European wind resource mapping by satellite images

Hasager, Charlotte Bay; Badger, Merete; Pena Diaz, Alfredo; Hahmann, Andrea N.; Badger, Jake; Karagali, Ioanna

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Charlotte Hasager, Merete Badger, Alfredo Peña, Andrea Hahmann, Jake Badger, Ioanna Karagali

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DTU Wind Energy
Department of Wind Energy
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Offshore wind energy perspectives

• By the end of July 2015 a European total of 3,072 offshore turbines are installed and connected to the grid, totaling a cumulative production capacity of 10 GW.

• The European Wind Energy Association has identified 26 GW of consented offshore wind farms in Europe and future plans for offshore wind farms totaling more than 98 GW.

➢ China (10 GW plan)
➢ Japan (1.45 GW plan investigation)
➢ South Korea (4.5 GW plans)
➢ Taiwan (600 MW by 2020)
➢ USA (according to the US Department of Energy 22 GW can come from offshore by 2030)

Sources: www.ewea.org and www.gwec.net
North Sea offshore wind farms map

Source: C4Offshore

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Motivation for satellite data

• Rapid growth in offshore wind energy

• For a decrease in uncertainty on the predicted mean wind speed at hub height of 0.1 m·s\(^{-1}\) there is an estimated saving worth around £10 million per year for 25 years for a large offshore wind farm project according to industry experts\(^1\)

• Installation of met-masts, floating lidar and lidar on platforms costly

• Meteorological modelling possible accurate around 5%

• Satellite data is on the shelf. Desk-top work is fast but it needs experts.

\(^1\)Hasager et al. 2013, Hub Height Ocean Winds over the North Sea Observed by the NORSEWInD Lidar Array: Measuring Techniques, Quality Control and Data Management, *Remote Sensing* 2013, 5(9), 4280-4303; doi:[10.3390/rs5094280](https://doi.org/10.3390/rs5094280)
Ocean winds from satellites

Radiometers (SSM/I)

Scatterometers (QuikScat)

Synthetic Aperture Radar (Envisat ASAR)
# Ocean wind fields from satellites

<table>
<thead>
<tr>
<th>Retrieved parameters</th>
<th>Radiometer</th>
<th>Scatterometer</th>
<th>Synthetic Aperture Radar (SAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wind speed</td>
<td>Wind speed and direction</td>
<td>Wind speed</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>$0.25^\circ$ lat/lon</td>
<td>$0.25^\circ$ lat/lon</td>
<td>$500$ m</td>
</tr>
<tr>
<td>Spatial coverage</td>
<td>Global</td>
<td>Global</td>
<td>Selected areas</td>
</tr>
<tr>
<td>Coastal mask</td>
<td>Cover open oceans only</td>
<td>Up to $70$ km from coastline</td>
<td>None</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>$4-6$ times per day</td>
<td>Twice daily</td>
<td>Variable – less than one per day</td>
</tr>
<tr>
<td>Temporal coverage</td>
<td>Systematically since 1987</td>
<td>Systematically since 1991</td>
<td>ScanSAR since 1995</td>
</tr>
<tr>
<td>Rain sensitivity</td>
<td>High (rain flags)</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
The SAR data archive at DTU Wind Energy

~15,000 ENVISAT ASAR scenes from ESA (2002-2011)

~10,000 Sentinel-1 scenes from ESA (2014 -> )
The New European Wind Atlas
SAR image coverage

Images frames over a given site have different spatial coverage and orientation
SAR image characteristics

- Image calibration is necessary
- Incidence angle dependency must be accounted for
- Projection to a geographical coordinate system is needed
SAR wind retrieval

Original brightness image

Wind speed map

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From wind to radar backscatter

Bragg / resonance scattering:

\[ \lambda_{Bragg} = \frac{\lambda_{radar}}{2 \sin \theta} \]

\[ \theta = \text{incidence angle (15-70°)} \]
\[ \lambda = \text{wave length (cm scale)} \]

Bragg waves ride on longer-period waves
Random variation occurs (speckle) → Pixel averaging is necessary
Empirical geophysical model functions (GMF):

\[ NRCS = U^{\gamma(\theta)} A(\theta) \left[ 1 + B(\theta,U) \cos \phi + C(\theta,U) \cos 2\phi \right] \]

