MARCH 5–6, 2019
EMBASSY SUITES BY HILTON, ALEXANDRIA, VA

Industry Requirements for Offshore Wind Information

What metocean information does industry need for assessment, wind plant design, development, and operations?

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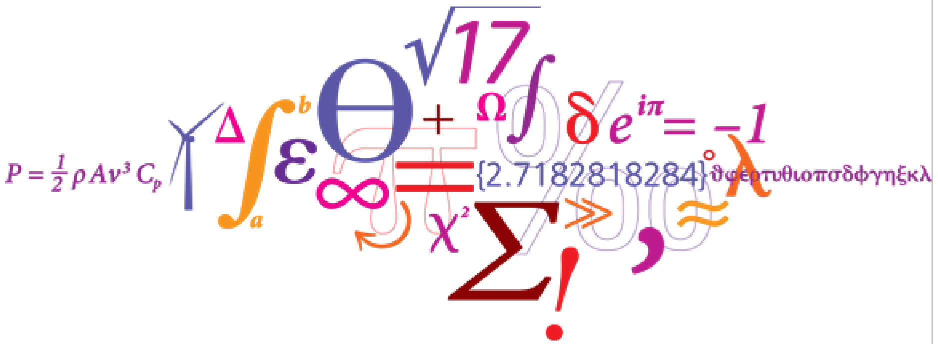


Outline

- Offshore wind farms wakes and clusters
- Wind-wave coupled modelling
- Leading edge erosion
- Satellite Synthetic Aperture Radar (SAR) wind maps
- Coastal wind speed gradient influences power production
- Offshore wind ressource
- Conclusions

Offshore wind farm wakes and clusters

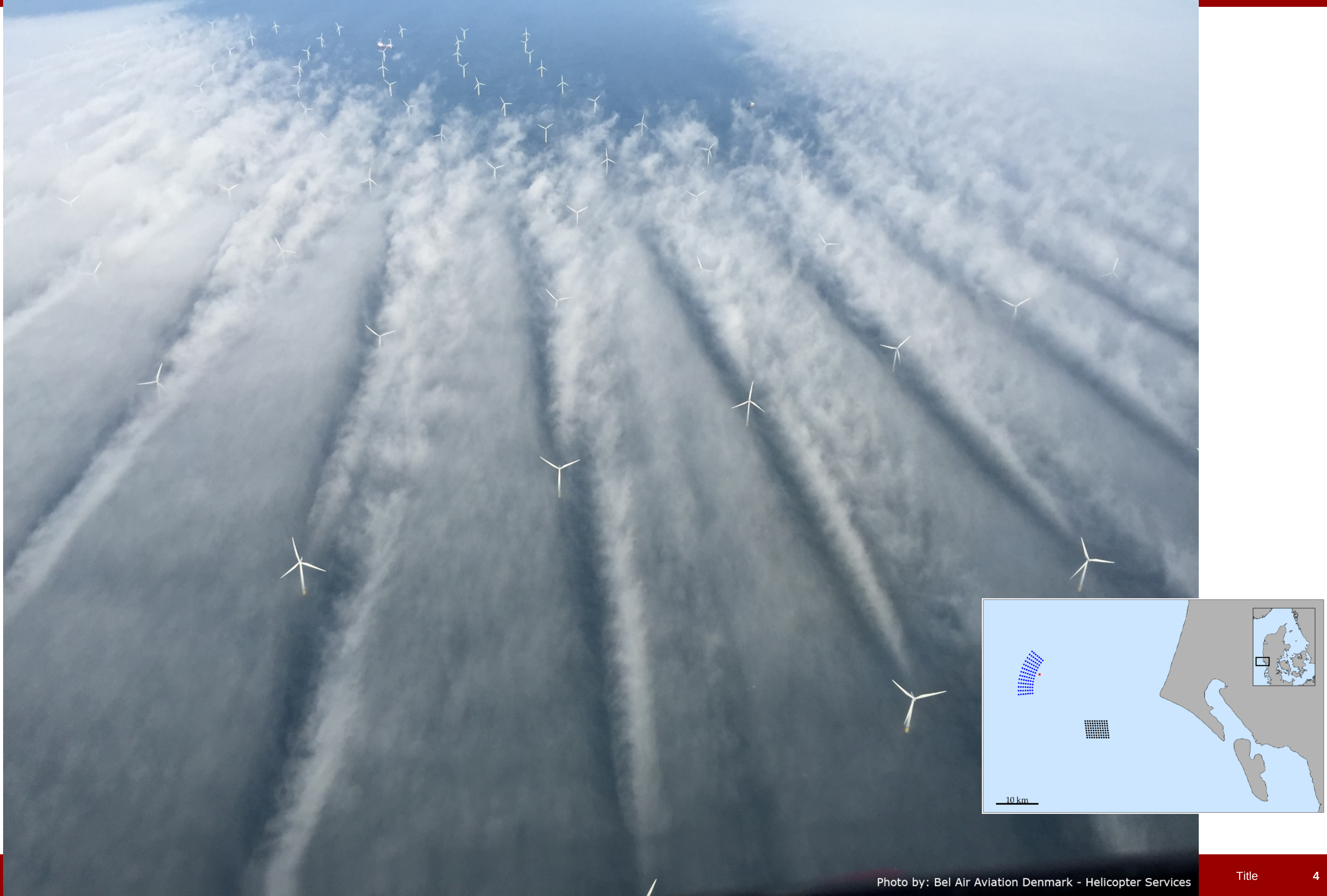
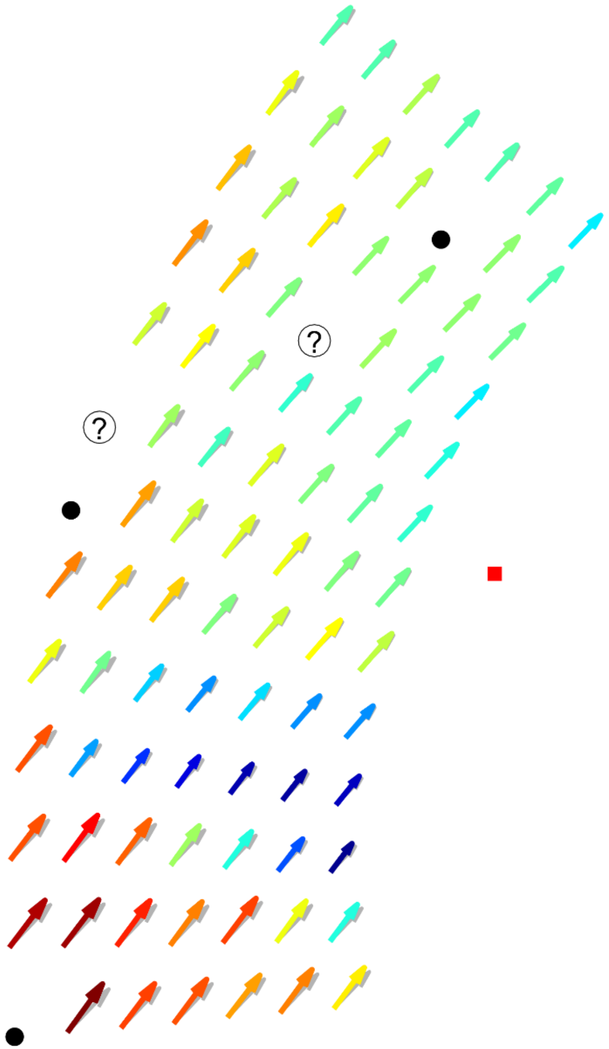


Photo by: Bel Air Aviation Denmark - Helicopter Services

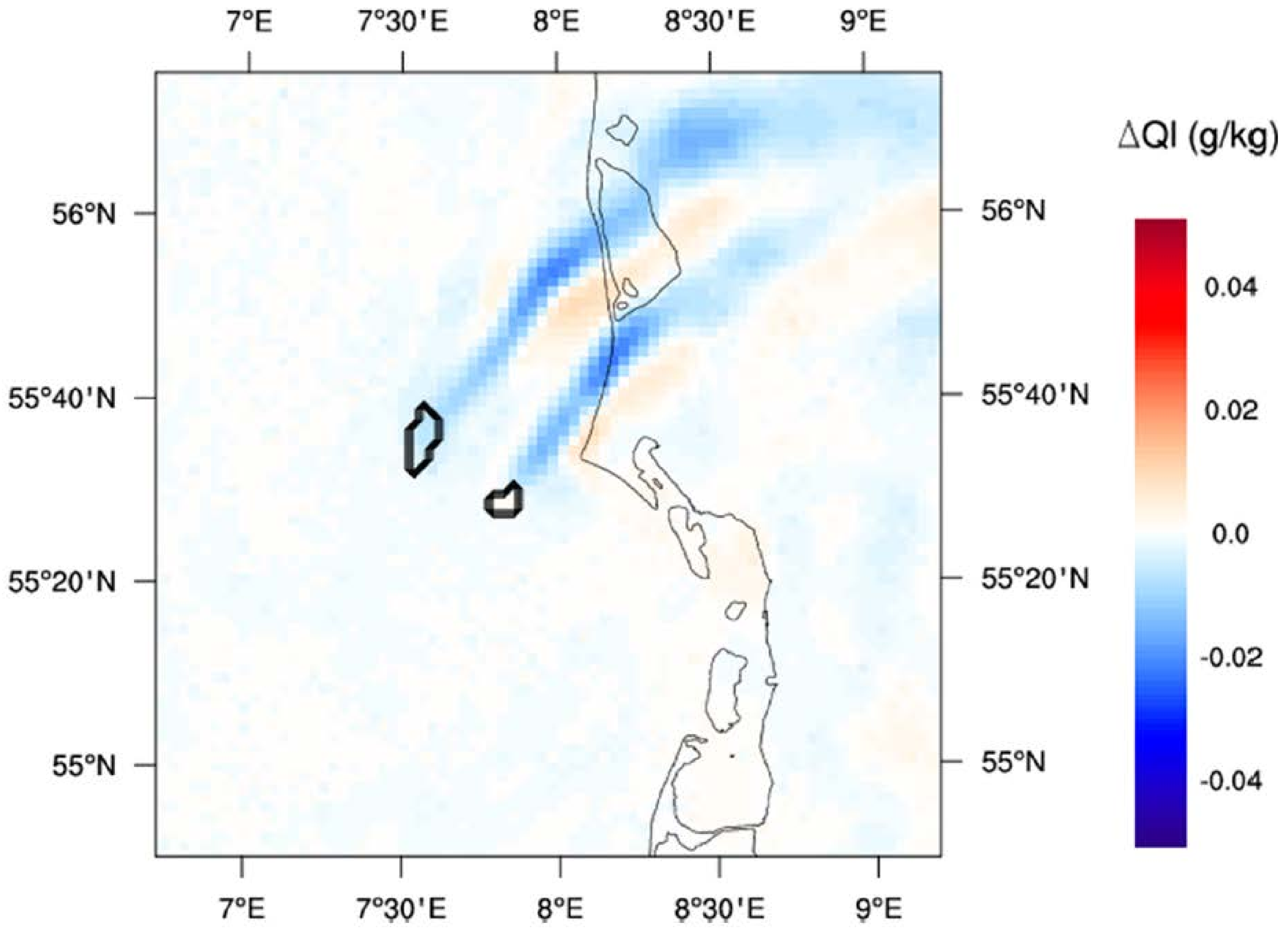
Wind speed pattern



Acknowledgement to Ørsted A/S.

