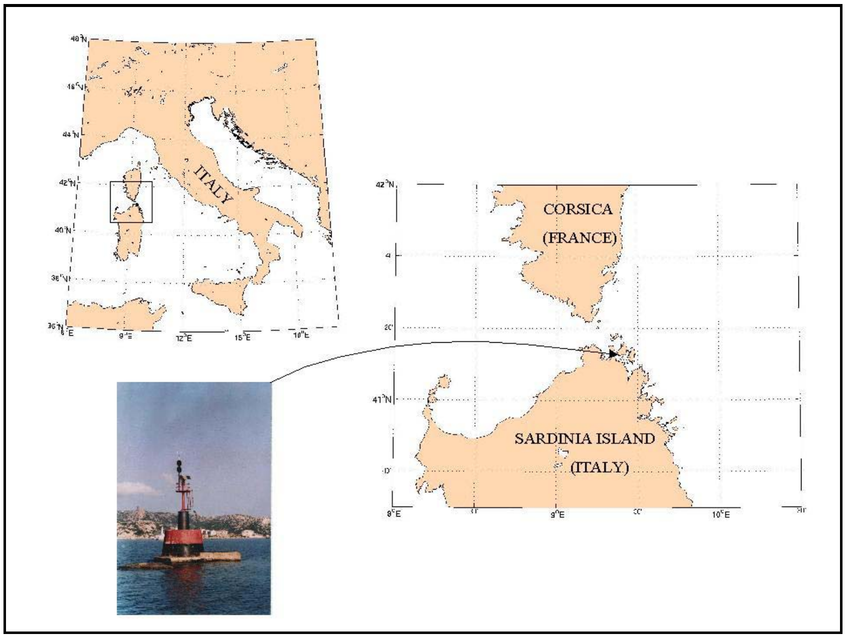
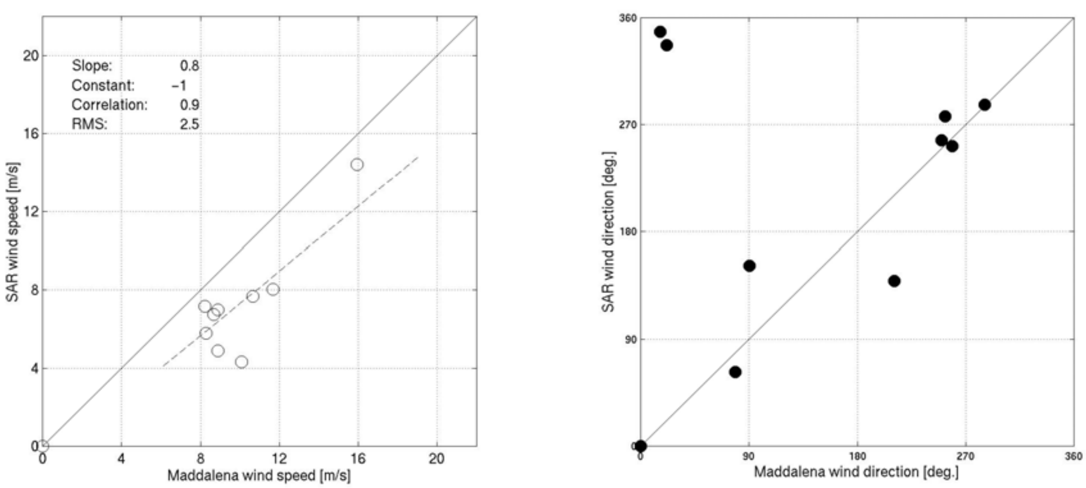



Figure 13. Map indicating the location of the Maddalena test site. In situ measurements were obtained from the meteorological station (photo), location indicated by an arrow.




(a) (b)

Figure 14. Comparison between SAR wind and in-situ wind at the Maddalena test site, speed (a) and direction (b).

Further investigation for the Maddalena site includes comparison to WASP and KAMM model results. From WASP the results of a fingerprint plot is shown in Figure 15. It shows that the mean wind speed at 10 m above ground level is 6.5 m/s and the seasonal and diurnal variations. The wind peaks in mid-afternoon. The dominant wind direction is westerly. Only westerly cases have been found and modelled in the present study.

