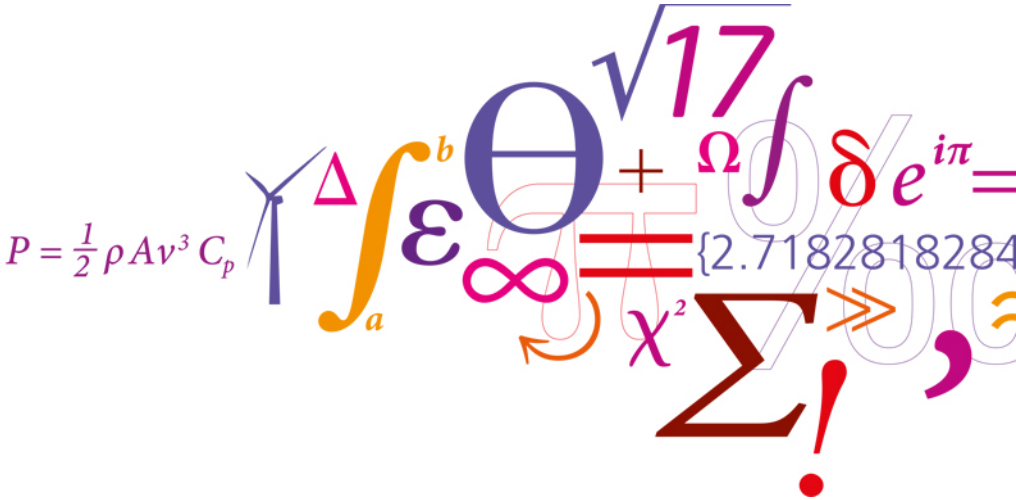
Offshore wind resource mapping in Europe from satellites

Charlotte Bay Hasager



Seminar at University of Auckland,
Dept. of Physics
1 April 2015

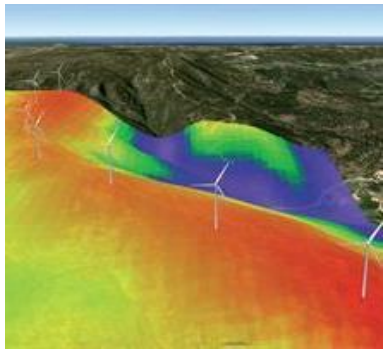
DTU Wind Energy
Department of Wind Energy

Content

- DTU Wind Energy
- Offshore wind turbines
- New European Wind Atlas
- Satellite remote sensing on surface ocean winds
- Offshore wind resource estimation
- Selected results
- Offshore wind farm wake examples
- Summary

DTU Wind Energy

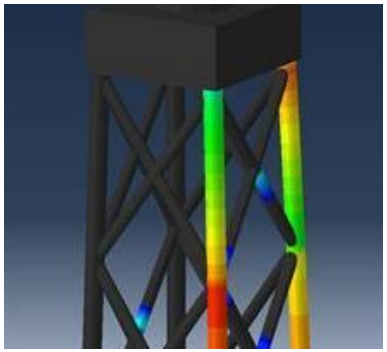
> 240 staff members
Including 150 academic staff members and 50 PhD students