Hasager, C.B., Nygaard, N. G., Volker, P. J. H., Karagali, I., Andersen, S. J., Badger, J. (2017): Wind Farm Wake: The 2016 Horns Rev Photo Case *Energies 10*(3), 317

Why did the fog clear?

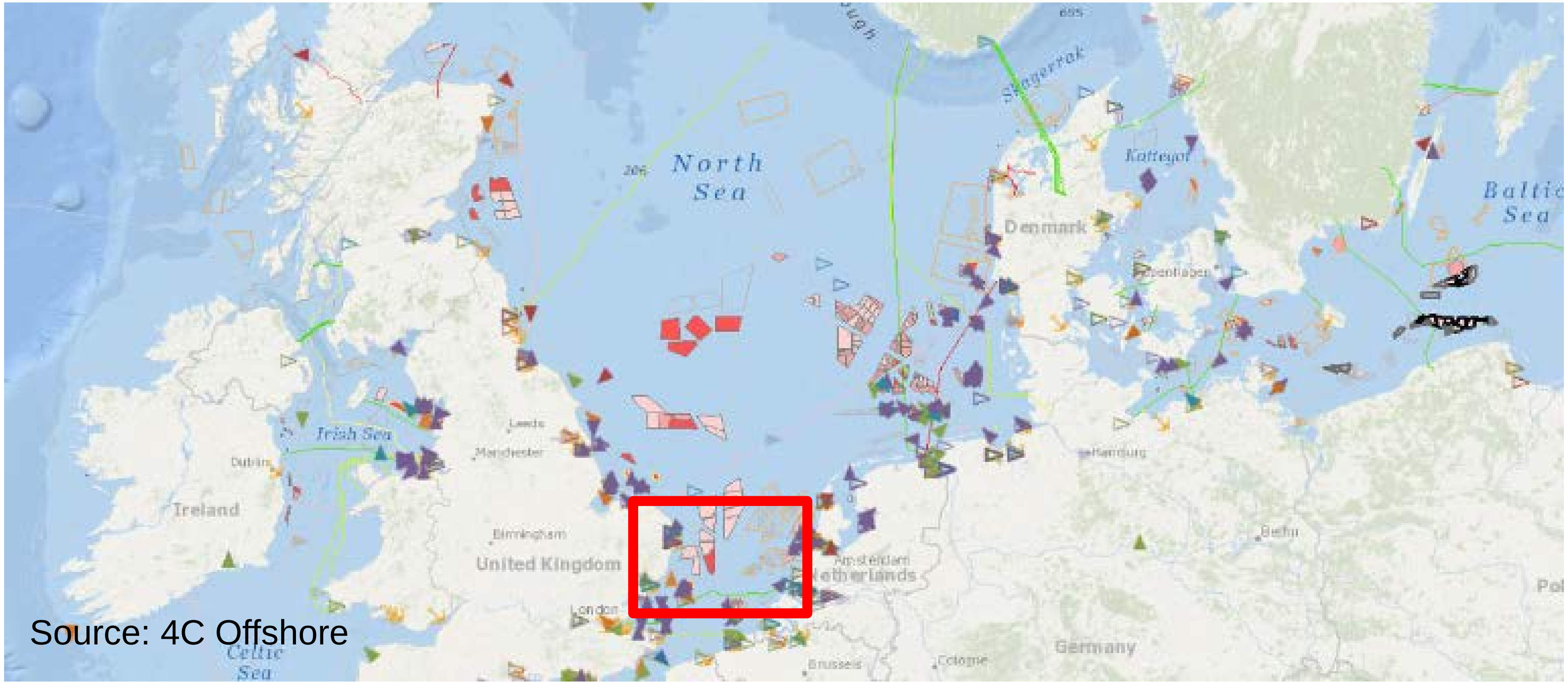


Difference in liquid water content due to wind farms

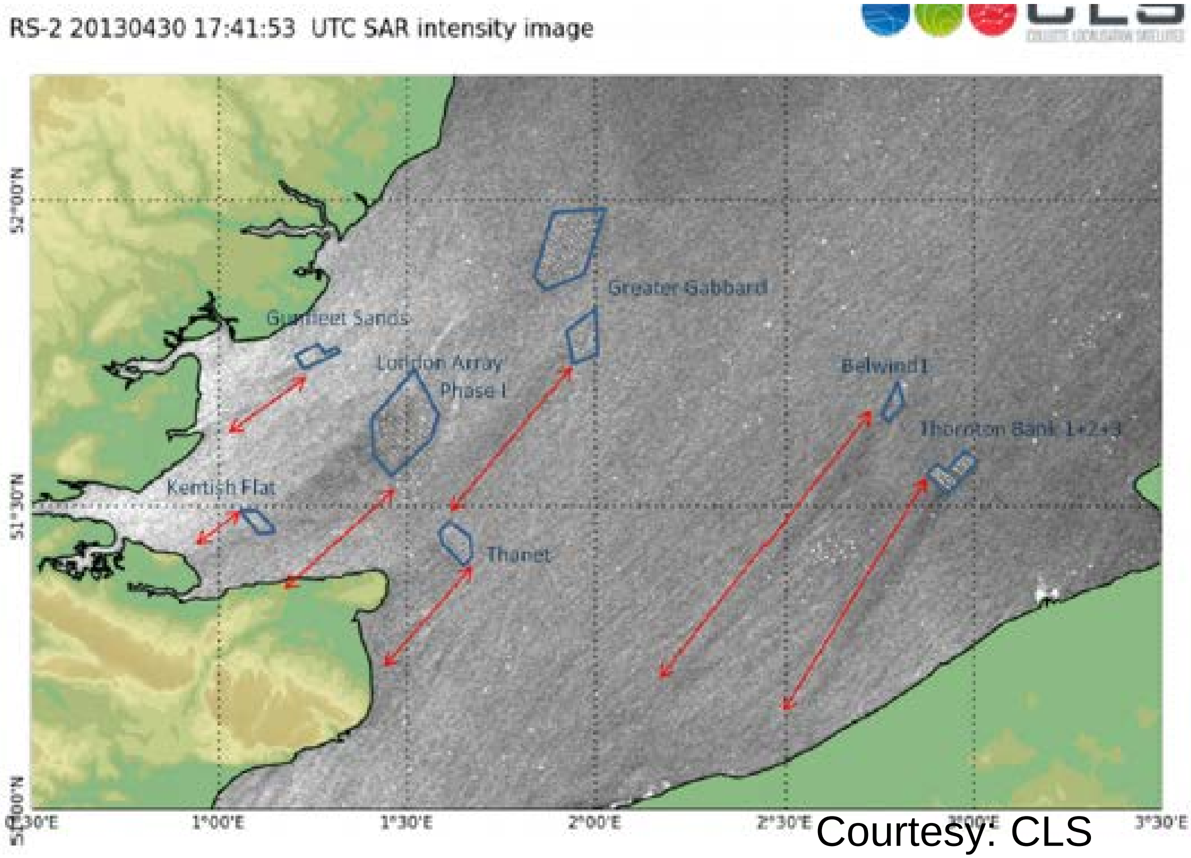
WRF model simulations with and without wind farm shows dryer air at hub height behind wind farms

Hasager, C.B., Nygaard, N. G., Volker, P. J. H., Karagali, I., Andersen, S. J., Badger, J. (2017): Wind Farm Wake: The 2016 Horns Rev Photo Case *Energies 10*(3), 317

