WIND ENERGY STUDIES OFFSHORE USING SATELLITE REMOTE SENSING

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Abstract

The wind provides a rich energy source, which can be exploited further in order to reach the energy goals of accessibility, availability and acceptability set up by WEC. A method is presented for the mapping of wind fields over the ocean using satellite remote sensing; the method can be extended to a mapping of wind resources. Further, effects of a large offshore wind farm in the North Sea, Denmark are described quantitatively from satellite measurements. Satellite images offer spatial information on ocean wind fields at a relatively low cost compared to measurements from meteorological masts; thus the technique is promising in terms of future wind energy studies.

1. Introduction

1.1. Current challenges for the energy industry

In the short to medium term, two major challenges for the energy industry are acknowledged by WEC. The first is the uneven distribution of modern energy systems in the world. Today, 1.6 billion people do not have access to modern energy and the number is expected to increase significantly over the next decades due to a fast growing population density in developing countries (WEC, 2000). Further, there is an increasing demand for energy in developing countries as they become more industrialized. This demand is particularly severe in countries such as India and China where the effect of large populations is combined with the effect of a fast developing economy. The second challenge is the growth of energy related pollution at different scales. Globally, the burning of fossil fuels results in emission of greenhouse gases of which CO_2 represents 70% (WEC, 2000). Coal is the most carbon intensive fuel but also the only fuel type available in many developing countries. A 'minimum regrets' policy is recommended until the effect of greenhouse gases on the global climate is known. Developing countries should not be held responsible for the present increased concentration of greenhouse gases, which originates from the development of industrialized countries. However, the new and expanding industries should build upon experiences from the developed world's energy industry. This is possible through technology transfer.

1.2. Delivering sustainability

Fossil fuels are thought to remain in adequate supply for many years to come but in longer terms, there is certainly a demand for renewable energy resources in the context of sustainability (WEC, 2001, 2003). Figure 1 shows fuels shares in the world; renewables account for 13.8 % of which geothermal, solar, tidal, wave and wind accounts for only 0.5 % all together.

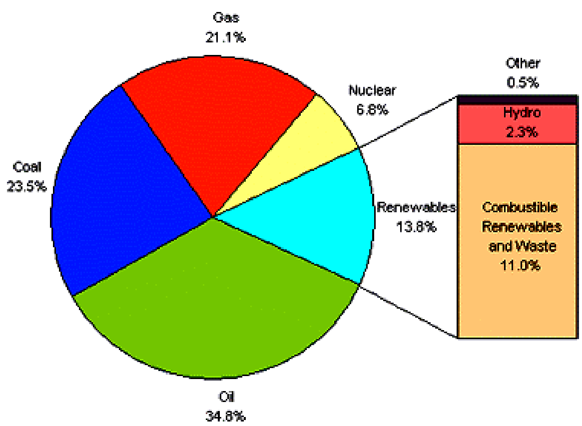

Figure 1. Fuels shares of world total primary energy supply in 2000 (reproduced from WEC, London, UK).

Renewables are a nearly unlimited supply of energy. The cost of development and support of new renewables may seem large compared to the price of fossil fuel however subsidies in terms of transportation, disposal of waste or energy supply are often hidden and not reflected in the price of fossil fuels. An instantaneous demand for alternatives to fossil fuels has arisen with the recent change of stability in the world and particularly in the Middle East where major oil resources are located; the crisis has led to soaring oil prices.

1.3. The wind as energy source

Wind power is attractive as a source of electricity because it is associated with very low greenhouse gas emissions per unit of electricity generated. In terms of *accessibility* the installation of wind turbines leads to an increasing diversity and a more secure energy supply to areas where other energy resources are sparse. Further, the cost of energy becomes more predictable relative to the fluctuating prices on fossil fuels, especially oil prices. The cost of wind energy is currently approaching the cost of conventional energy but comparisons are not easily made due to different structures of national markets (Milborrow, 1999). Economical factors such as interest rates and repayment periods vary between nations and so does the distribution of subsidies.

Wind energy is *available* almost anywhere in the world. As the annual mean wind speed goes up, the cost per energy unit decreases, hence careful siting of wind turbines is crucial in order to obtain maximum production at minimum cost. Siting is typically based on wind measurements obtained over at least one year from a meteorological tower located in the area of interest. The local wind climate and potential power production is predicted using for example the Wind Atlas Analysis and Application Program (WAsP). The WAsP programme has been used in the production of national or regional wind atlases for many countries in the world (see http://www.wasp.dk). The recent opportunity of using satellite remote sensing for the estimation of winds looks promising in terms of wind resource prediction. Generally, the cost of satellite scenes is less than the cost of establishing a meteorological tower; a further advantage is that satellite images show spatial variability whereas traditional measurements are obtained at one point. Satellite derived wind measurements are less accurate than measurements from a meteorological tower hence the satellite scenes can provide a first wind resource assessment, which can then be followed up by detailed measurements.