Meteorology

Wind Energy Systems

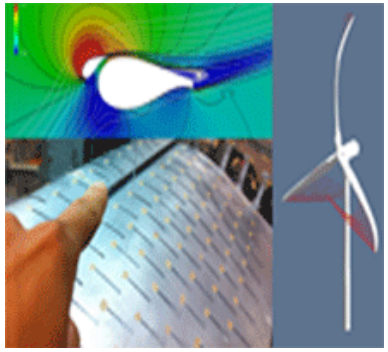
Test and Measurements



Wind Turbines

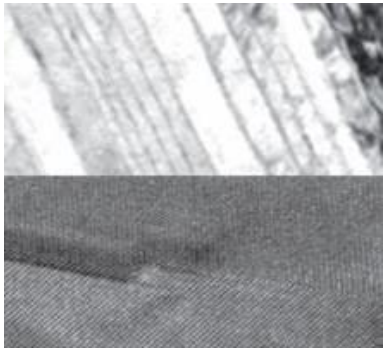
http://www.vindenergi.dtu.dk

Fluid Mechanics



Aeroelastic design

Composite and Materials Mechanics



Materials Science and Characterisation

International wind turbine standards - IEC

a) Safety & functional requirements

↓

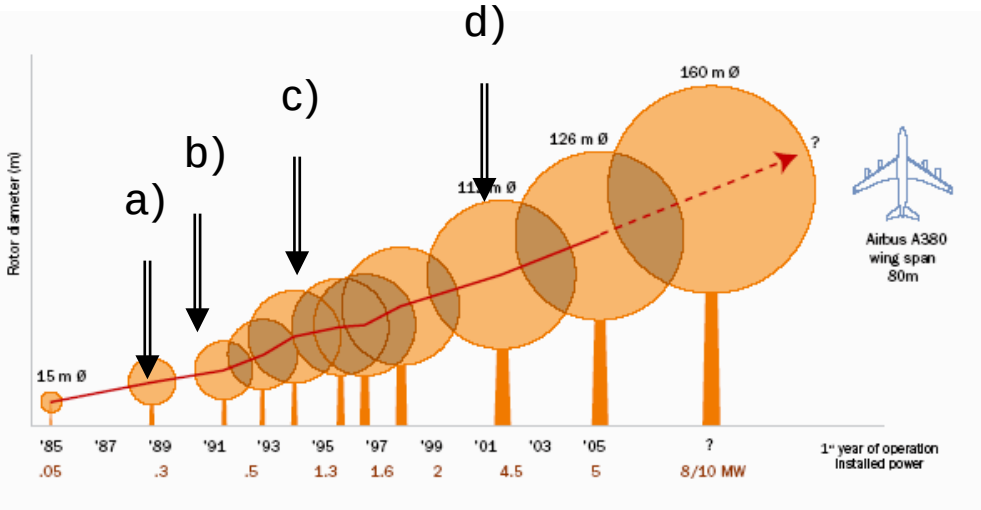
b) Test methods

↓

c) Certification procedures

↓

d) Interfaces & Component

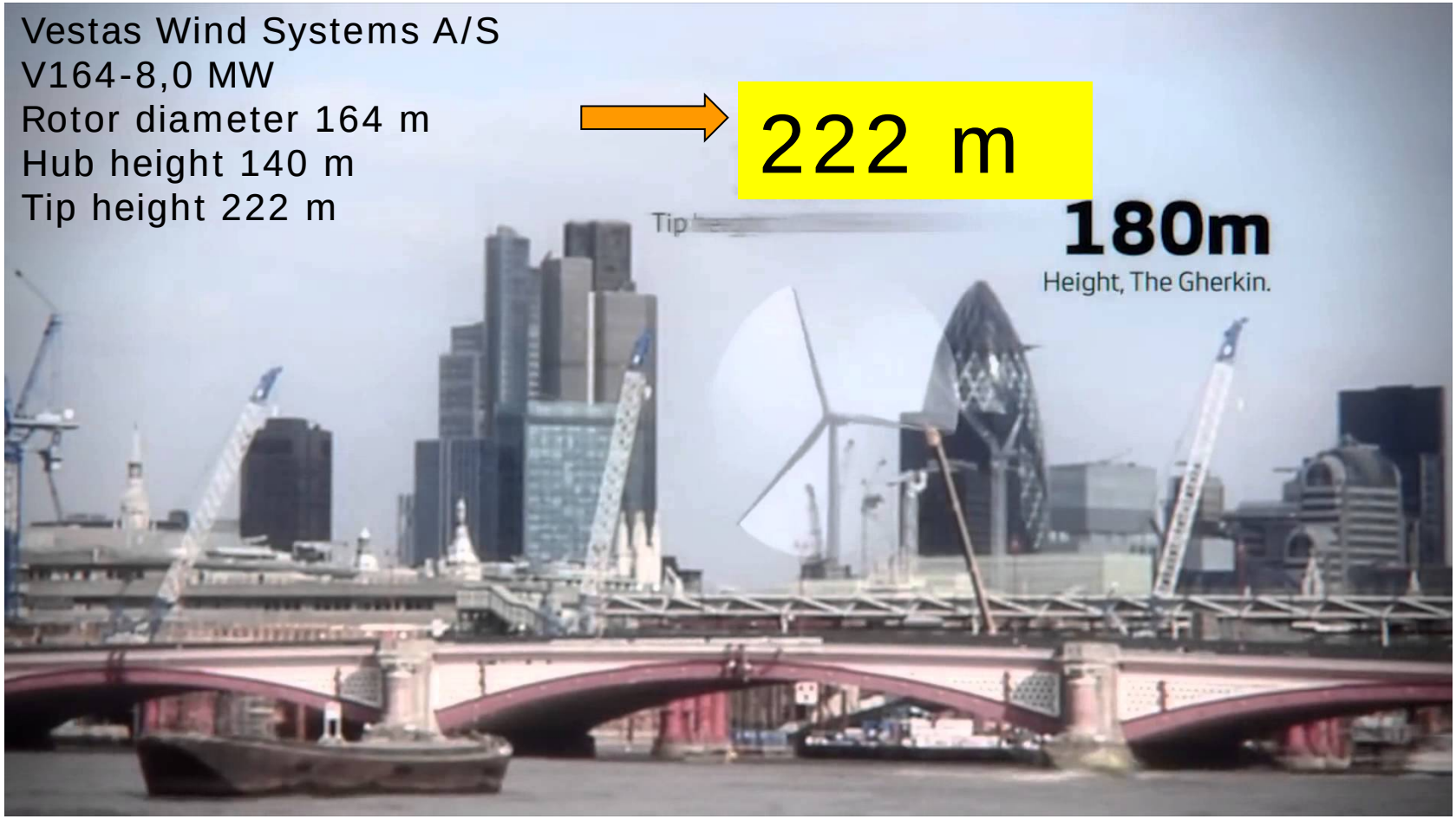


IEC TC88: IEC 61400 series:

IEC 61400-1 Design requirements
IEC 61400-2 Small wind turbines
IEC 61400-3 Design requirements for offshore wind turbines
IEC 61400-4 Gears for wind turbines
IEC 61400-(5) Wind Turbine Rotor Blades
IEC 61400-11, Acoustic noise measurement techniques
IEC 61400-12-1 Power performance measurements
IEC 61400-13 Measurement of mechanical loads
IEC 61400-14 Declaration of sound power level and tonality
IEC 61400-21 Measurement of power quality characteristics
IEC 61400-22 Conformity Testing and Certification of wind turbines
IEC 61400-23 TR Full scale structural blade testing
IEC 61400-24 TR Lightning protection
IEC 61400-25-(1-6) Communication
IEC 61400-26 TS Availability
IEC 61400-27 Electrical simulation models for wind power generation

Wind Energy – Test and measurements

Vestas 8 MW at Østerild 2015



Vestas 8 MW

New European Wind Atlas (NEWA)