Northern European offshore wind farms



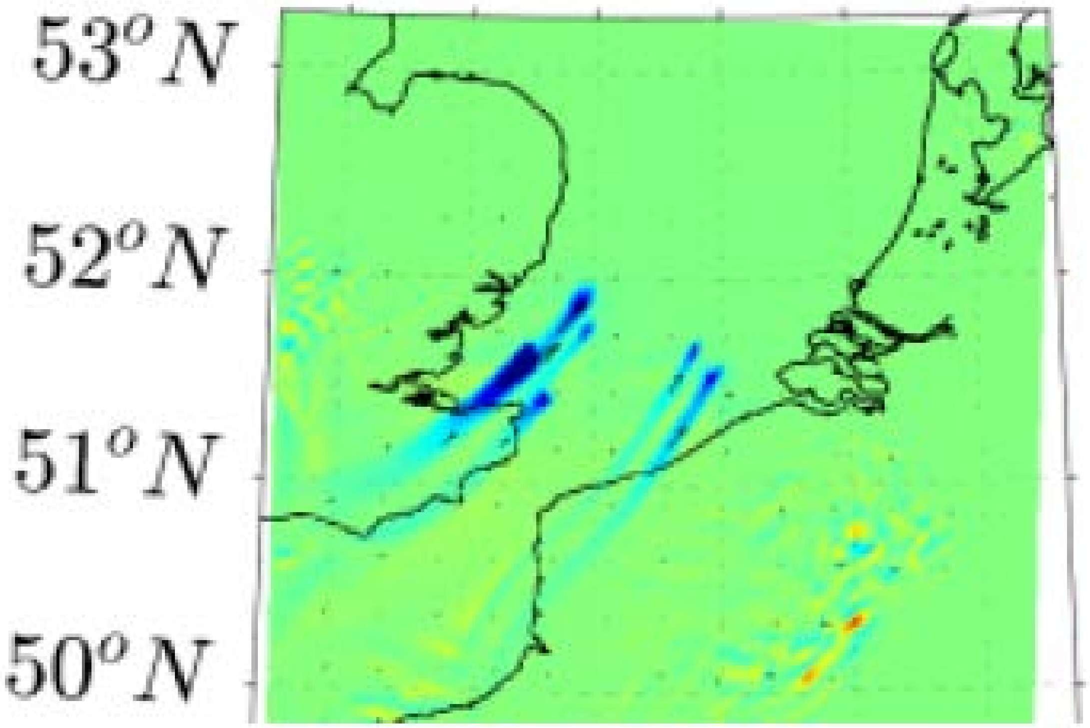
Wind farm cluster effects



Satellite SAR shows wind farm wakes

RADARSAT-2 from Data and Products © MacDonald, Dettewiler and Associates Ltd

WRF-EWP minus WRF

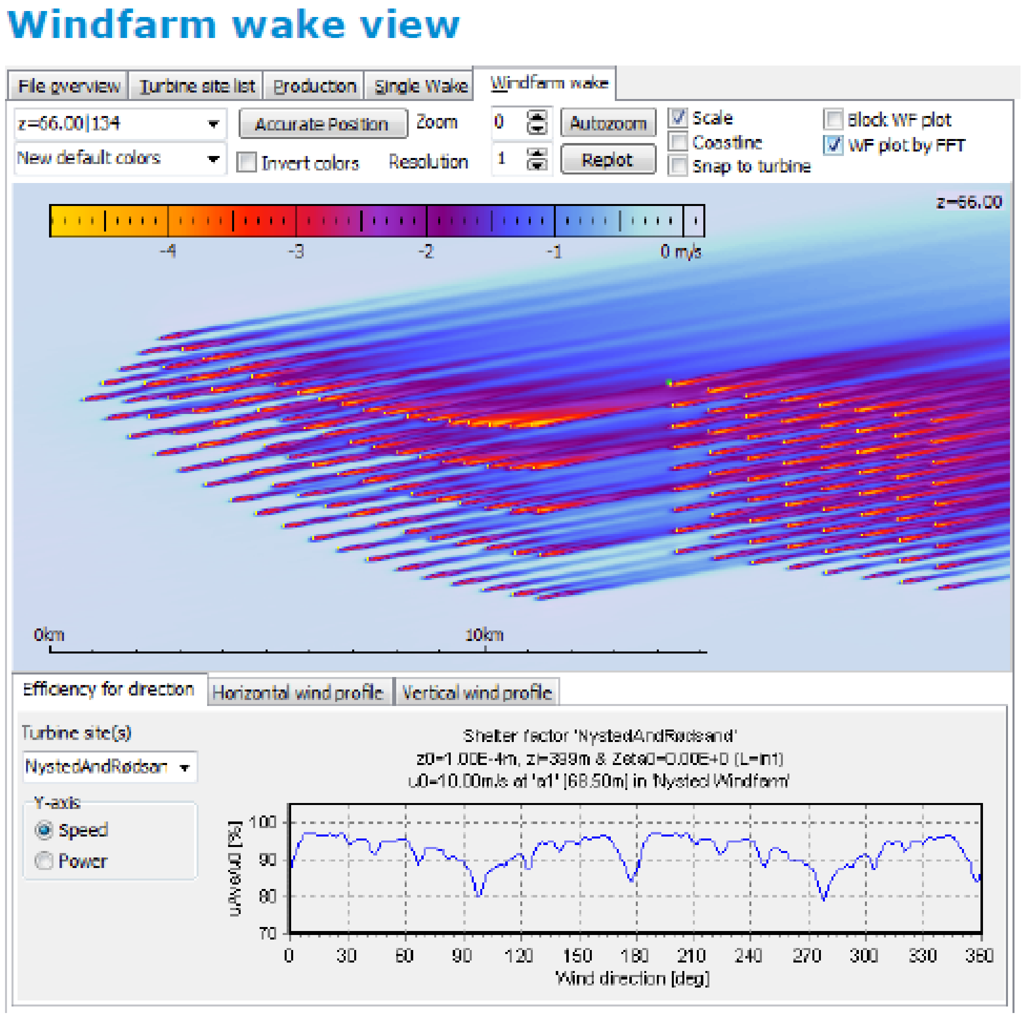


WRF shows wind farm wakes

Courtesy: Du, Volker and Larsén (2018): OffshoreWake project report WP3 (the simulation is done using COAWST modeling system, mostly by Du J)

Hasager, C. B., Vincent, P., Badger, J., Badger, M., Di Bella, A., Pena Diaz, A., ... Volker, P. (2015). Using Satellite SAR to Characterize the Wind Flow around Offshore Wind Farms. Energies, 8(6), 5413-5439. DOI:10.3390/en8065413

FUGA : Wake model for large offshore wind farms



- Solves a linearized CFD model: Mixing length, k-ε or 'simple' ($\nu_t=\kappa u_* z$)
- Mixed-spectral formulation
- Massive use of look-up-tables (LUTs) and preLUTs (used to make LUTs)
- Superposition of wakes
- No numerical diffusion
- No spurious mean pressure gradient
- 100000 times faster than CFD

http://www.wasp.dk/fuga

Ott, S., & Nielsen, M. (2014). Developments of the offshore wind turbine wake model Fuga. DTU Wind Energy. DTU Wind Energy E, No. 0046

Wind wave coupled modelling

Wind-Wave-Wake coupled modelling and application

Write to: xgal@dtu.dk

Xiaoli G. Larsén, Jana Fishereit, Patrick Volker, Marc Imberger, Andrea Hahmann, Poul Sørensen, Jake Badger, Matti Koivisto, Kaushik Das, Petr Maule, J. Du

A fully-coupled modeling system for offshore applications that:

1) Takes into account of the dynamical relations between wind, wave, ocean and wind farm wakes (Fig. 1, Fig. 2)
2) Can be used for forecasting met-ocean conditions
3) Can be used for wind resource assessment with farm wake effect calculated
4) Can be used for offshore operation and maintenance
5) Can be used for obtaining design parameters, e.g. extreme wind and extreme wave (e.g. Fig. 3)

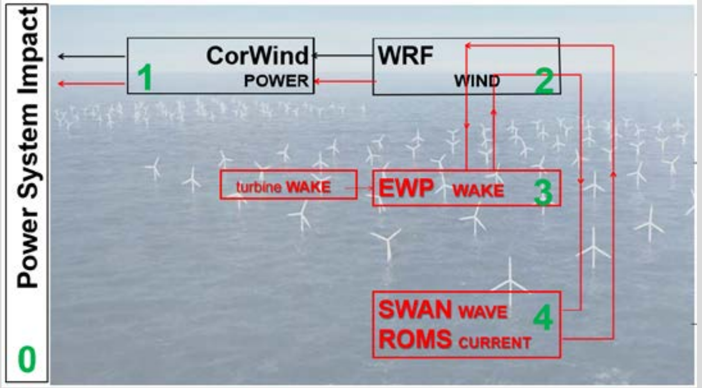


Fig. 1 The modeling system for offshore wind, coupling wind, wave and wakes and convert wind to power system

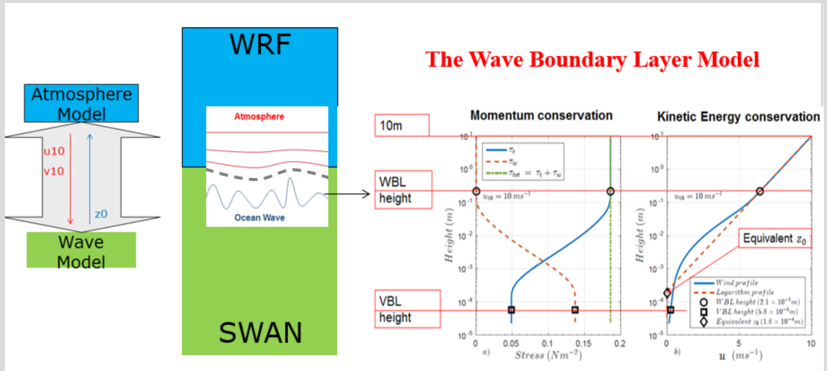


Fig. 2. WRF and SWAN are coupled through Wave Boundary Layer (WBL) Model that uses momentum conservation in WBL, avoiding parameterization of roughness length.

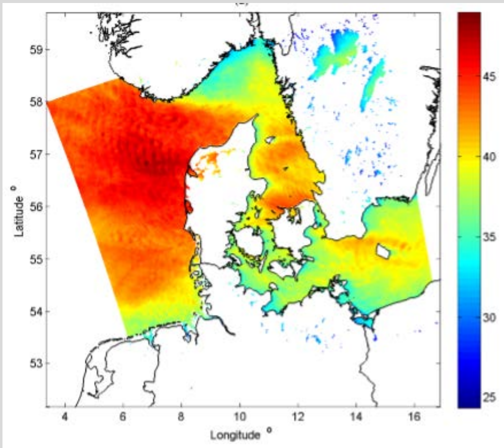
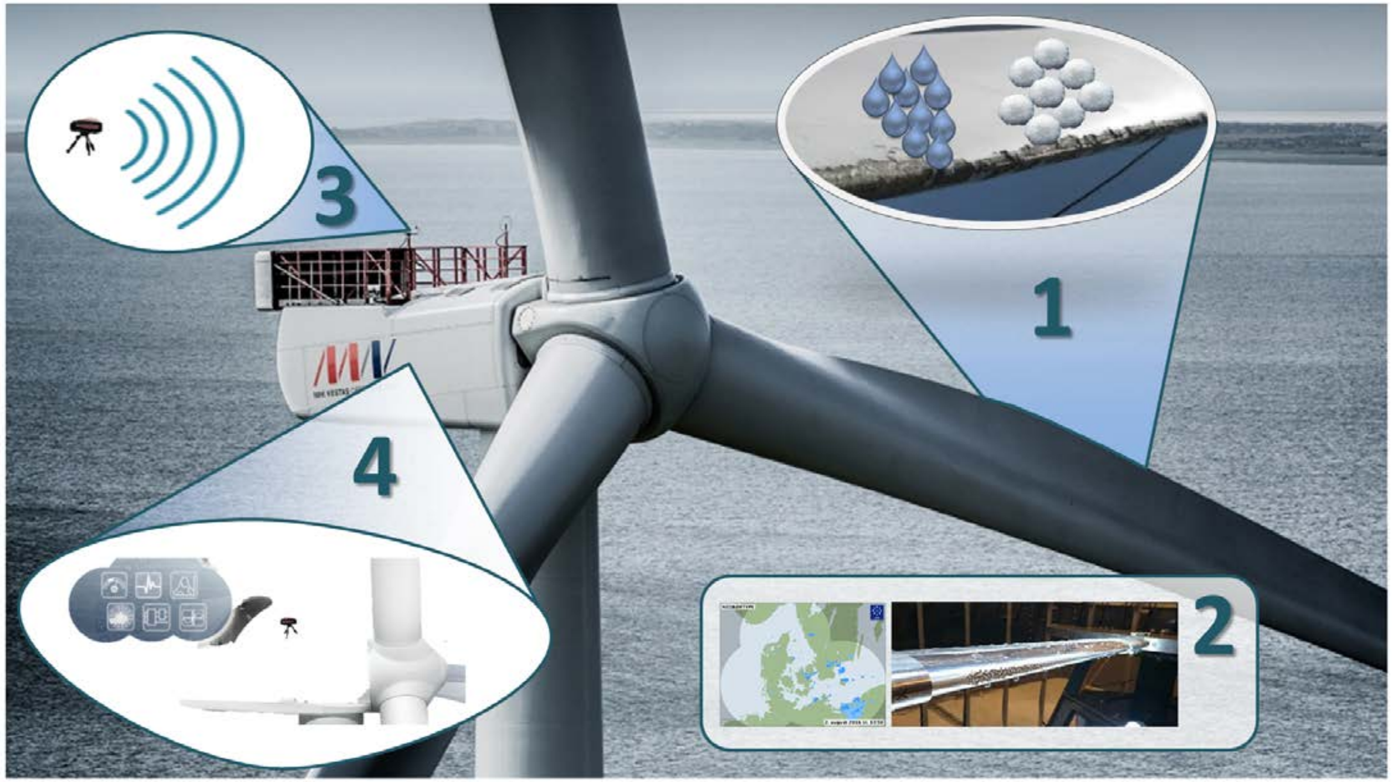