The *acceptability* of wind energy is high when it comes to air pollution but, as for any other energy resource, there are drawbacks. The presence of wind turbines affects the landscape visually and the energy production is associated with noise. Some argue that wind turbines are disturbing for birds migration; this is still to be further investigated. Placement of wind turbines offshore makes wind energy much more acceptable because the turbines are not heard and in some cases hardly seen from land. Present offshore wind farms are all located in shallow areas; the establishment of wind farms in deeper parts of the ocean remains a challenge for the future.

The worldwide capacity of wind energy is fast growing; in 2003 a growth rate of 26% was obtained and by the end of 2003 a total capacity of approximately 40,000 MW was installed (IEA, 2004). So far, wind power facilities have mainly been installed in developed countries (Figure 2) in order to reach local targets for the reduction of greenhouse gas emission. The largest capacity is found in Germany, whereas Denmark has the largest capacity per capita.

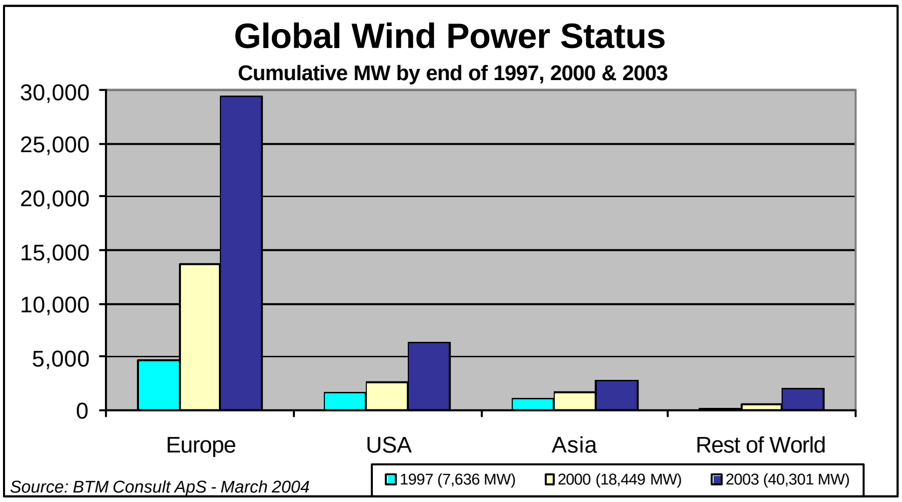

Figure 2. Global distribution of wind power (reproduced with permission from BTM Consult Aps).

1.4. Danish wind energy

Denmark has a relatively long history of wind power production as wind energy has been on the political agenda since 1975. A large industry with numerous spin-off companies has developed out of some early pioneer projects on the design and testing of turbines and blades. Today, wind energy represents 20% of Denmark's energy consumption and the energy has been successfully integrated in the power system (IEA, 2004). Developing countries who wish to implement wind energy can very well benefit from the wind energy experience gained in Denmark over many years. Through a transfer of knowledge or products, the latest technology can be implemented in such countries to immediately obtain the most efficient energy production. Projects to increase technology transfer are already running; one is the United Nations SWERA project, which aims to provide a database of wind and solar power resources for 13 developing countries with the aid of various institutions from the developed world including the Risø National Laboratory, Denmark (see http://swera.unep.net/).

In some parts of Denmark, the density of wind turbines on land has reached the maximum acceptable, hence a further increase of capacity can only take place through replacement of old and relatively small turbines with new, higher capacity models. Figure 3 reflects this tendency as the number of turbines in Denmark has decreased since 2001 whereas the total capacity has increased.

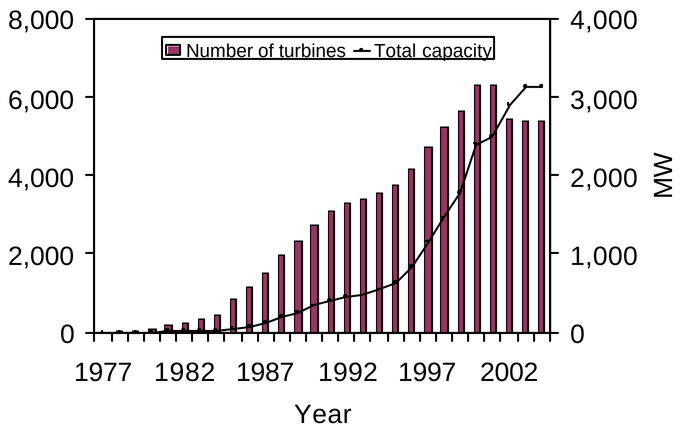

Figure 3. Number of turbines and total wind energy capacity in Denmark (source: Danish Energy Authority).