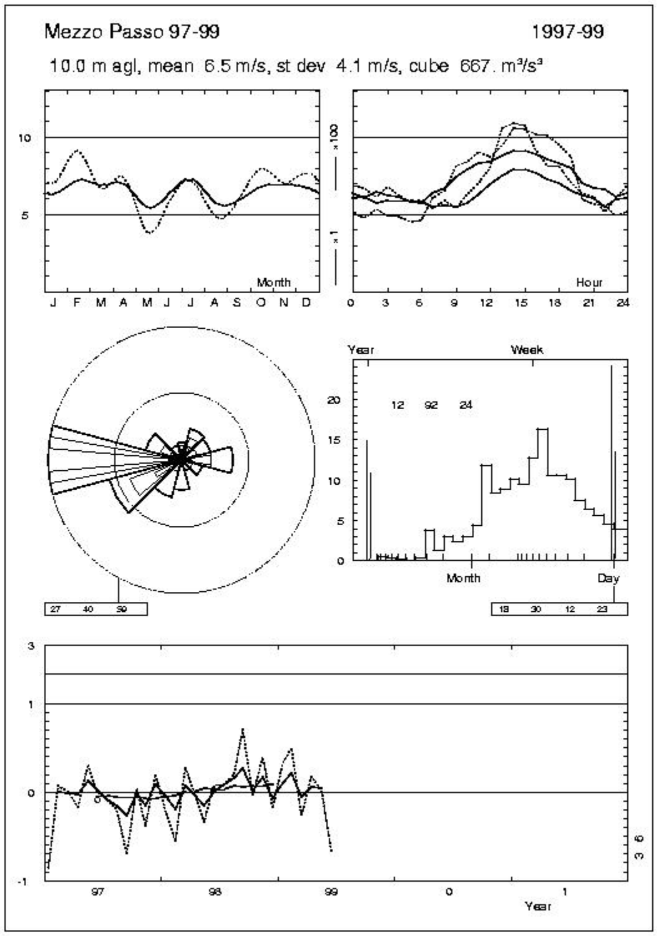



*Figure 15. Mezzo Passo fingerprint plot.*

**KAMM2 mesoscale and WASP comparison to ERS-2 SAR**

The KAMM2 mesoscale model calculations for Maddalena have mainly been performed with a grid containing 101*101*61 cells for an area which is 150 km*150 km, i.e. 1.5 km horizontal resolution. A few runs with 1 km and 2 km resolution have been performed to test grid independence. The aerodynamic roughness length (GLCC, 2001) used for the mesoscale model is shown in Figure 16. The orography used for the mesoscale model calculations with 1.5 km horizontal resolution is shown in Figure 17a. The orographic data originates from the Global 30 Arc-Second Elevation Data Set (GTOPO30, 2001). However, because KAMM2 is sensitive to non-smoothness of the computational grid, the orography is filtered with a Gaussian filter. More filtering is applied near the boundary than near the middle of the domain. Figure 17a depicts the filtered orography. For comparison, the unfiltered orography is shown in Figure 17b. (Hasager et al. 2002a).

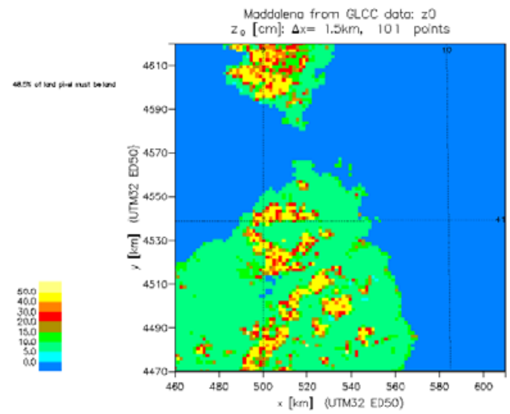



*Figure 16. Aerodynamic roughness length map (cm) of Maddalena with 1.5 km horizontal resolution used for the KAMM2 mesoscale model calculations.*