DTU Wind Energy coordinator: Prof. Jakob Mann

Eight participating countries

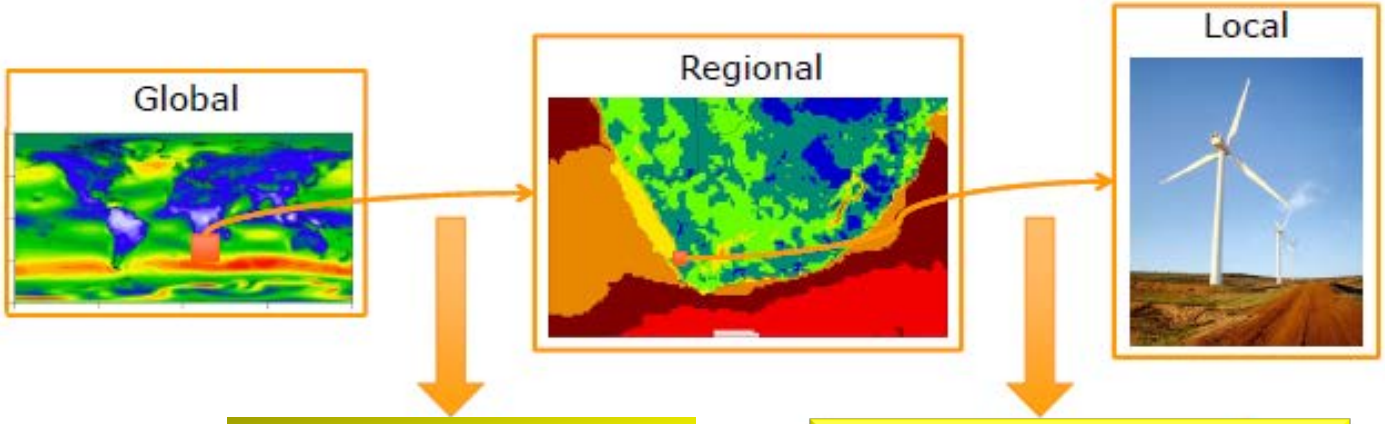
Most of Europe will be covered including **offshore**

Project period: 1 March 2015 to 1 March 2020 (5 years)

New European Wind Atlas (NEWA)