Future development in Danish wind energy is expected to occur offshore where 2 MW or larger turbines can be installed on much higher towers than acceptable on land. Six offshore wind farms are currently running as demonstration projects in Denmark; these have a total capacity of 406 MW, which corresponds to 80% of the world's offshore capacity by the end of 2003 (IEA, 2004).The construction of wind farms offshore is more costly than land based installations but the cost is balanced by a higher production due to the increased wind speed at larger hub height. Generally, the cost of wind energy has decreased as technology has improved.

Figure 4 shows the price development of one kWh up to 1999; more recent data on the total annual cost of Danish wind energy production does not exist.

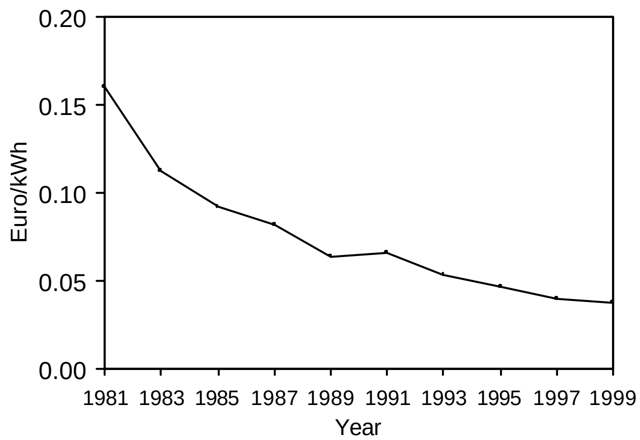

Figure 4. Cost of wind generated electricity in Denmark (source: Danish Energy Authority).

1.5 Wind energy studies offshore using satellite remote sensing

This paper addresses the energy goals of availability and acceptability in relation to offshore wind farms. A method is presented for mapping of wind speed using satellite remote sensing; this technique can be extended to mapping of wind resources. Further, impacts of a large offshore wind farm on the local wind climate are investigated from the satellite data. The downstream distance over which a reduced wind speed occurs is estimated and the reduction is described quantitatively. This information is useful in terms of acceptability but it also leads to an estimate of the necessary spacing of wind farms in order to gain maximum capacity at all wind directions. Positioning of multiple wind farms adjacent to each other is cost efficient. As the most ideal sites for wind farming become occupied, multiple offshore wind farms will probably be found in some places. Currently, the construction of a second wind farm is planned next to the Horns Rev wind farm, which already has the largest offshore capacity in Denmark.

2. Wind retrieval from satellite images

2.1 Synthetic aperture radar (SAR)

SAR instruments are active microwave sensors operating at centimeter scale wavelengths. The radar signal penetrates clouds and light rain and is independent of sunlight so that SAR systems operate day and night. Emitted radiation interacts with surface roughness elements whose size is comparable to the wavelength of the radar beam. The proportion of the radar signal scattered from the earth surface back to the sensor is known as the backscatter coefficient. In offshore areas, the SAR signal interacts with gravity-capillary waves with typical wavelengths of 4-7 cm. These waves respond instantaneously (within less than one second) to the strength of the local wind, whereas longer period waves are generated over much larger time scales. Although long period waves do not interact with the SAR signal, they may influence the backscatter coefficient through tilt modulation of the surface on which the centimeter scale waves are superimposed. Since the caps of centimeter scale waves tend to align perpendicular to the local wind, the backscatter coefficient is also wind direction dependent.

2.2 Derivation of winds from SAR

In order to derive wind fields from SAR, either wind speed or direction must be known *a priori*. In terms of wind energy studies it is normally the wind speed that is desired, therefore the wind direction is used as input. In situations where meteorological measurements are not available, information on wind direction may be obtained with a 180° ambiguity from wind streaks that are seen on some SAR images as a striping aligned with the wind direction (Mourad *et al.,* 2000). The derivation of wind direction from streaks has been carried out through fast Fourier transformation (Lehner *et al.,* 1998, Furevik *et al.,* 2002) and recently through wavelet analysis (Fichaux and Ranchin, 2002; Du *et al.,* 2002). Alternatively, wind directions may be obtained from atmospheric models (Monaldo *et al.*, 2001) or from scatterometer measurements (Monaldo *et al.*, 2004). Scatterometers are satellite borne active microwave sensors that provide both wind speed and direction although at a much lower spatial resolution compared to SAR.