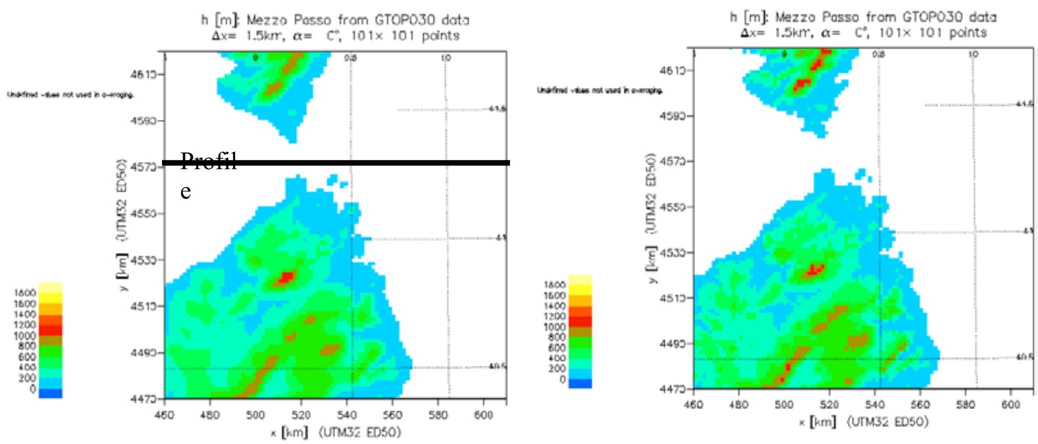



*Figure 17. Filtered orography in meters (a) of Maddalena with 1.5 km horizontal resolution used for the mesoscale model calculations. The unfiltered orography (b) is shown for comparison. A horizontal profile is indicated in graph a.*

The five cases treated in the study of Maddalena are listed in *Table 3*. These cases have been selected from a larger set of nine cases. The reason is that it is necessary for the wind speed measured at the mast to be stationary for at least a few hours and that the reanalysis data surface wind speed at 10 m height compares well to the in-situ data. Otherwise the mesoscale model cannot be expected to perform well if the applied large scale forcing is not realistic. Weather charts and NOAA AVHRR satellite images have also been studied to infer possible fronts and avoid modeling those cases (Hasager et al. 2002a).

Table 3. Cases of the Maddalena study.

| **Case** | **SAR scene date, time (UTC)** | | **Reanalysis date, time (UTC)** | |
|---|---|---|---|---|
| 1 | 05.21.1997 | 21:37 | 05.22.1997 | 00:00 |
| 2 | 12.27.1997 | 10:06 | 12.27.1997 | 12:00 |
| 3 | 04.11.1998 | 10:06 | 04.11.1998 | 12:00 |
| 4 | 07.25.1998 | 10:06 | 07.25.1998 | 12:00 |

| | | | | |
|---|---|---|---|---|
| 5 | 12.12.1998 | 10:06 | 12.12.1998 | 12:00 |

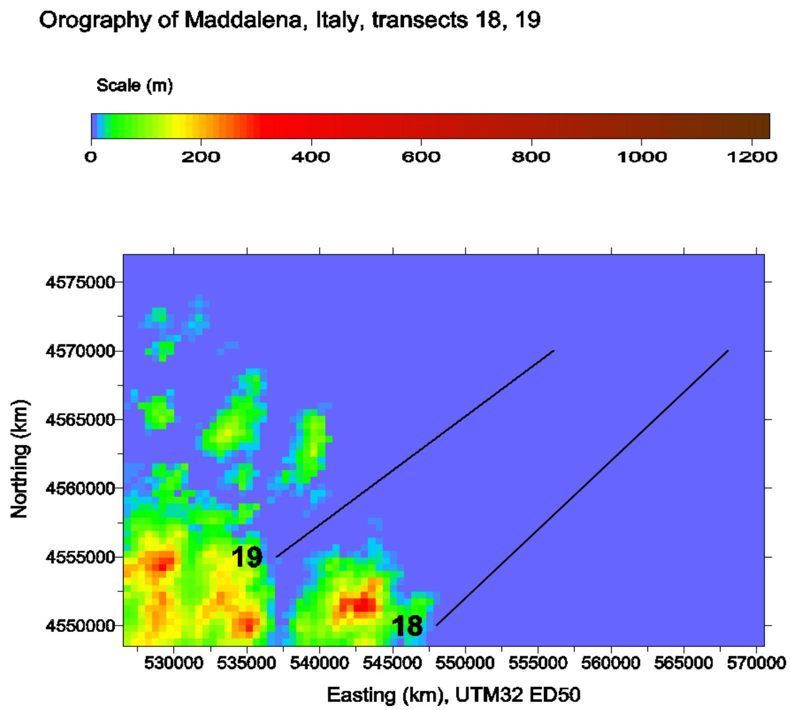



*Figure 18. Transects used for comparing model results and ERS-2 SAR for Maddalena.The transect starts near land.*

Wind speed from ERS-2 SAR, KAMM2 and WAsP in the horizontal transect number 19 (Figure 18) is shown in Figure 19a. The in-situ wind direction is from the Southwest whereas the reanalysis wind direction is from the West-northwest. For the modeling of wind speeds the offset in wind direction means that the KAMM2 model does not model an offshore flow but an alongshore flow. Therefore the KAMM2 model does not capture the roughness change from land to sea in the start of the horizontal transect. The WAsP model captures the land–sea roughness change. The SAR wind speed map shows increasing wind offshore as expected for an offshore flow. The increase appears along the first 5 km of the horizontal transect and also at the10-15 km offshore distance. Further out at sea, the general levels of the wind speed of SAR and the mesoscale model have a correspondence within the expected margin of error of 2 m $s^{-1}$ of the KAMM2 model.