Fig. 3 The 50-year wind at 100 m

selected PUBLICATIONS:

Larsén et al. 2019: Estimation of offshore extreme wind from wind-wave coupled modeling, Wind Energy
Du et al. 2017: The use of a wave boundary layer model in SWAN. J. Geophys. Res.:Oceans.DOI: 10.1002/2016JC012104
Larsén et al. 2017: On the effect of wind on the wave field during the development of storm Britta. Ocean Dynamics,DOI 10.1007/s10236-017-1100-1
Volker et al. 2015: The explicit wake parameterization V1.0: a wind farm parameterization in the mesoscale model WRF. *Geosci. Model. Rev.* 8:3715-3731.

Leading edge erosion



1.	**Research hypothesis:** Erosion damage is mainly generated during heavy precipitation (big drops of rain or hail), which occurs in a very little fraction of the turbines operation time. By reducing the tip speed of the blades in these few hours a significant extension of the leading edge lifetime can be obtained with negligible loss of production.
2.	**Methodology:** Define rain and hail erosion classes to quantify leading edge blade in-field and in lab testing. Correlations between rain intensity, droplet size, impact speed, materials properties, etc. will be established.
3.	**Measurement Device:** Low-cost prototype for precipitation measurement on site and real time warning device enabling modern control of wind turbines.
4.	**Erosion safe mode:** A safe mode control based on the erosion classes to control the wind turbine, reducing the tip speed under severe conditions – preventing aerodynamic degradation and reducing maintenance costs.

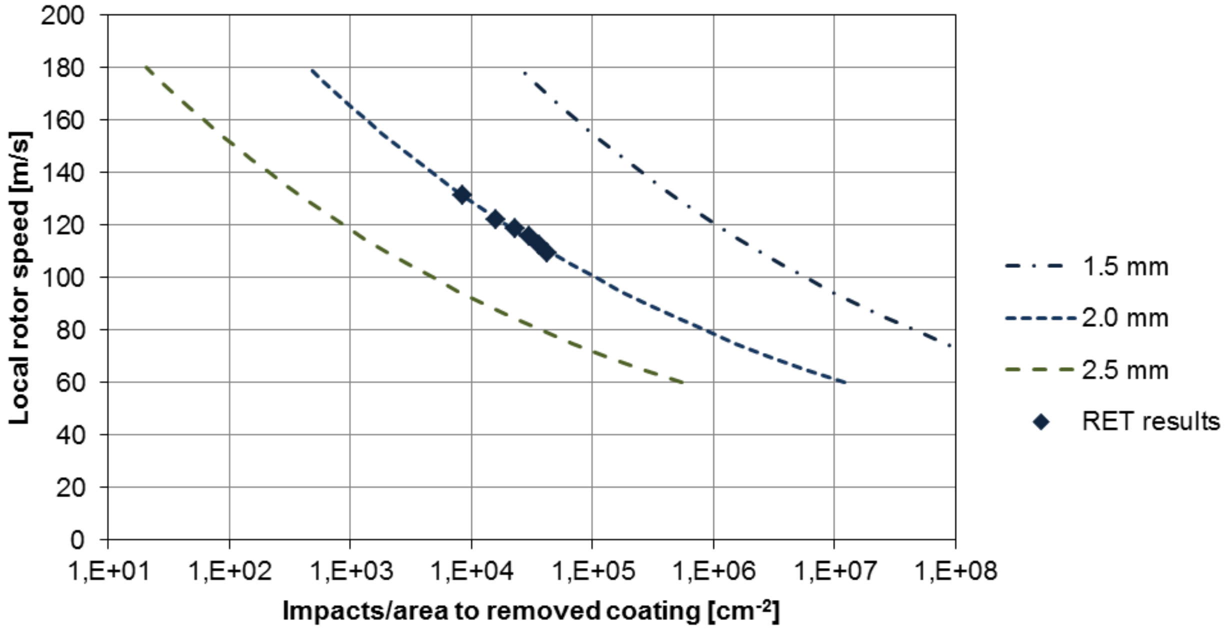
www.rain-erosion.dk

Rain Erosion Tester

Example of specimen

Bech, Hasager and Bak 2018 Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science,* https://doi.org/10.5194/wes-2017-62

Wöhler curves for droplet diameters of 1.5, 2.0 and 2.5 mm



Bech, Hasager and Bak 2018 Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science,* https://doi.org/10.5194/wes-2017-62

Control strategies

Apart from a reference case where it is assumed that there is no erosion, six different control strategies are investigated based on the model for expected lifetime for the blade leading edge:

- Control strategy 1 with expected life time of 1.6 years
- Control strategy 2 with expected life time of 10.4 years
- Control strategy 3 with expected life time of 24.4 years
- Control strategy 4 with expected life time of 53.9 years
- Control strategy 5 with expected life time of 106.5 years
- Control strategy 6 with expected life time of infinite many years

Bech, Hasager and Bak 2018 Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science,* https://doi.org/10.5194/wes-2017-62

Calculation of the life time of the blade leading edge with no reduction of the tip speed. Control strategy 1

Rain intensity [mm/hr]	Droplet size [mm]	Percent of time [%]	Hours pr year [hrs/year]	Blade tip speed [m/s]	Hours to failure [hrs]	Fraction of life spent pr year [%]
20	2.5	0.02	1.8	90	3.5	51
10	2.0	0.1	8.8	90	79	11
5	1.5	1	88	90	3606	2.4
2	1.0	3	263	90	745710	0.0
1	0.5	5	438	90	2830197826	0.0
				Sum of fractions [%]:		64
				Expected life [years]:		1.6

Bech, Hasager and Bak 2018 Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science*, https://doi.org/10.5194/wes-2017-62

Calculation of the life time of the blade leading edge with reduction of the tip speed to 70m/s and 80m/s, respectively: Control strategy 2

Rain intensity [mm/hr]	Droplet size [mm]	Percent of time [%]	Hours pr year [hrs/year]	Blade tip speed [m/s]	Hours to failure [hrs]	Fraction of life spent pr year [%]
20	2.5	0.02	1.8	70	46	3.8
10	2.0	0.1	8.8	80	263	3.3
5	1.5	1	88	90	3606	2.4
2	1.0	3	263	90	745710	0.0
1	0.5	5	438	90	2830197826	0.0
				Sum of fractions [%]:		9.6
				Expected life [years]:		10.4

Bech, Hasager and Bak 2018 Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science*, https://doi.org/10.5194/wes-2017-62

Cost of operation and maintenance

- Energy price:
  - 50 €/MWh
  - 250 €/MWh
- Inspection cost:
  - 500 €/rotor
  - 1500 €/rotor
- Repair cost
  - 10000 €/rotor
  - 20000 €/rotor