Empirical algorithms describe the relationship of wind speed to the backscatter coefficient. The CMOD-4 algorithm has been developed by Stoffelen and Anderson (1997); originally for the purpose of scatterometer calibration. Later, the algorithm has been applied to SAR data for the derivation of winds (e.g. Hasager *et al.,* 2002). In the CMOD algorithms, the backscatter coefficient is a function of incidence angle, wind speed and wind direction. Model output of wind speed is given at 10 m assuming that the atmospheric stability is neutral such that the logarithmic profile law is valid (i.e. the wind speed increases logarithmically with height). Since the CMOD algorithms are derived from open water conditions, some bias is expected as they are applied to fetch-limited seas where the surface roughness is influenced by a number of parameters additional to the wind stress. In near-shore areas, atmospheric noise may be caused by changes of the atmospheric stability and the development of internal boundary layers. Parameters such as water depth, underwater topography, tidal currents, sea ice and surfactants (e.g. oil or algae) may cause oceanic noise (Clemente-Colón and Yan, 2000). It has been shown that CMOD-4 can map wind speeds between 2 and 26 m s^{-1} with and accuracy of $\pm$ 2 m s^{-1} (Hasager *et al.*, 2004)

3. Study site and data

The Horns Rev wind farm is located in the North Sea at a distance of 14-20 km offshore from the Danish coastline. 80 wind turbines, each with a capacity of 2 MW, are placed at water depths of 5-15 m. The turbines have a hub height of 70 m and a rotor diameter of 80 m, or a total height of 110 m. A meteorological mast is located northwest of the wind farm and recently, two additional towers have been erected to the east of the farm. Undisturbed measurements of wind speed and direction are thus available at any wind direction.
The ERS-2 satellite operated by the European Space Agency (ESA) passes over Horns Rev three times per month at an altitude of 785 km. On board the satellite is a SAR instrument which scans the earth surface at incidence angles of 20-26 degrees in 100 km wide bands. 26 ERS-2 SAR scenes have been purchased since the Horns Rev wind farm became operative in December 2002. Of these scenes only 12 are found suitable for wake studies; the rest of the scenes are captured on days with low wind speed (< 2 m s^{-1}) or they display disturbance in various ways. Each of the SAR scenes covers 100 km by 100 km with a spatial resolution of 25 m. For the analysis, subimages of 50 km by 50 km are extracted; the area covered by the subimages is shown in Figure 5.

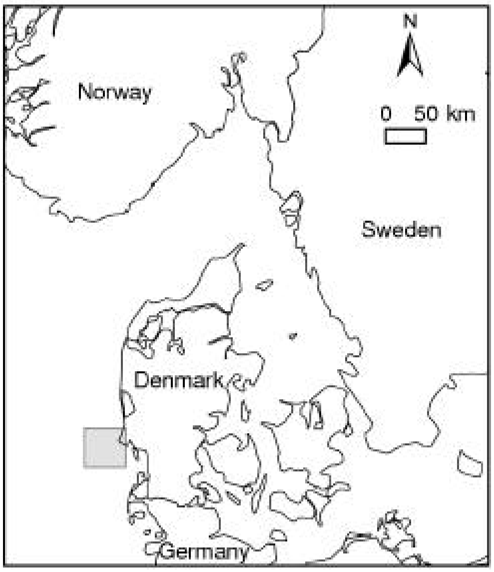

Figure 5. Map of Denmark and surroundings; the grey box indicates the 50 km by 50 km site at Horns Rev.

All SAR scenes are calibrated to display backscatter coefficients using the BEST tool provided by ESA. The calibration procedure includes pixel averaging to a pixel size of 100 m; this is to reduce the random noise always found in SAR images (i.e. speckle). Before the CMOD-4 algorithm is applied to the backscatter images, pixels are further averaged up to 400 m to match the algorithm, which has been developed for pixel sizes in the order of 500 m. At the Horns Rev site, accurate measurements of wind direction are readily available from the meteorological masts. Measurements are given as 10 minute averages; in contrast the SAR scenes are snapshots captured over very few seconds. Deviations may occur between the time averaged and the instantaneous wind directions. To eliminate fluctuations, hourly averages of the mast measurements of wind direction are used as input to the CMOD-4 model.