The SAR wind speed maps capture features not present in the model results. In other investigated cases, a similar oscillating behavior of the SAR derived wind speeds with transect position is observed. These features may be caused by atmospheric mechanisms similar to land-sea breezes driven by horizontal temperature gradients in the sea temperature or deviations in the SAR derived wind speeds due to physical phenomena related to the fetch limitations.

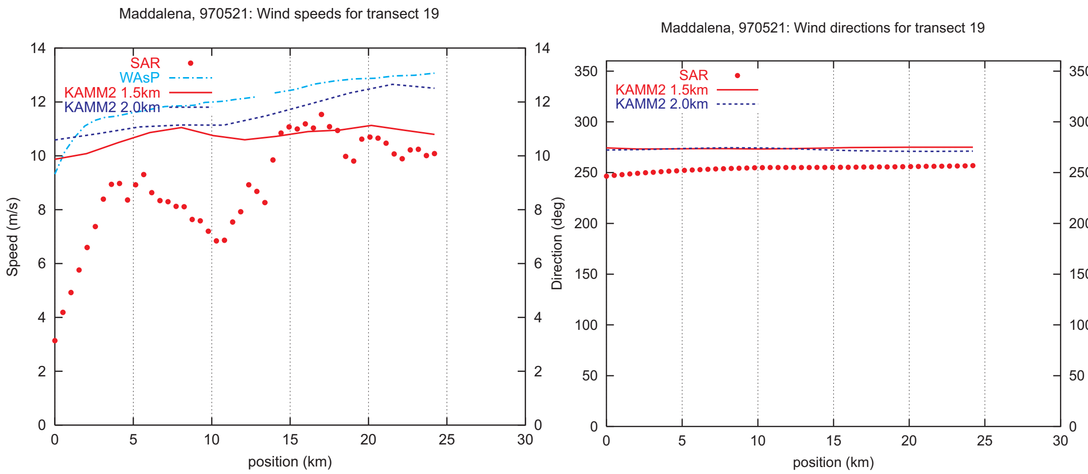



*Figure 19. Comparison of SAR, WAsP and KAMM2 model results for horizontal transect 19 for see figure 12.7 for the position for wind speed and wind direction.*

Comparison of SAR wind speeds and KAMM2 model result for a **long** horizontal transect indicated and shown in Figure 17a.

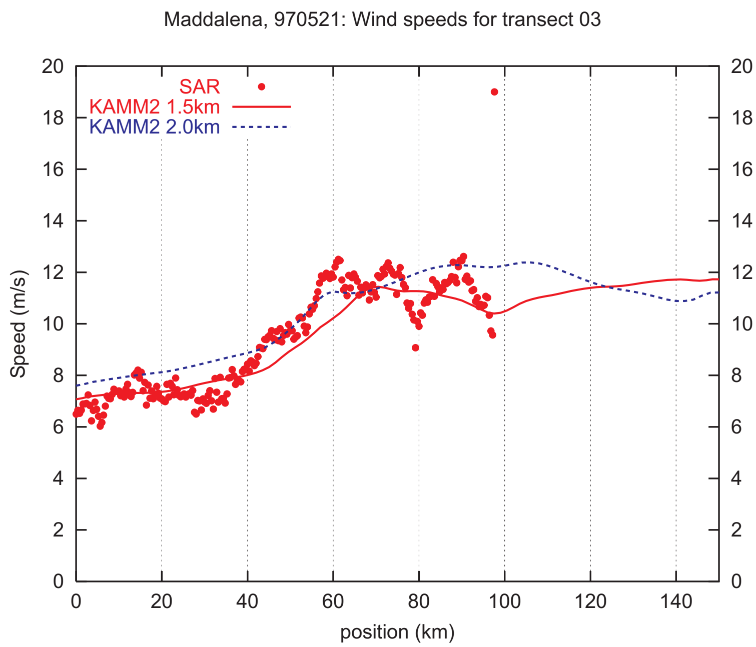



*Figure 20. Wind speeds from ERS-2 SAR compared to KAMM2 model results for a long horizontal transect. The position of the transect is indicated in Figure 17.*

In summary, the WASP model gives very good results for the near-coastal area. This is especially important for a site such as Maddalena where orography and roughness of the island in the vicinity of the mast is pronounced. This means that the in-situ observations are biased from the coastal flow, hence has to be corrected prior to comparison to ERS-2 SAR wind validation. Further offshore (at distances greater than 10 km) the KAMM2 model results generally are in better agreement with the ERS-2 SAR observations than with the WASP model results. This is explained by the mesoscale effects of Corsica to the North of the site, that has a very significant influence on the mesoscale flow. The WASP model does not capture such features whereas the KAMM2 model is able to do it. The data set of only 9 cases is too smaller for firm (statistical) conclusions (Hasager et al. 2002a).