- \( NRCS \) = radar backscatter [dB]
- \( U \) = wind speed at 10 m [m/s]
- \( \theta \) = incidence angle [degrees]
- \( \phi \) = relative wind direction [degrees]

Model functions apply to open oceans and neutral atmospheric stability.
The nominal accuracy on wind speed is +/- 2 m/s.
Accuracy of the wind direction input

Horns Rev M2

\[ R^2 = 0.91 \]
\[ \text{RMSE} = 27.5 \]
\[ y = 0.97x + 5.20 \]
\[ N = 145 \]

Egmond aan Zee

\[ R^2 = 0.94 \]
\[ \text{RMSE} = 23.4 \]
\[ y = 0.93x + 17.8 \]
\[ N = 195 \]
Accuracy of the wind speed retrieval at 10 m

Horns Rev M2

\[ R^2 = 0.88 \]
\[ \text{RMSE} = 1.26 \]
\[ y = 0.98x - 0.14 \]
\[ N = 149 \]

Egmond aan Zee

\[ R^2 = 0.81 \]
\[ \text{RMSE} = 1.47 \]
\[ y = 0.91x + 0.42 \]
\[ N = 197 \]
Wind field retrieved from Sentinel-1a, 25 April 2015 at 05:40 UTC
Wind fields retrieved from Sentinel-1a over Jeju Island, South Korea
DTU Wind energy processing chain

1. **Download and pre-processing**
   - APL/NOAA SAR Wind Retrieval Software

2. **Long-term storage**
   - SAR
   - GFS
   - Ice

3. **Wind retrieval**
   - Wind maps (netCDF)

4. **Long-term storage**
   - S-WAsP

5. **Data base**
   - Database (MySQL)

6. **Wind resource maps**
   - S-WAsP
   - (ascii, netCDF)

DTU’s add-on for wind resource assessment
Wind resource mapping
Baltic Sea existing and planned offshore wind farms

Model validation

Wind atlas output and verification

Mean wind speed from the IRENA Global Wind Atlas

Mean wind speed from Envisat ASAR
Wind farm wakes

Wind farm wake from SAR

Radarsat-2, 2013/07/01 17:33

Image courtesy CLS, France
Offshore wind farm wake


DTU Wind Energy, Technical University of Denmark
Motivation for lifting winds to hub-height

(from the IPCC April 2012 report on mitigating climate change)
Wind profile equation

The equation to estimate the mean wind speed at height above the ground is:

\[ u_z = \frac{u_*}{\kappa} \left[ \ln \left( \frac{z - d}{z_0} \right) + \psi(z, z_0, L) \right] \]
Long-term histograms of stability

Mast observations

WRF model data

Long-term stability correction from WRF


*DTU Wind Energy, Technical University of Denmark*
Friction velocity from the satellite \( \text{ENW} \):

\[
\begin{align*}
    u_{10 \text{SAR}} &= \frac{u^*_{\text{SAR}}}{\kappa} \ln \left( \frac{10}{z_0} \right) \\
    \text{where} & \quad z_0 = \alpha_c \frac{u^2_{\text{SAR}}}{g}
\end{align*}
\]
Frequency distribution of $1/L$

$$L_{WRF} = -\frac{UST^3 T2}{g \kappa HFX}$$

**Baltic Sea: 6 years of WRF**  
**South China Sea: 3 years of WRF**

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Long-term stability correction profiles

Baltic Sea

South China Sea
Long-term stability correction

Baltic Sea

South China Sea
Mean wind speed at 100 m

Baltic Sea

South China Sea

Extrapolating satellite winds to turbine operating heights. *JAMC* (in review)
Summary of SAR advantages and limitations

Advantages:

• A high spatial resolution (sufficient to reveal meso-scale wind phenomena)

• Coastal seas are covered (still the most important for offshore wind energy applications)

Limitations:

• Wind retrievals are valid for the height 10 m

• A limited number of samples exists for statistical analyses
Acknowledgements

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Remote Sensing Systems (RSS)

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The Johns Hopkins University, Applied Physics Laboratory (JHU/APL)
Collecte Localisation Satellites (CLS)

**Mast observations:**

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