Figure 6 (left) shows an example of a backscatter image captured on March 01, 2003 where the wind direction and the wind speed obtained from the meteorological tower at 60-62 m was 124° and 8.5 m s^{-1}, respectively. The Horns Rev wind farm is visible in the image and the single turbines are distinguished. Generally, the turbines are more distinguishable at low wind speeds. Figure 6 (right) shows the same scene after the CMOD-4 algorithm has been applied; bright areas indicate a high wind speed whereas darker areas indicate a reduction of wind speed. The wind farm is no longer visible due to the lower spatial resolution of the wind map however the turbines can be identified from their geo-coordinates on rectified images. Rectification is based on the geo-information stored with each SAR scene; this yields a more accurate positioning than models generated from ground control points due to the poor representation of land in the images.

4. Description of wake effects

4.1 Spatial means of wind speed

Several of the selected SAR images show an area with relatively dark pixels on the downstream side of the Horns Rev wind farm where there is a wind wake (i.e. a reduction of the mean wind speed). To describe the wake effect quantitatively, spatial averages of wind speed are calculated within a set of boxes lined up parallel with the mean wind; each box has dimensions of 4 by 8 pixels or 1.6 km by 3.2 km. Boxes containing wind turbines are biased because the turbines are expected to add to the surface roughness, thereby increasing the backscatter coefficient and the calculated wind speed. A set of boxes is drawn on the image in Figure 6 (right).

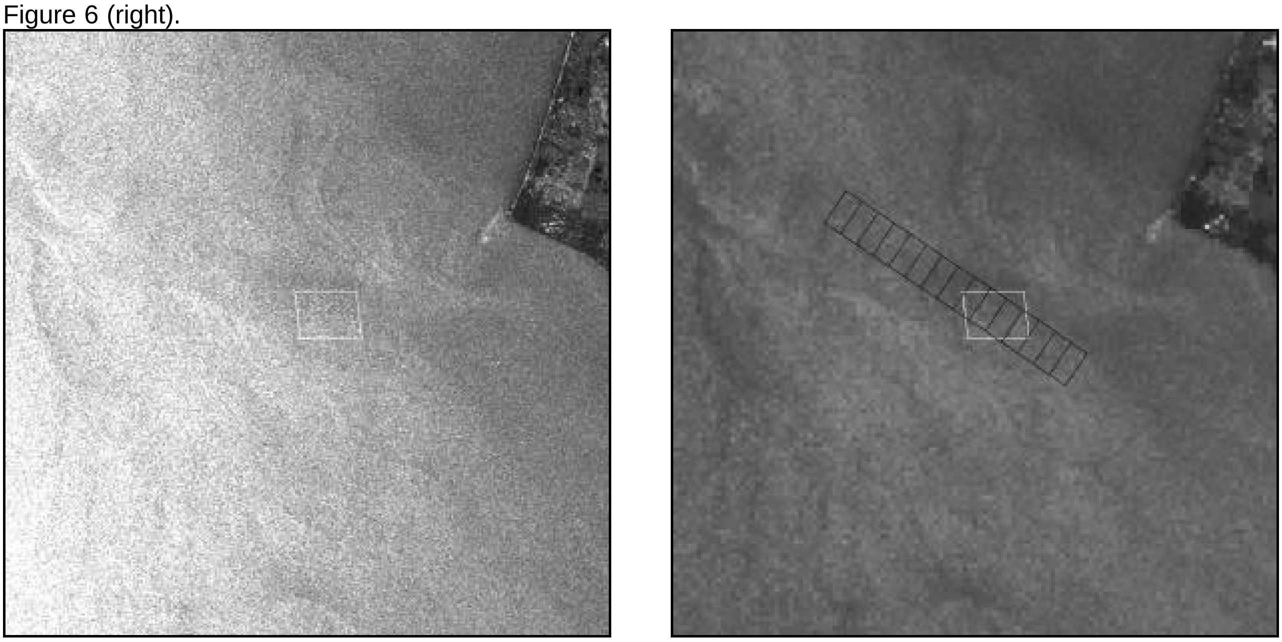

Figure 6. Subsection (50 km by 50 km) of ERS-2 SAR scene captured on March 01, 2003; the Horns Rev wind farm is indicated by white trapezoid. **Left:** raw image showing backscatter coefficients; **right:** map of wind speed and the set of boxes used to calculate spatial means of wind speed.

Transects of the calculated mean wind speed for the SAR wind map of March 01, 2003 are shown in Figure 7; data within the grey box are positively biased by the wind farm structure and should thus be neglected. One transect shows the distribution of mean wind speed directly upstream and downstream of the wind farm as it is based on calculations within the boxes drawn in Figure 6 (left). A mean wind speed of 7.1 m s^{-1} is found just upstream of the wind farm; immediately downstream of the farm the wind speed has decreased to 6.5 m s^{-1}. A minimum of 6.3 m s^{-1} is found approximately 2.5 km downstream of the last turbine; from this point the wind speed gradually increases with distance. 7 km downstream of the wind farm, the wind speed has reached the value obtained upstream of the farm.