# 8 WEMSAR tool

The WEMSAR tool consists of two modules: a SAR wind retrieval module and a statistical module (Figure 21).

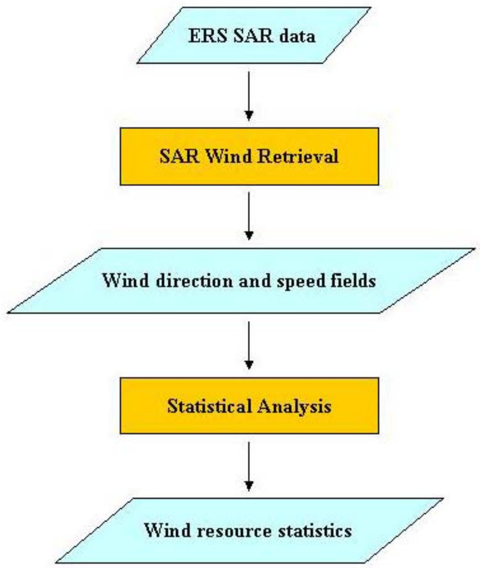



Figure 21. The WEMSAR tool.

The first part was developed for wind retrieval from ERS SAR images (Furevik and Espedal, 2002). The module reads calibrated image files and the associated header files from the ERS SAR toolbox (Now updated to the BEST software after the advent inclusion of ENVISAT ASAR). The images are reduced to approximately 1000x1000 pixels with a pixel size of 100 m by 100 m. The wind retrieval module is sketched in more detail in Figure 22. If the user inserts a wind direction from in situ observations one single wind direction is used over the whole 100 km by 100 km image. Otherwise the wind directions are calculated from image spectra in boxes of 12.5 km by 12.5 km over the image. The user has the possibility to remove erroneous vectors before the directions are interpolated to the whole field before the C-band models are used. New models (e.g. CMOD5, and ENVISAT and RADARSAT imagery) are planned facilitated at a later stage.

The output is binary float files of wind speed and wind direction at a pixel size of 400 m by 400 m.

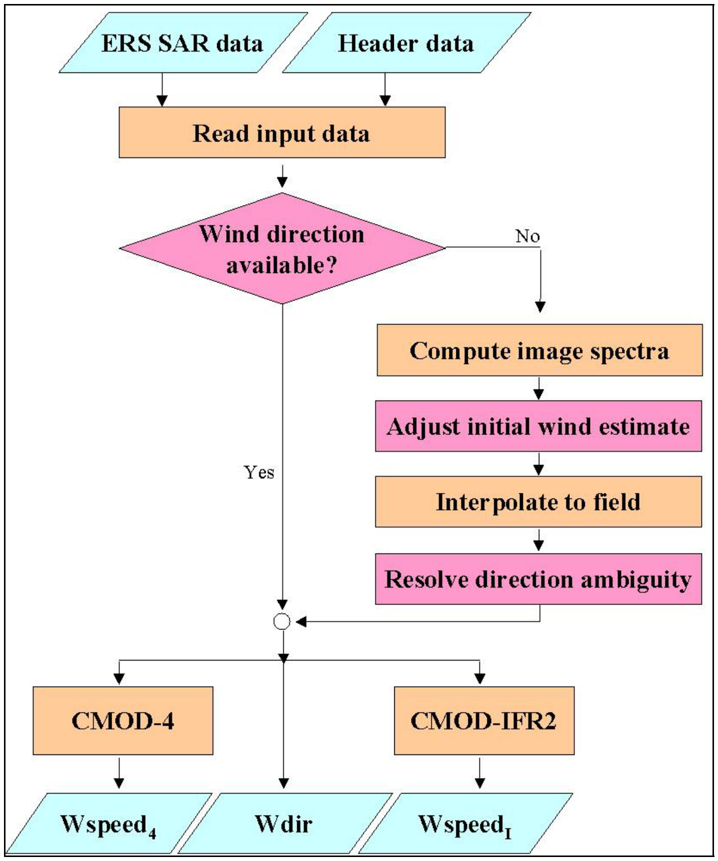



*Figure 22. The SAR wind retrieval module of the WEMSAR tool. Input is calibrated image files and output is files of wind speed from two models CMOD-4 and CMOD-IFR2 and wind direction. Pink boxes are where the user is asked to provide input.*

### RWM (Risø WEMSAR Module)

The output files from the wind mapping module are read into the statistical module named RWM (Risø WEMSAR Module). In this module all the satellite wind fields are treated together to provide wind climate input to the WAsP micrositing model.