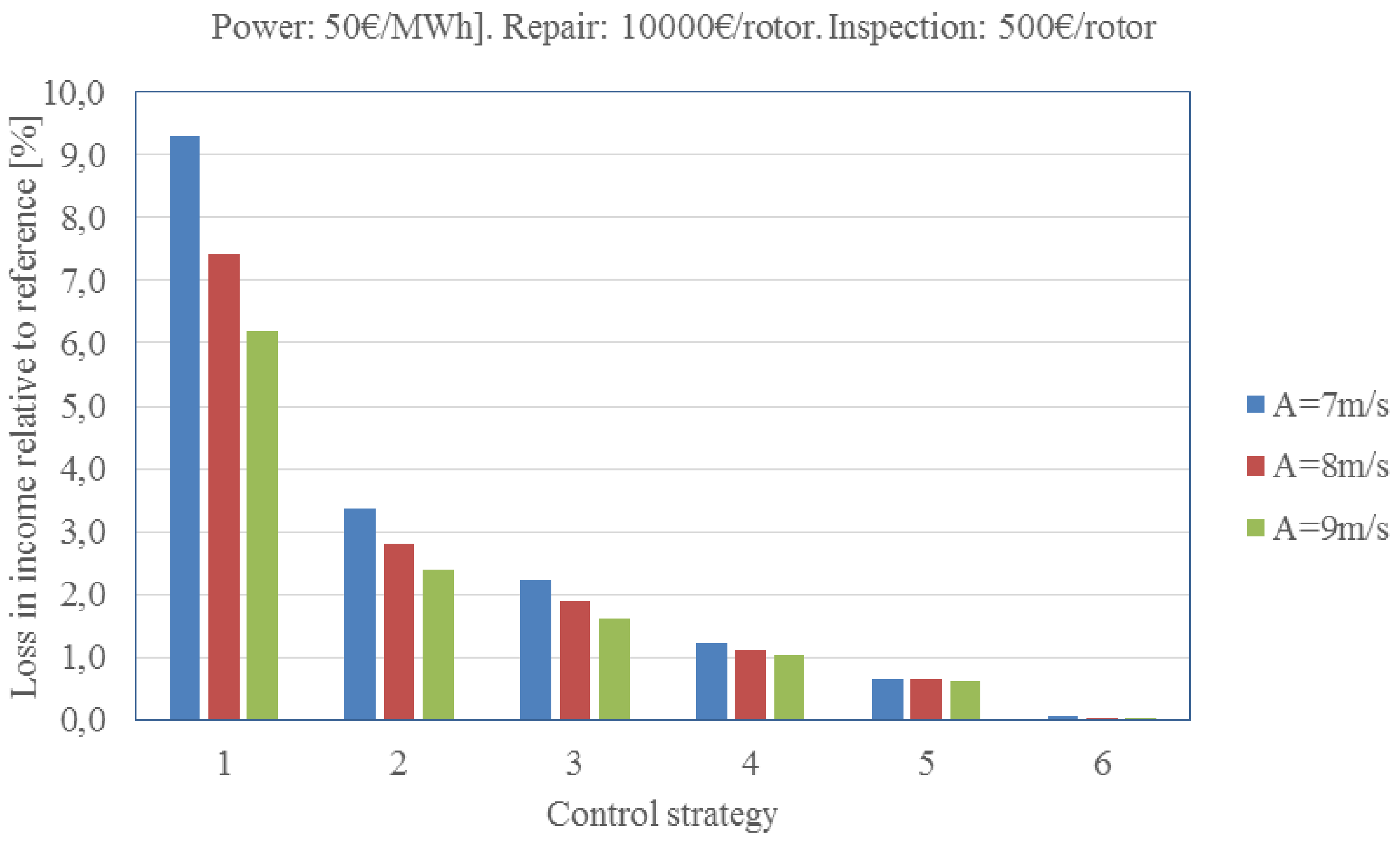
- Control strategy 1: 10 inspections and 9 repairs
- Control strategy 2: 10 inspections and 1 repairs
- Control strategy 3: 5 inspections and 0 repairs
- Control strategy 4: 5 inspections and 0 repairs
- Control strategy 5: 2 inspections and 0 repairs
- Control strategy 6: 2 inspections and 0 repairs

Stand still of 1 day inspected

Stand still of 2 days repaired

Bech, Hasager and Bak 2018 Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science*, https://doi.org/10.5194/wes-2017-62

Loss of income due to erosion, inspection and repair



Bech, Hasager and Bak 2018 Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. *Wind Energy Science,* https://doi.org/10.5194/wes-2017-62

Satellite SAR wind maps

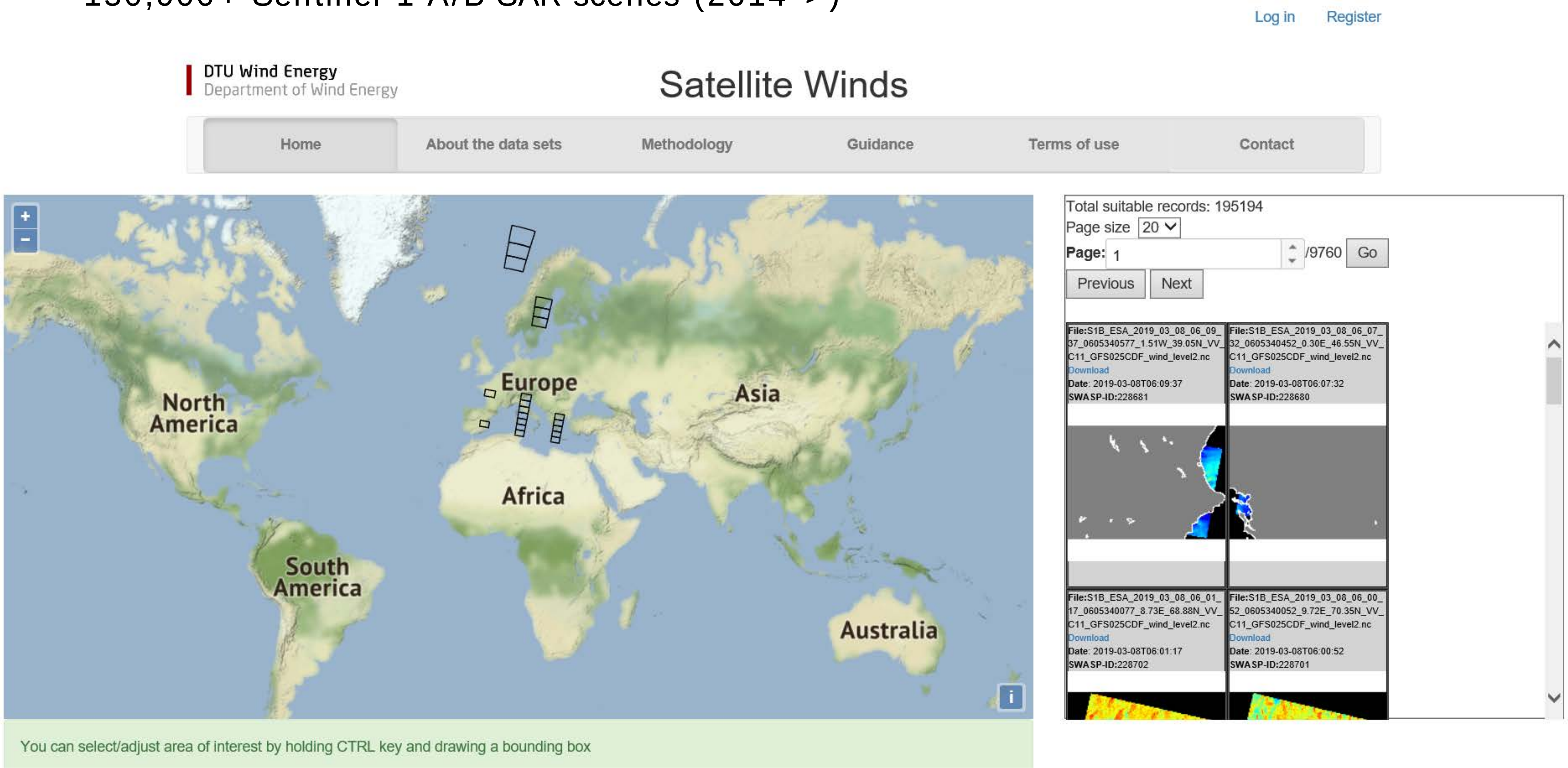
Coastal wind speed gradient and power production

Offshore wind resource

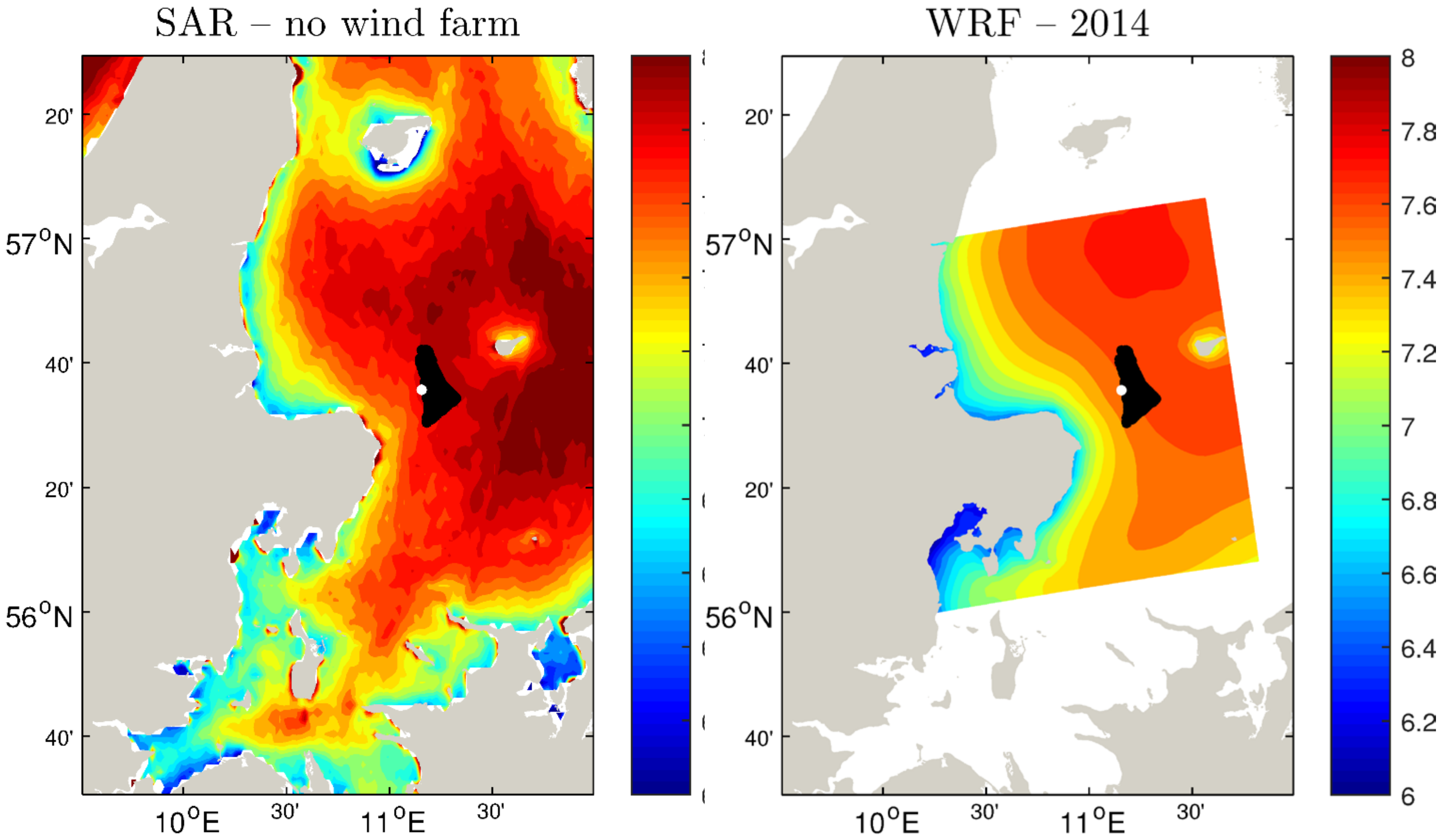
Satellite SAR wind data archive at DTU

- 30,000+ ENVISAT ASAR scenes (2002-2011)
- 150,000+ Sentinel-1 A/B SAR scenes (2014->)