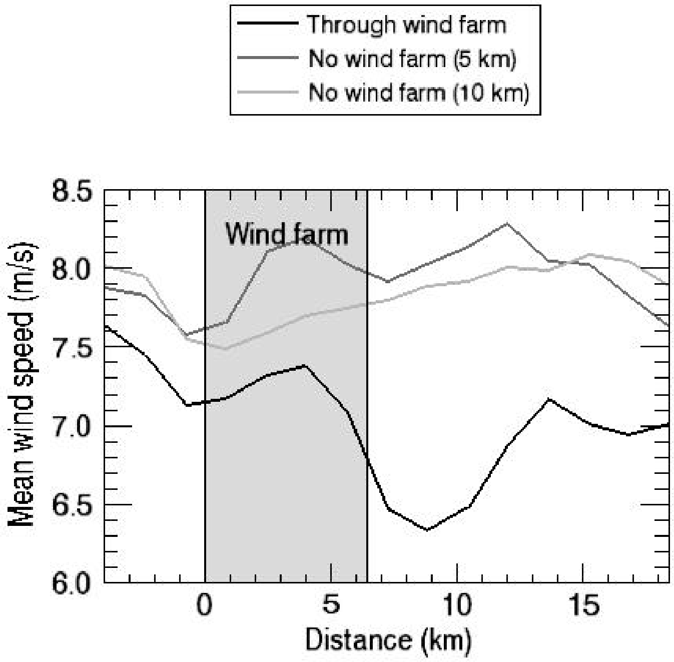

Figure 7. Distribution of mean wind speed on SAR wind map from March 01, 2003. Wind direction: 124 degrees. Different lines show different transects through the wind map; the 'No wind farm' transects run 5 km and 10 km south of the 'Through wind farm' transect.

Statistics are also calculated some distance away from the wind farm where the flow conditions are presumably not influenced by any of the turbines. Practically, the set of boxes has been displaced with 5 km and 10 km to the south, respectively. The resulting distribution of mean wind speed is shown as two additional transects in Figure 7; both of these transects show higher values and less variation compared to the first transect. A box displacement of 5 km may not be sufficient to avoid all effects of the wind farm since some of the trends in the original transect are recognized 5 km to the south.

In summary, the wind farm causes a change of velocity in the order of 1 m s^{-1} and free stream conditions are re-established 7 km downstream of the farm on March 01, 2003. A similar reduction of the calculated mean wind speed is found for 4 other SAR scenes out of the 12 selected and the results also agree well with a preliminary wake model for offshore wind farms described in Hasager *et al.* (2004). The model is an 'added roughness model'. Assuming a logarithmic velocity profile, sea surface roughness (z0) is determined from the 10 m wind speed (U) derived from SAR measurements using an equation derived by Charnock (1955). Based on z0 derived from the satellite data, the wake model can be used to calculate wind speed at any height. In Figure 8, satellite derived and modelled wind speed at 10 m is shown after the model free stream velocity has been set equal to the upstream conditions derived from the SAR. In addition, the wind speed at hub height (i.e. 70 m) is shown.