Figure 23 displays wind statistics of data calculated by a footprint-averaging of the selected satellite fields. The top-left table shows the wind speed and directions in the selected scenes. The top-right panel shows the observed wind climate statistics in the *.tab format of the WAsP program. The middle-right panel shows a report of the calculations, selected options, etc. The bottom-left panel shows the cumulated wind-speed distribution both empirical probabilities and model fit and the bottom-right panel shows the similar directional distribution. The uncertainty of the Weibull fit is illustrated in the table next to the graph.

As there will only be a limited number of satellite images available (typically less than 100), the statistics are described carefully. Barthelmie and Pryor [2003] describe the statistics in detail. Furthermore the footprint averaging is important as described in Hasager et al. (2002a), and by Nielsen et al. (2002c, 2002d).

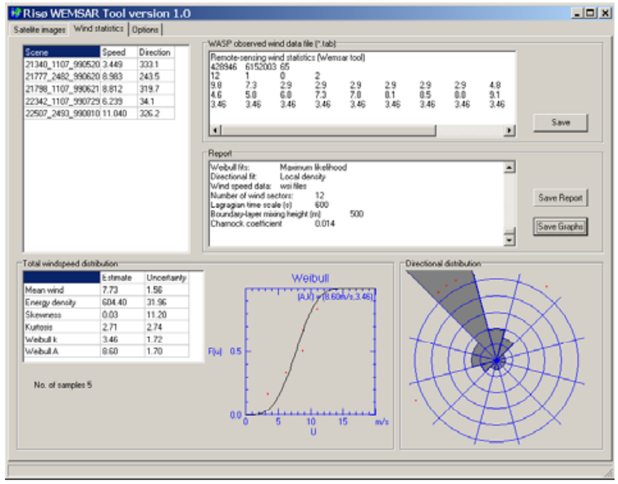


*Figure 23. The wind statistics sheet of the tool.*

The results on wind climate statistics from the RWM tool are then to be imported into the software WAsP (see http://www.wasp.dk/, a commercial software used worldwide in more than 100 countries. The newest version WAsP 8 is sold in more than 1000 copies). An example of how the satellite SAR wind speed maps are used instead of a classical observed wind climate is shown in Figure 24.

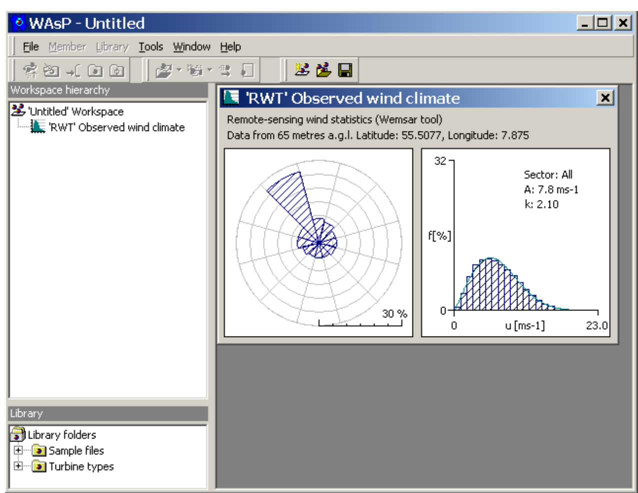



*Figure 24. The resulting statistics shown in the WasP program.*

Development of the tool has included the following considerations

- how accurately does ERS-2 SAR wind speed maps provide wind speed and wind direction
- averaging from image space to time space (footprint averaging)
- wind climate statistics with a limited number of samples

- accuracy reporting

Each of these issue are investigated and validated prior to the development of the prototype WEMSAR tool. All issues are described through publications, e.g. at two major wind energy conferences the WEMSAR tool and methodology was presented as posters;

- Paris, France: Global Wind Power Conference and Exhibition, (Hasager et al. 2002d)

- Naples, Italy: Offshore Wind Energy in the Mediterranean and other Seas (OWEMES), (Hasager et al. 2003b).

On both occasions the posters were awarded first prize for design and content.

The final major presentations of the tool for the wind power community will be oral (Madrid, Spain: European Wind Energy Conference and Exhibition (EWEC), Hasager et al. 2003c; and OWEMES conference, Italy, Furevik et al., 2003), and to the satellite image community (Hasager et al. 2003d).

