Coastal Wind Mapping from Satellite SAR: Possibilities and Limitations

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Abstract

Satellite remote sensing of ocean wind fields from Synthetic Aperture Radar (SAR) observations is presented. The study is based on a series of more than 60 satellite scenes from the Horns Rev in the North Sea. The wind climate from the coastline and 80 km offshore is mapped in detail with a resolution of 400 m by 400 m grid cells. Spatial variations in wind speed as a function of wind direction and fetch are observed and discussed. The satellite wind fields are compared to *in-situ* observations from a tall offshore meteorological mast at which wind speed at 4 levels and temperatures at two levels are analyzed. The mast is located 14 km offshore and the wind climate is observed continuously since May 1999. At the site, the Horns Rev wind farm is in operation since December 2002. The study also includes a demonstration of the possibility to map the wake effect of the wind farm from satellite SAR observations. The wake is observed as a reduction in mean wind speed behind the wind farm compared to the upwind conditions.

1. On ERS-2 SAR satellite images

The European Space Agency (ESA) has from year 1991 to 1996 received SAR imagery from the ERS-1 satellite and from year 1995 to present from the ERS-2 satellite. Both are in polar sun-synchron orbit and carry identical instruments namely the SAR scanner. It records C-band VV polarized observations. The Earth is mapped with a spatial resolution around 25 m by 25 m within a 100 km broad swath. For a given local site (e.g. in the North Sea), the number of observations is around three scenes per month.

2. On retrieval of offshore winds from ERS-2 SAR satellite images

In the current project, the method for retrieval of ocean winds from the ERS-2 SAR satellite images is based on application of an empirical geophysical model function developed for satellite scatterometer observations. It is the CMOD4 model by Stoffelen & Anderson (1997) that is used through a software developed at the Nansen Environmental and Remote Sensing Centre in Norway (Furevik & Espedal 2002). The CMOD4 model is only able to solve for wind speed under the condition that the wind direction is known *a priori*.

Briefly described the normalized radar cross section (backscattered values) measured by the SAR is a function of the surface roughness of the ocean. The ocean surface roughness is a function of the near-instantaneous wind field. The surface wind generate a spectrum of capillary and short gravity waves. For a given wind direction in relation to the satellite SAR viewing geometry, the mean wind speed at 10 m height above sea level is related to this wave spectrum. To reduce speckle error inherent in the SAR system, a grid cell size of 400 m by 400 m grid is used for the wind speed mapping.

Wind direction estimation from SAR streak directional analysis using two-dimensional Fast Fourier Transform (Gerling 1986) is available in the software by (Furevik & Espedal 2002). Streaks in SAR images are associated with Langmuir cells and boundary layer rolls.

3. The data set

ERS-2 SAR scenes are collected between May 1999 and January 2004 from the Horns Rev site in the North Sea. In November 2001 construction activities began, and the image data then may be disturbed by these activities and are not included in the general study of the wind climate at Horns Rev. It is important to select only observations without any disturbances when the major aim is to verify the applicability of the CMOD4 algorithm for the site of investigation. At Horns Rev meteorological observations are collected at a tall meteorological mast located 14 km offshore and owned and managed by Elsam Engineering. The data are kindly made available for the study. Further details on the meteorological data are available by (Sommer 2003). The processing of the met-data is described in (Hasager et al. 2004). Most importantly, the observations are averaged into hourly mean values at the time of the satellite overpasses and corrected for sea level changes. Observations from 4 heights (15, 30, 45 and 62 m) are extrapolated by the neutral log-wind profile to 10 m height. This is the height corresponding to SAR satellite-based wind speed maps.

4. Results

The result of comparing CMOD4 to *in-situ* observations from the met-mast is described in (Hasager et al. 2004). It was tested to use the *in-situ* wind direction as *a priori* information to CMOD4. It was also tested to use wind direction retrieved from analysis of streaks in the SAR images. The *in-situ* wind direction seems to provide the best estimate as the standard error from linear regression between *in-situ* wind speed and SAR-retrieved wind speed was the lowest (around 0.9 ms^{-1}).

Mean ocean wind speed maps at the Horns Rev site separated into onshore and offshore flow condition are calculated based on 20 and 16 SAR scenes, respectively. *In-situ* wind direction is used as input to CMOD4. The so-called wind index defined as SAR mean wind speed normalized with *in-situ* mean wind speed are shown in figure 1.