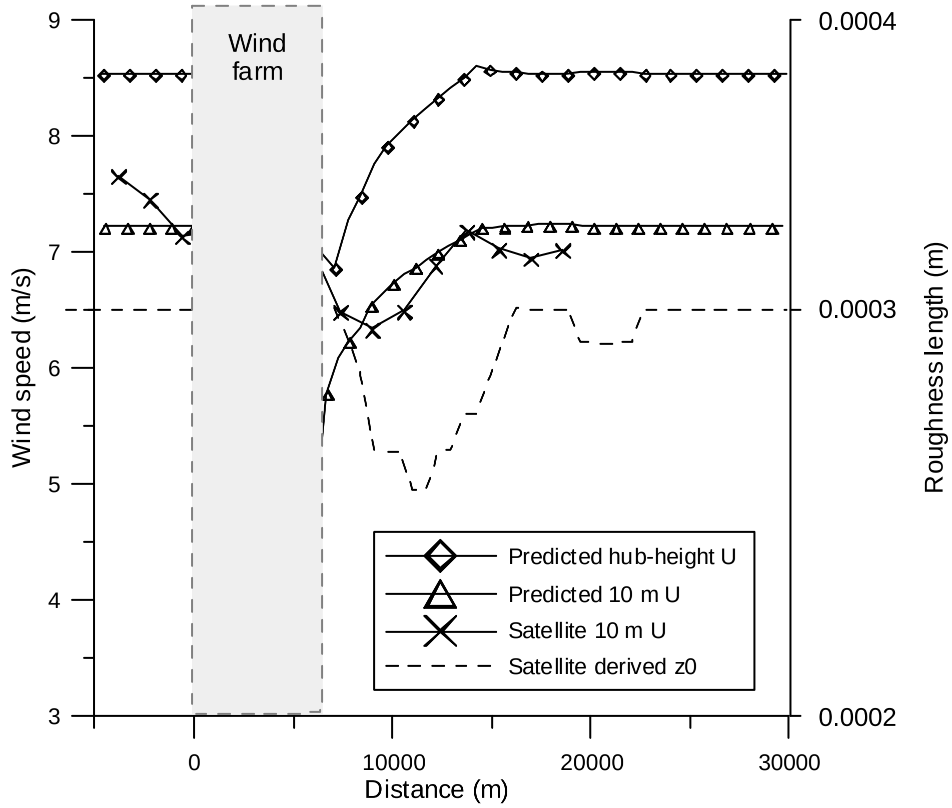

Figure 8. Wind speed derived from satellite measurements on March 01, 2003 and from an 'added roughness' wake model (from Hasager *et al.* (2004)).

4.2 Speed-up effect with offshore winds

3 SAR wind maps display a continuous increase of mean wind speed regardless of the presence of wind turbines. The 3 corresponding SAR scenes are all captured with offshore directed winds, therefore the increase of wind speed with distance is assumed to originate from speed-up effects as the wind picks up over the sea. An example based on data from June 29, 2003 is shown in Figure 9, where all of the three transects show a net increase of 1-2 m s^{-1} over a distance of approximately 20 km. Wake effects downstream of the wind farm are disguised due to the relatively strong speed-up.

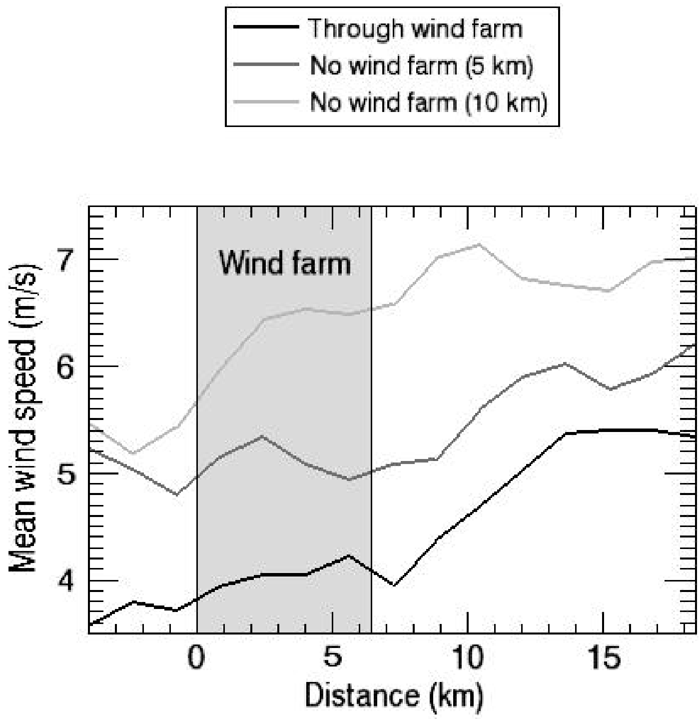

Figure 9. Distribution of mean wind speed on SAR wind map from June 29, 2003. Wind direction: 62 degrees. Different lines show different transects through the wind map; the 'No wind farm' transects run 5 km and 10 km south of the 'Through wind farm' transect.

4.3. Effects of underwater bottom topography

Some of the SAR wind maps display spatial variability of wind speed that cannot be associated with the Horns Rev wind farm. From inspection of all the SAR scenes available, it is clear that underwater bottom topography, particularly the submerged reef on which the wind farm is built affects the surface roughness and the radar signal. An example is shown in Figure 10 where an ERS-2 scene captured on December 21, 2003 (left) is compared to a bathymetry map of Horns Rev (right). The submerged reef has a curved outline, which is recognized on both the bathymetry map and the SAR image. Effects of bottom topography on SAR images seem to depend on oceanographic parameters such as currents or waves since the reef is only visible on some images. 2 scenes are excluded from the present wake study because effects of the bottom topography seem to coincide in space with the wake downstream of the wind farm.