The validation of each part is here given in brief in section 9 (Validation chapter). The tool is available by agreement with NERSC and RISOE.

# 9 Tool validation

Tool validation includes all scientific sub-components of the prototype WEMSAR tool and the overall assessment of the user-friendliness (technical appearance) of the software. Furthermore it should include a test validation at the Horns Rev site. But this has due to time-limitation not been completely fulfilled. Work is in progress and will be fully reported in Hasager et al. (2003c, 2003d) and Furevik et al., (2003).

*Validation scientific sub-components:*

1. how accurately does ERS-2 SAR wind speed maps provide wind speed and wind direction
2. averaging from image space to time space (footprint averaging)
3. wind climate statistics with a limited number of samples
4. accuracy reporting

**1.**The validation study on wind speed and wind direction retrieval to offshore in-situ observations at Horns Rev in the North Sea shows a bias on wind speed of –1.7 m/s with a correlation coefficient of 0.88. The wind direction is biased 31 degrees with a correlation coefficient of 0.95. The results are for 16 cases calculated by CMOD-IFR (Hasager et al. 2003a).

**2.**Averaging from space to time is done through footprint analysis. It is demonstrated that noise in the SAR wind speed maps introduce error into truly footprint weighted methods, therefore it is recommended to use simple footprint averaging (Hasager et al. 2002c, see Nielsen for further detail on the footprint theories in Hasager et al. 2002a).

**3.**Wind climate statistics assessed from a limited number of samples has been treated in detail (Pryor et al. 2002, Barthelmie and Pryor, 2003a). The uncertainties on the Weibull statistics are further discussed in two notes (J. Mann, 2002; M. Nielsen 2002, available from the authors at Risø). The validation has included not only samples from Horns Rev but also offshore data from masts at Vindby, Denmark and a few buoys worldwide.

**4.**The accuracy reporting is inherent in the statistical methodologies applied in thed RWT part of the tool concerning the limited number of samples (as compared to typical hourly one-year climate data). The uncertainty is reported directly through the tool for the applied case. The uncertainty is given for mean wind speed, energy density, skewness, skewness, Weibull A and k. (see figure 11). The accuracy of WASP for use at an offshore location is described in Hasager et al. 2002b)

*Validation user-friendliness*
The WEMSAR prototype tool is technically developed in two parts. One for the calculation of wind speeds and wind directions, the other for the statistical treatment. The first part is developed at NERSC and evaluated at RISOE and NEG-Micon. The second part is developed at RISOE and evaluated at NEG-Micon.

**5.**The calculation of wind speed and wind direction from raw image data from ERS-2 SAR PRI is done in three steps.

- The first step is to access a raw image file of the type precision (PRI format), typically on cd-rom from one of the PAF (Processing and Archiving Facilities) belonging to ESA (European Space Agency) member states. The method of finding one or more relevant ERS SAR scenes is by use of the software DESCW freely available from http://earth.esa.int/services/catalogues.html. At this web site it is necessary to sign up as a user and get a user-id and password. This is done in a few minutes. The DESCW software allows one to browse the image archive specified by satellite, sensor, date intervals and geographical location. In many cases quick-look images are available online showing the imaged area. This is a very useful feature. Having decided on the scene(s) to retrieve, it is possible to order online (and by email). The cost depends on the use, currently around 150 Euro per scene for research* and 1200 Euro for commercial application.
  The time needed to browse the archive for an experienced user is of the order of 10-15 minutes, however up to a few hours for a beginner. Delivery of historical data from the archive can be done in two-three days. Delivery of new data needs to be ordered in advance (for ENVISAT around three weeks, for ERS-2 around two weeks ahead of time).
  *A research application needs to be submitted and granted prior to ordering.

- The second step relies on the use of the freely available software for calibration of the SAR signals. At the time of the early development of the WEMSAR tool, this software was called SAR Tool Box (STBX). In the documentation for the wind retrieval software (Furevik and Hamre, 2002), the use of STBX version is described and two very useful files for calibration (proc_calib.ini) and geo-correction (geoconv.ini) in dos mode is available. During the latest months of the project, ESA has launched a new version called BEST (Basic ENVISAT SAR Toolbox). This is available at http://earth.esa.int/services/best/ and it includes calibration procedures for ERS-1 SAR, ERS-2 SAR and ENVISAT ASAR There exist extensive material for help for the software and it is a user-friendly software with a windows display. It is possible to read within the proc_calib.ini file and the geoconv.ini files which options in fact has to be chosen within the BEST software.
  The raw SAR image file is rather large (it typically stays on the CD-ROM but may be copied to the harddisk to increase the processing speed) and also the derived files are

very large. Two at 258 Mb and one at 129 Mb occur on the harddisk after the calibration process. These may however soon be deleted again as only some smaller files are needed in the next processing step.