https://satwinds.windenergy.dtu.dk/



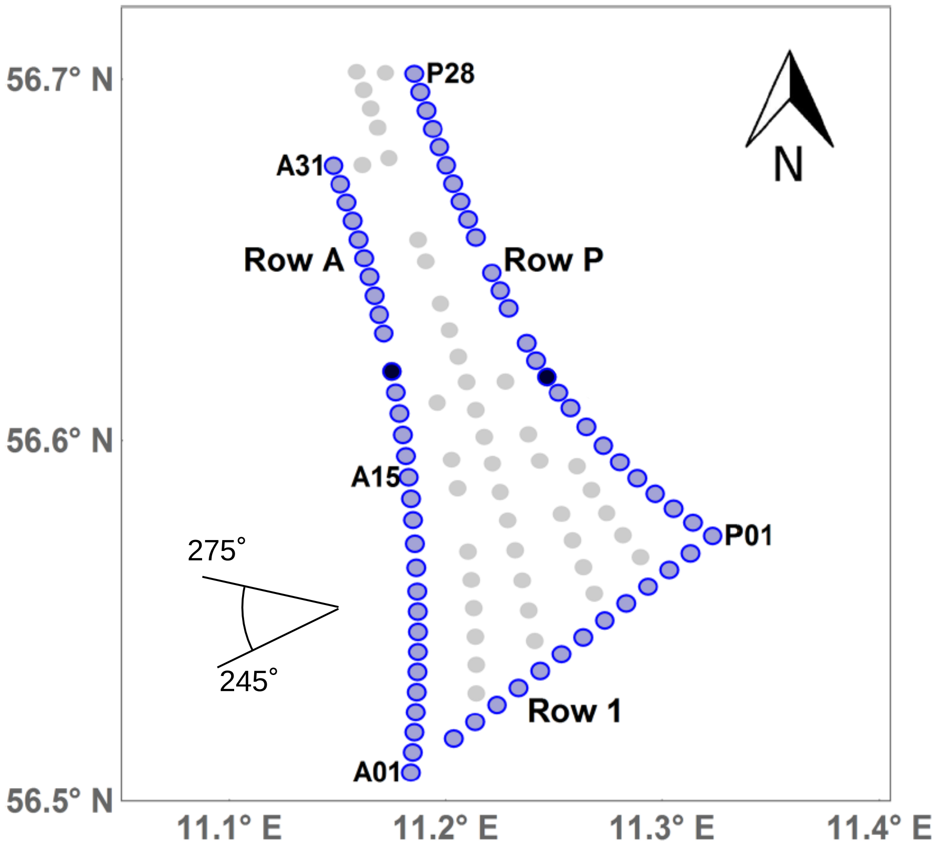
Kattegat Strait mean wind speed



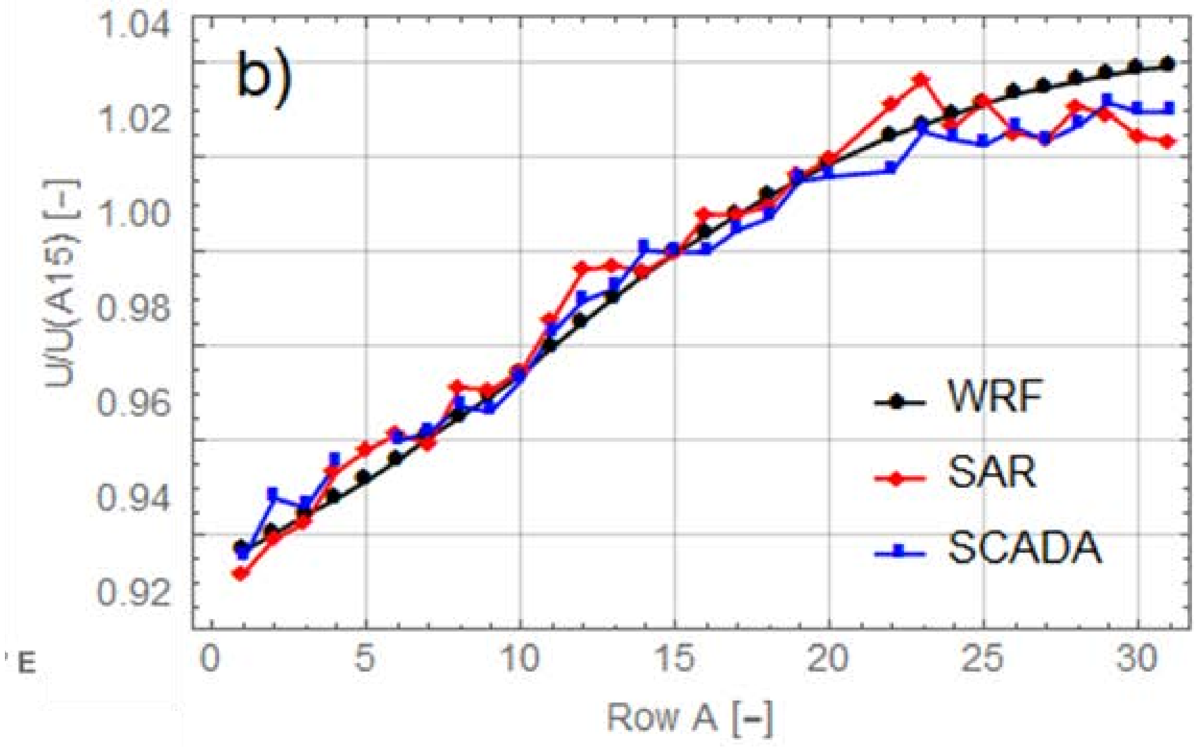
Peña, A & Hahmann, A. N. 2017, 30-year mesoscale model simulations for the “Noise from wind turbines and risk of cardiovascular disease” project. DTU Wind Energy E, vol. 0055

Ahsbahs, T., Badger, M., Volker, P., Hansen, K.S., Hasager, C.B. 2018 Applications of satellite winds for the offshore wind farm site Anholt. *Wind Energy Science* https://doi.org/10.5194/wes-2018-2

Anholt wind farm

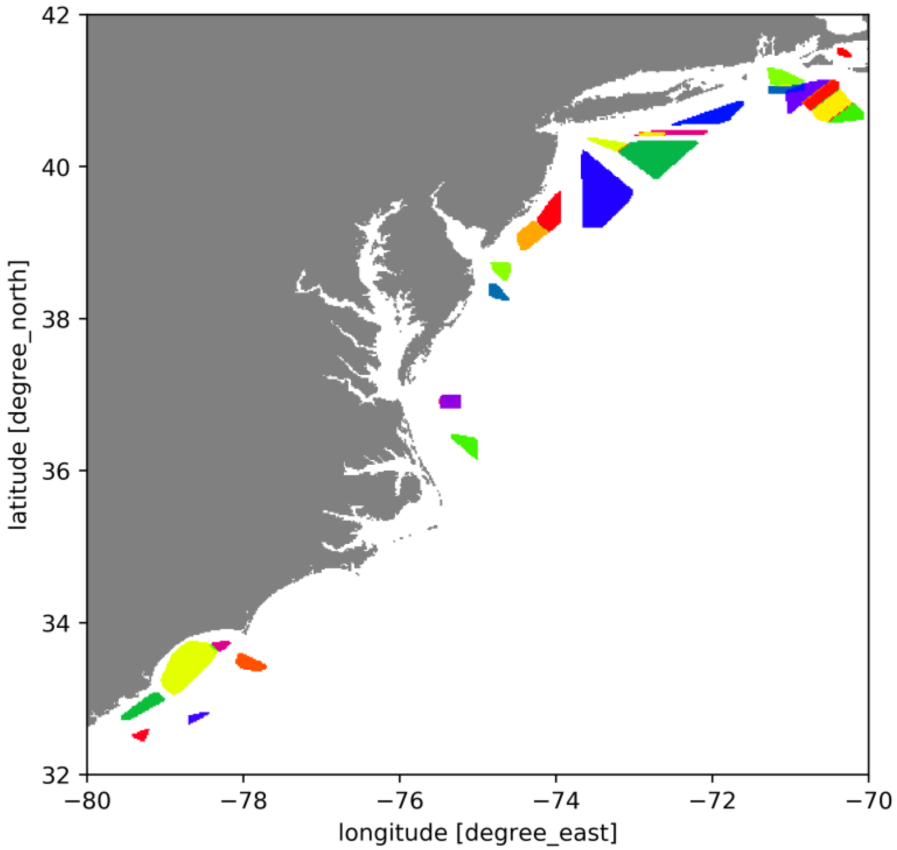


Mean wind speed normalized at turbine 15



Ahsbahs, T., Badger, M., Volker, P., Hansen, K.S., Hasager, C.B. 2018 Applications of satellite winds for the offshore wind farm site Anholt. *Wind Energy Science*
https://doi.org/10.5194/wes-2018-2

Potential wind farm locations US East Coast



25 designated areas

Satellite SAR mean wind speed map and comparison to WRF model mean wind speed was shown at the workshop.

The results are in preparation for final publication.