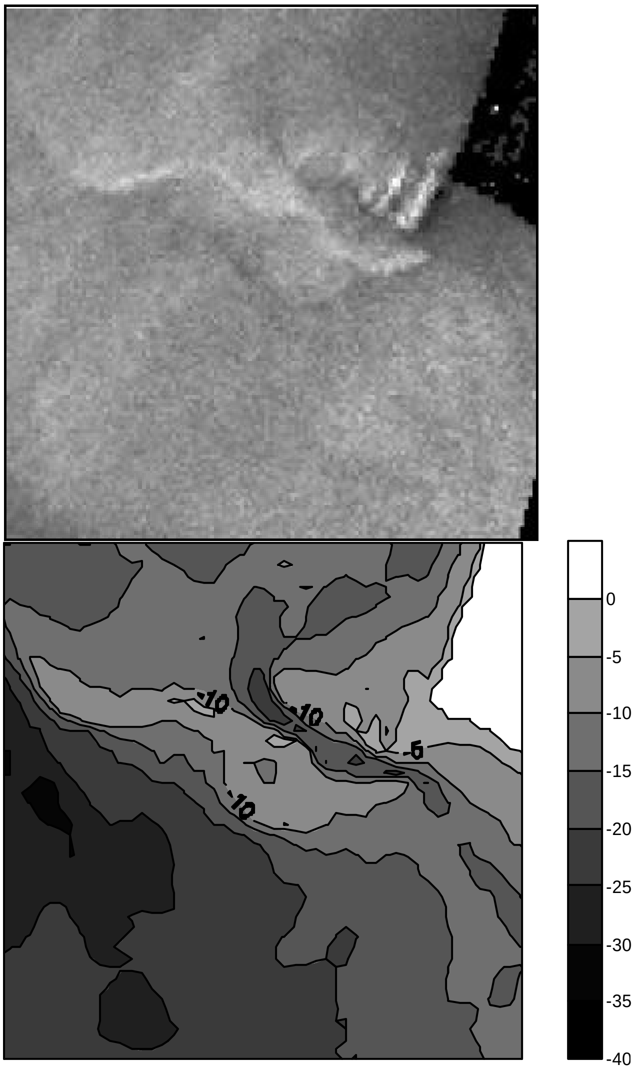

Figure 10. Left: Subsection (50 km by 50 km) of ERS-2 SAR scene captured on December 21, 2003; **right:** bathymetry map covering the same area as the SAR scene (source: DHI Water & Environment).

5. Discussion

Of the 26 SAR scenes studied, it was possible to identify wind wakes on 5 scenes. The images provide new and useful information on the decrease of wind speed as the wind flow passes an offshore wind farm and it is also possible to determine the downstream distance over which the wind speed increases until the free stream velocity is obtained. The satellite based study provides a valuable estimate of the effect of large offshore wind farms on the local wind climate at a height of 10 m. The information can be used in the verification of wake models, which provide estimates of the wind speed at any height downstream of the wind farm. Good agreement was found between satellite based and model based derivations of wind speed downstream of the Horns Rev wind farm.

It is highly recommended that 'quick looks' are studied before any purchase of SAR images, if available. However, most SAR scenes must be pre-ordered from the space agencies, which leaves no opportunity to perform quality checks in advance. For the present study 26 SAR scenes were purchased. Some scenes were neglected from the analysis due to atmospheric disturbances or they were captured on days with low wind speed (< 2 m s^{-1}). Other scenes were found suitable for wake studies but they later displayed speed-up effects that were strong enough to disguise the wake effect downstream of the wind farm. Effects of bottom topography on the sea surface roughness and the derived wind speed is another problem that can not be ignored in wake studies since most offshore wind farms are located in shallow water. One way to get around the problem is to identify the precise location of topographic features on the sea bed and create a mask to exclude these features from the individual SAR images analysed. In the present study, SAR scenes with topographic effects were simply left out.

The results presented here can possibly be extended to the area inside large offshore wind farms if the spatial resolution in the SAR wind map is improved. A pixel size of approximately 100 m by 100 m will allow one to identify single wind turbines and exclude the pixels containing the turbines from the calculation of mean wind speed. The wind speed derived will then originate from the 'true' roughness of the sea, which is created by small scale wind generated waves. Future objectives also include studies of other types of SAR data: the ERS-2 satellite is now replaced by ENVISAT, which is able to capture data in several different modes, some of which may be suitable for wind energy studies. Further, airborne SAR data have been captured over Horns Rev during the Autumn 2003, these are expected to yield information on winds at a much higher spatial resolution compared to the satellite borne SAR instruments.

6. Conclusion

In conclusion it is demonstrated through the present study that:

i) wake effects from offshore wind farms can be quantified from satellite SAR images.

ii) careful selection of SAR scenes is necessary in order to avoid various forms of disturbance.

iii) satellite remote sensing offers a range of opportunities to improve the current knowledge about wind fields over the ocean and the wind as an energy resource.

Acknowledgements

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