The calibration process of a full ERS-2 SAR PRI scene takes around15-20 minutes for an experienced user. For a beginner this may be somewhat longer, especially including the installation of the software, e.g. one-three hours.

- The third step is the application of the software developed by Furevik and Hamre at NERSC. This is a tool built on the CMOD4 algorithm (Stoffelen and Andersson, 1993) and the CMOD-IFR (Quilfen et al. 1998). The calibrated image files and some additional small files are used. The software is called from the dos-command line and the wind streak arrows come up. It is easy to de-select the non-useful arrows. The wind speed and wind direction maps are then calculated quickly (in a few seconds). The most time-consuming is to de-select the wind streak arrows that should not be used and it is a partly “subjective” procedure. It is very important to have additional information on the general wind direction, in order to do this process in a reliable method.

# 10 Marketing

## 10.1 Market situation

Wind is a significant and valuable renewable energy resource. It is safe and abundant and can make an important contribution to future clean, sustainable and diversified electricity supplies. Unlike other sources of energy, wind does not pollute the atmosphere and does not create any hazardous waste.

The infrastructural requirements of wind are modest, whilst the potential direct gains in employment are considerable. It is a "high-tech" industry. Ninety percent of the world's wind turbine manufacturers are European, with a combined annual turnover of more than one billion Euros. The overall economic profile of wind power compares favourably. Whereas the cost of most forms of energy is bound to rise with time, the costs of wind energy are actually coming down.

According to the European Wind Energy Association (EWEA), the installed capacity in Europe has increased by about 40% per year in the past six years. Today wind energy projects across Europe produce enough electricity to meet the domestic needs of 5 million people. The wind energy industry has set a goal for 60,000 MW of wind energy capacity to be installed by 2010, which would provide electricity for about 75 million people.

EWEA estimates are:

The world market for wind turbine-generated power in 2002 was assessed at about 7000 MW, of which less than 10% is likely to be deployed in coastal or offshore sites, short-term. The market demand is expected to increase in the years to come, as estimated by EWEA:

| YEAR | Total Installed (MW) | Installed Offshore (MW) |
|---|---|---|
| 2010 | 60,000 | 5,000 |
| 2020 | 150,000 | 50,000 |

Wind power is now a mature industry with a growing potential to make a significant impact on the energy scene in Europe and develop a major export industry.
In the years to come, the percentage of offshore wind power installations will increase. Several European studies have confirmed that most states have accessible offshore wind energy resources equal to at least 20% of current consumption, while many have considerably more. This calls for new and innovative solutions applicable in planning and siting of wind turbine parks.

Thus, Wemsar intend to present the project results to existing industries and consulting organizations, facing the need for efficient and less costly planning and siting of wind turbine parks.

## 10.2 Action Programs

The Wemsar results will be exploited and presented in accordance with the following action plan:

1. June – July 2003: Assess and prioritise future work needed to develop commercial Wemsar products, tools and services.
2. August – September 2003: Establish a business model for the marketing effort comprising the Wemsar Consortium as one operating entity, or a business model of sub-organizations part of the Wemsar Consortium
3. September 2003: Identify European projects in a pre-planning phase, and offer proof-of-concept to one or more of these projects, with the aim to demonstrate added value.
4. September 2003: Approach Airtricity to sell wind-results, and compare these with already performed in-situ measurements. Airtricity that starts build-out of the offshore Arklow Bank Wind Park during the summer of 2003 is a provider of green electricity in Ireland
5. October 2003: Identify priority targets such as trade-shows, pre-planning projects outside Europe.

# 11 Recommendation of future WEMSAR tool.

The WEMSAR tool consists of ERS SAR wind retrieval and a statistical analysis, as an add-on to the widely used WAsP micrositing model. However, decision-making regarding wind turbine siting and area planning is a complex matter, especially in coastal regions. The process generally involves both private and public organizations, with varying interests, demands and needs. Today no system is able to handle all these variables in an efficient manner.

A future wind mapping system should combine all available wind data with bathymetry and conflict information, into a GIS based system for coastal regions. The system should handle SAR from ERS, Radarsat and Envisat and scatterometer data. Important wake-turbulence effects from wind turbines should also be studied and results incorporated in the wind resource modelling.

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