A raw ERS-2 SAR scene is shown in figure 2, and here the wind farm is clearly visible. It is the 80 small white dots in a trapezoid-shaped outlay. On this day (July 30th, 2002) the wind was easterly around 7 ms^{-1} but no wake behind the turbines is found as the wind farm was still in the construction phase and the turbines not operating.

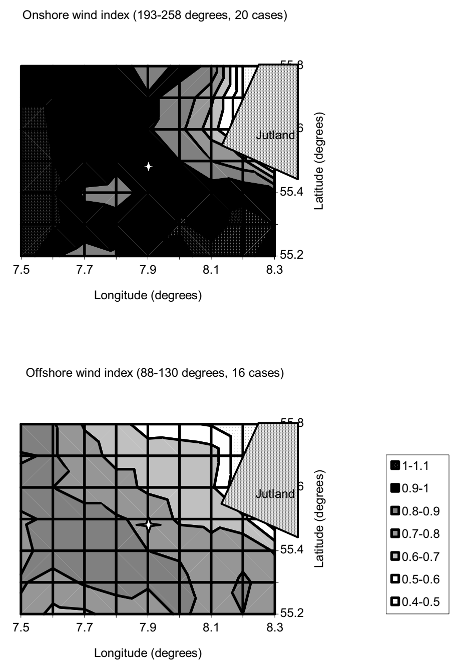

Figure 1. Regional wind index map for onshore conditions (upper panel) and offshore conditions (lower panel). The star indicates the met-mast.

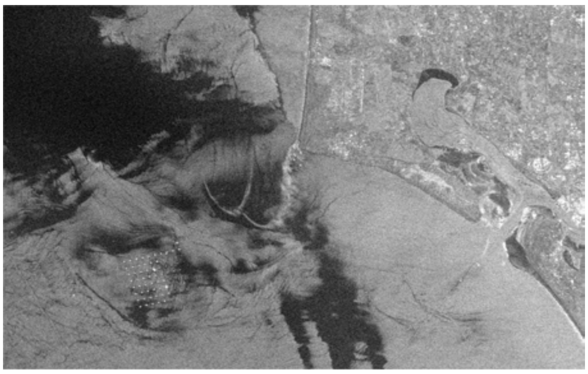

Figure 2. ERS-2 SAR scene from RAPIDS (http://www.rapids.nl) showing Horns Rev wind farm.

5. Discussion

The advantage of using satellite-based ocean wind mapping is that it is possible to provide spatial wind information rather than point observations as from a met-mast. The limitation of SAR-based wind mapping is the poorer absolute accuracy (around 1 to 2 ms^{-1}) compared to classical wind observations. The relative accuracy in SAR-based wind mapping is around $0.6ms^{-1}$. This is a limitation of the system due to speckle noise.

The wind index maps show that for onshore conditions the SAR wind speed is approximately the same as the *in-situ* wind speed. The wind index is between 0.9 and 1.1, i.e. slightly below or above the *in-situ* data. Only close to the coastline is a reduction in wind speed found. For offshore cases the wind index is always below 0.9 and near the met-mast the index ranges between 0.7 and 0.8. Closer to the coastline a further reduction in wind speed is found. This is anticipated as it is well-known that the wind speed is lower near the coast and gradually increases offshore. The decrease in wind speed is faster for onshore flow that offshore flow according to figure 1. These observations may be relevant for verification of modeled winds in the coastal zone.

A discussion of the applicability of the CMOD4 algorithm in the coastal zone is also relevant. For onshore cases the SAR wind maps compare very well to *in-situ* data, whereas a negative bias in the SAR wind maps is found for offshore flow. It may be that the ocean surface roughness (wave spectrum of capillary and short gravity waves) is not in equilibrium with the winds observed at the met-mast for offshore flow but only for onshore.

The Horns Rev wind farm is in operation and a series of ERS-2 SAR scenes are received from ESA for an investigation of the wake effect. It is found that the mean wind is reduced behind the wind farm and the observations compare reasonably to wake models. The wake effect is characterized by a lower mean wind speed downwind of the wind farm compared to the upwind conditions as the wind farm. The results are preliminary.

6. Conclusion

Satellite SAR observations can be used to assess the mean wind climate in a coastal region. Differences between onshore and offshore mean flow patterns are identified. There is a high spatial gradient for onshore flow (quick slow down just upwind of the coastline) and a moderate gradient for offshore flow (moderate speed-up as the wind moves from land to sea). Wake effects can clearly be identified in ERS-2 SAR satellite scenes.

7. Acknowledgements

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