Please contact
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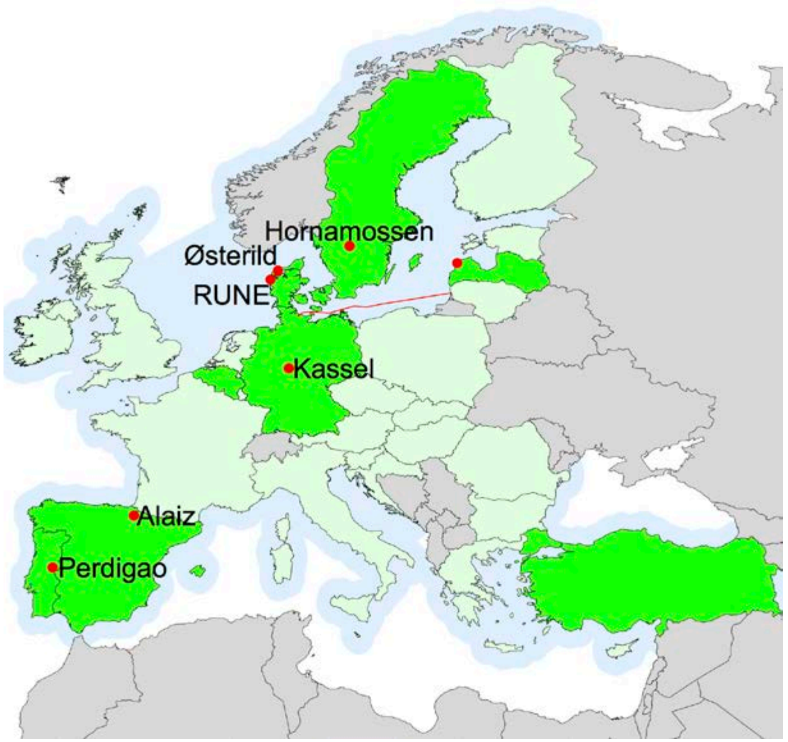
New European Wind Atlas

- Resource assessment & spatial planning
- Cover all EU member states & some Associated Countries
- Reduce overall uncertainties in determining wind conditions
- Offshore wind atlas extent: 100 km
  - Mesoscale models
  - Satellite winds
  - Experimental measurements

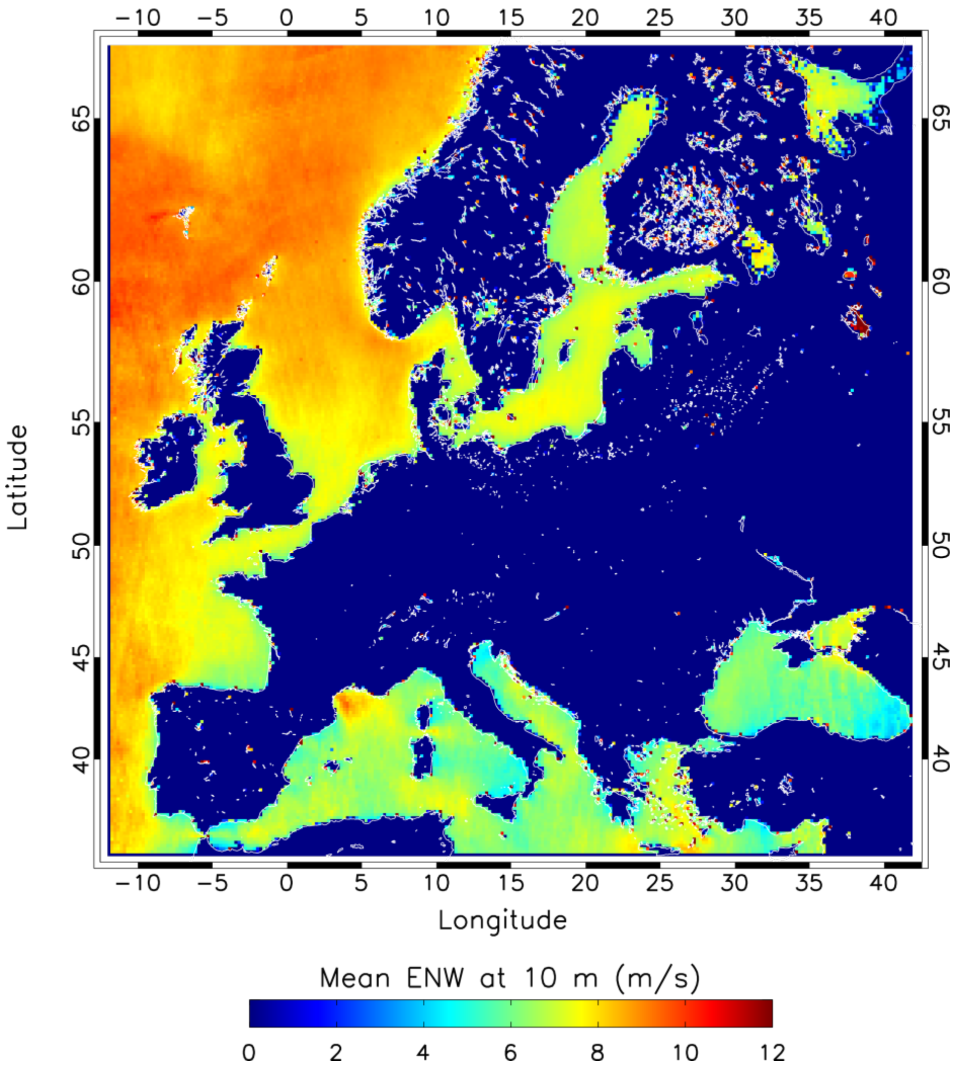


http://www.neweuropeanwindatlas.eu/

New European Wind Atlas

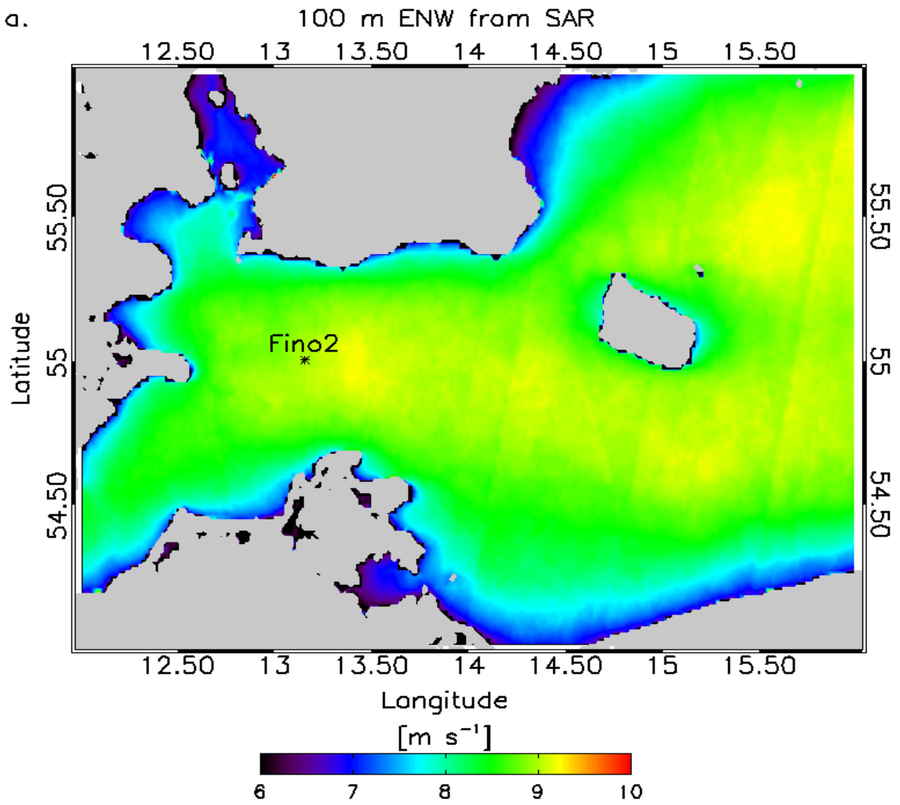
SAR-based mean wind speed map of Europe

10-m height wind atlas from Sentinel-1 and Envisat SAR, 2002-2016, at 2 km resolution

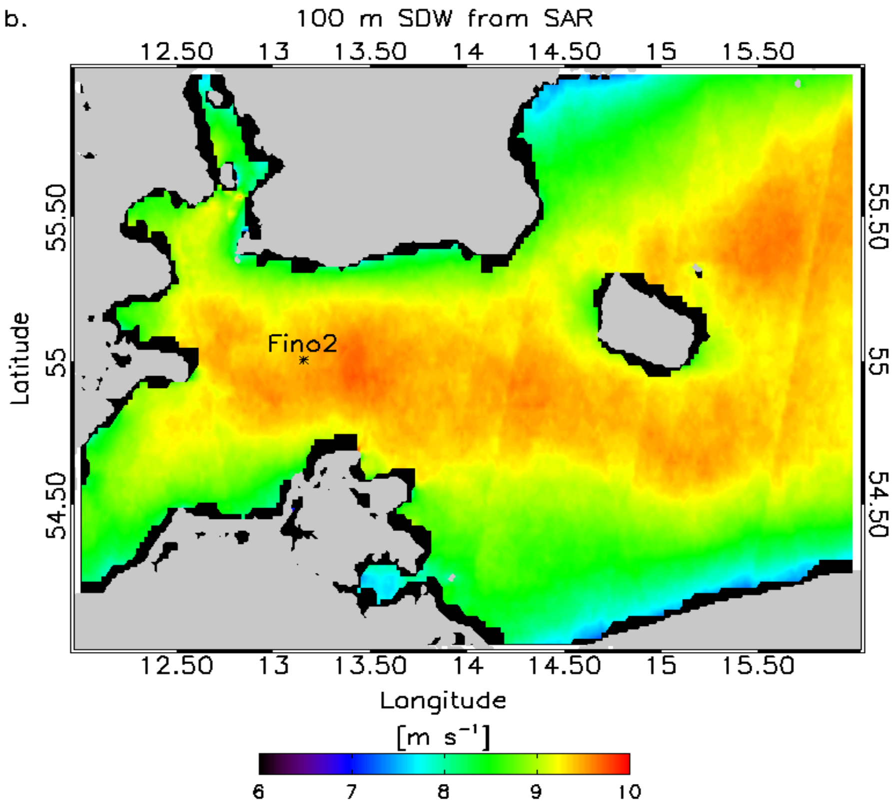


Courtesy: ESA and Copernicus for Envisat ASAR and Sentinel-1 scenes.

Wind speed extrapolation from 10 m to hub-height



Without stability correction



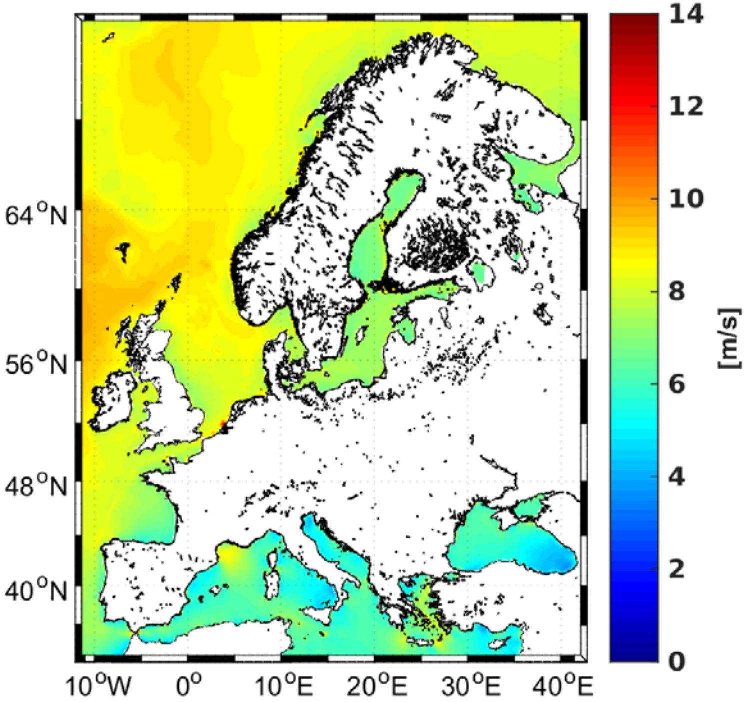
With stability correction

Badger, M. et al.(2016): Extrapolating satellite winds to turbine operating heights, *Journal of Applied Meteorology and Climatology,* 44, 975-991, doi: 10.1175/JAMC-D-15-0197.1.

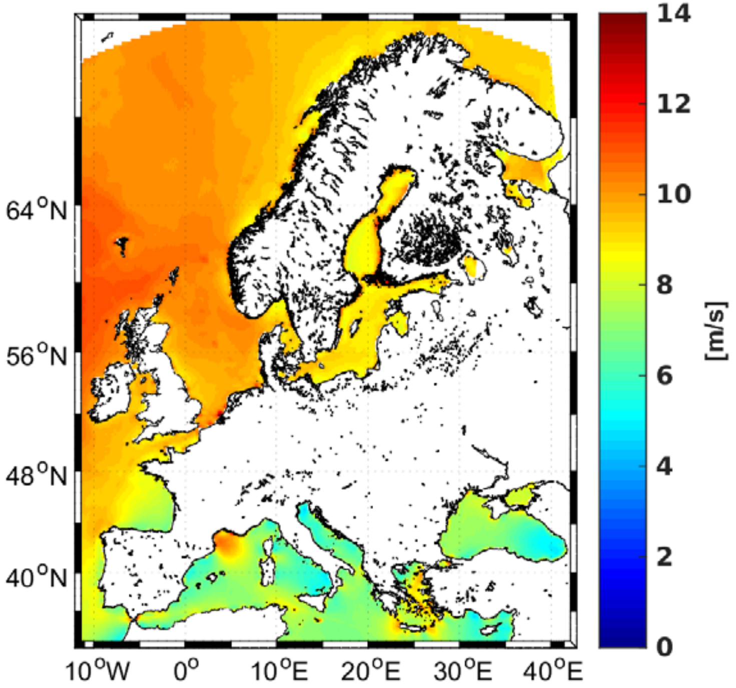
Courtesy: ESA for Envisat ASAR scenes.

New European Wind Atlas

ASCAT Wind Atlas



10m



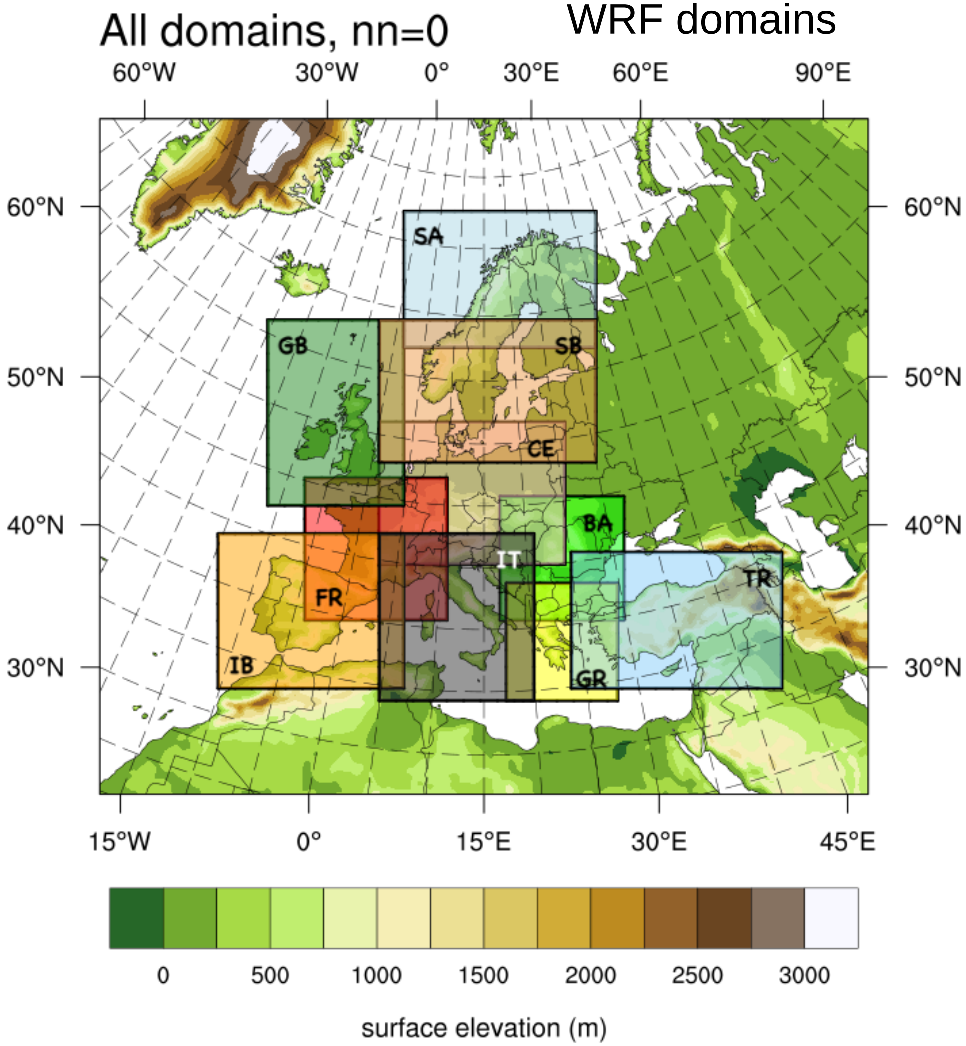
100m

Karagali et al., 2018. New European Wind Atlas offshore, Journal of Physics – Conference Series, 1037 (5).

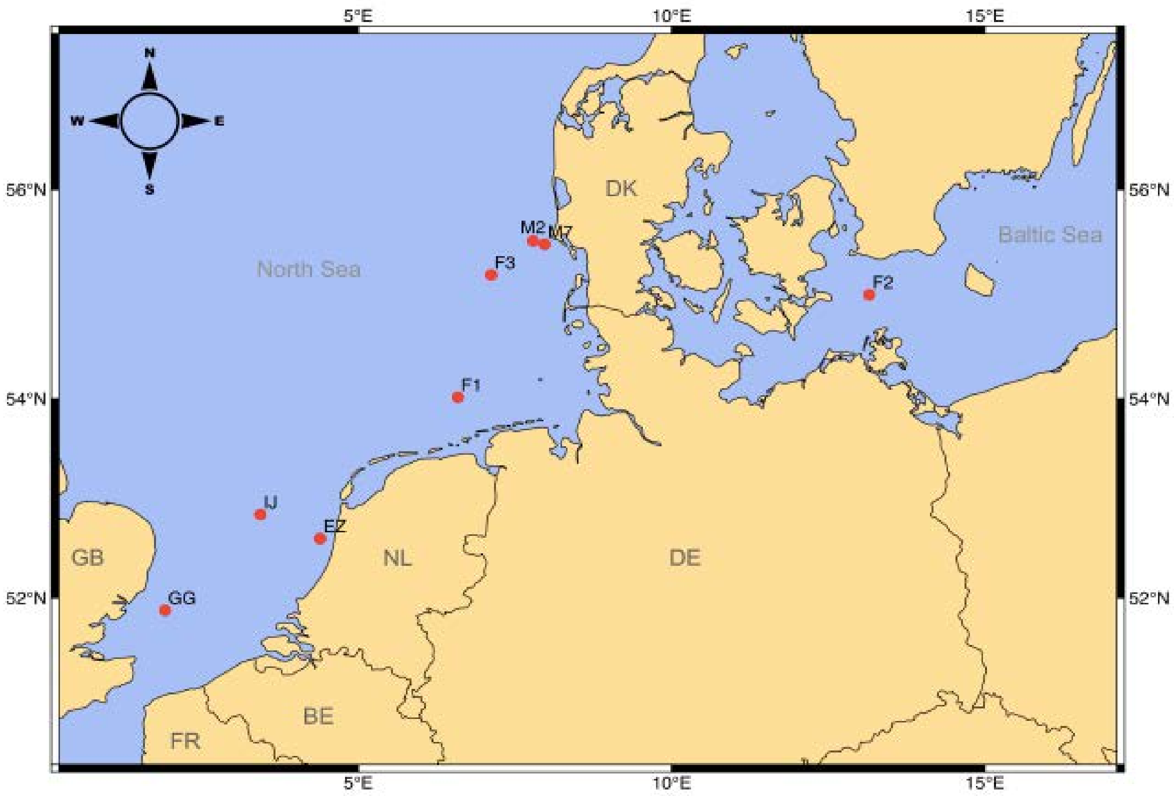
Courtesy: EUMETSAT and CMEMS

New European Wind Atlas

WRF domains



Map of tall offhore met-masts used for validation



New European Wind Atlas

- First release at Wind Europe Conference in Bilbao 2-4 April 2019

- Final release at
- Wind Europe Technology Workshop: Resource assessment 2019

27 – 28 June, Brussels, Belgium

The 5th edition of this technology workshop will focus on reducing uncertainty in wind farm resource assessment.

Conclusions

- Wind farm wakes within and between wind farms (clusters)
- *Observe and model the wake effects (e.g. SAR data, WRF and FUGA)*
- *Wind-wave coupled modelling to power production and extreme winds*

- Leading edge erosion caused by heavy rain
- *Rain erosion at blades to be predicted (and avoided)*

- Coastal wind speed gradient influences power production
- *Observe and model coastal wind speed gradients to predict production*

- Large archive on satellite wind maps for applied use
- *Wind ressource modeling and measurements are necessary to reduce uncertaincy*

- **Recommendation: to study offshore meteorology wind and rain!**