Wind resource assessment and extreme wind

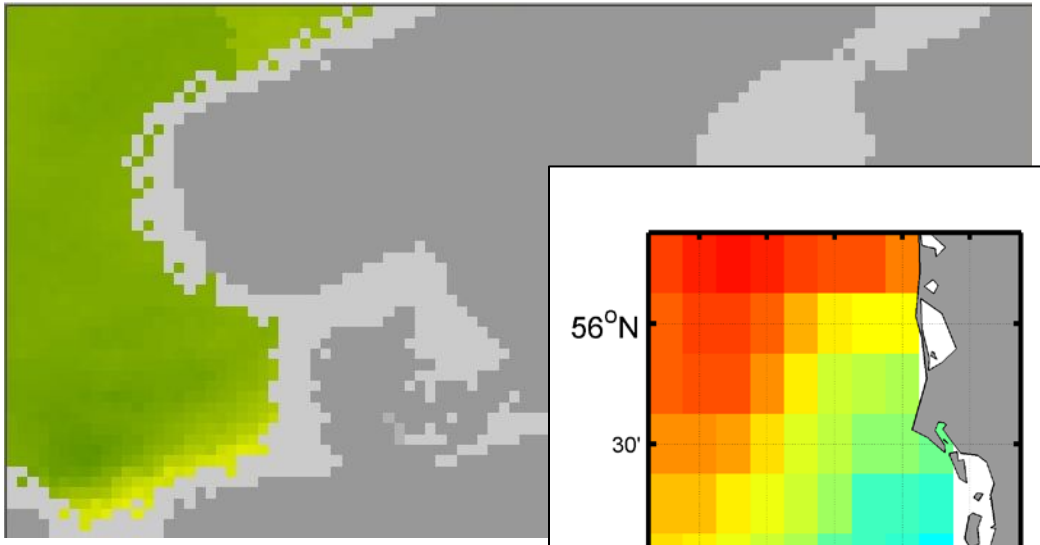
Downscaling model chain



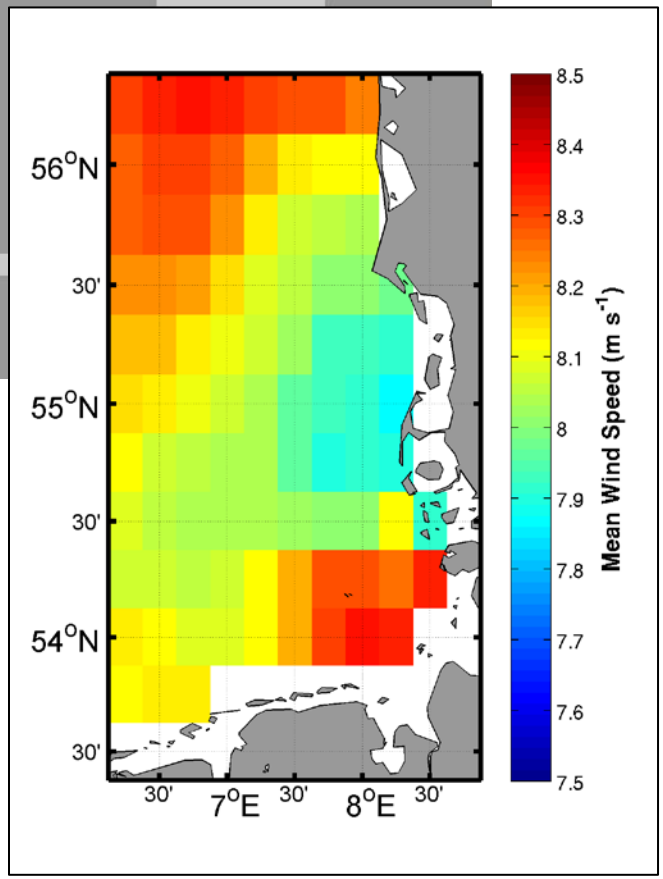
Mesoscale modeling
KAMM, WRF etc.

Microscale modeling
(WAsP, WAsP engineering, CFD, etc)
+
observation

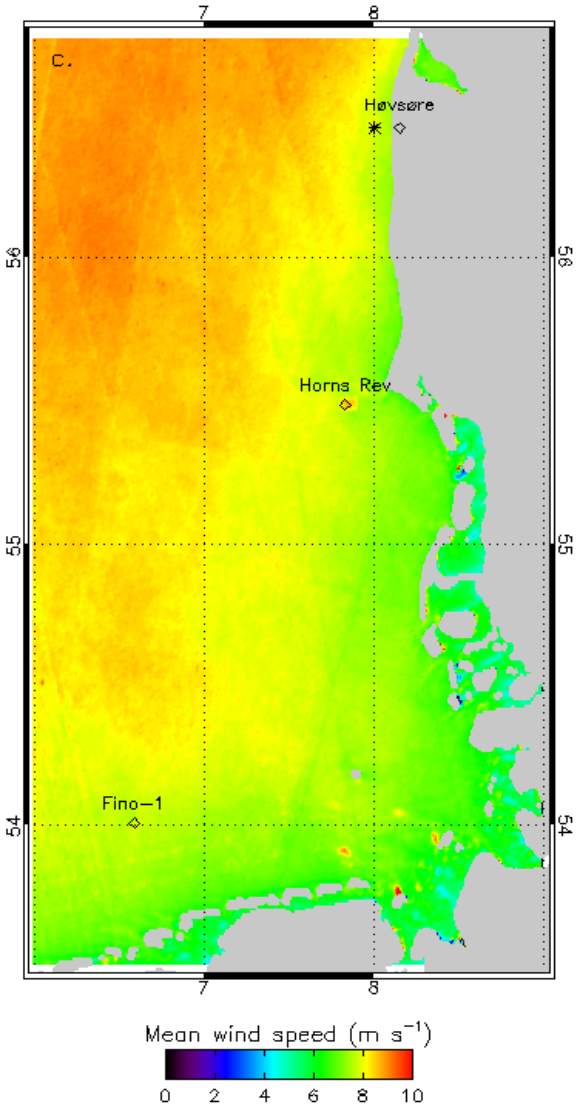
Level of detail for satellite wind products



SSM/I



QuikScat



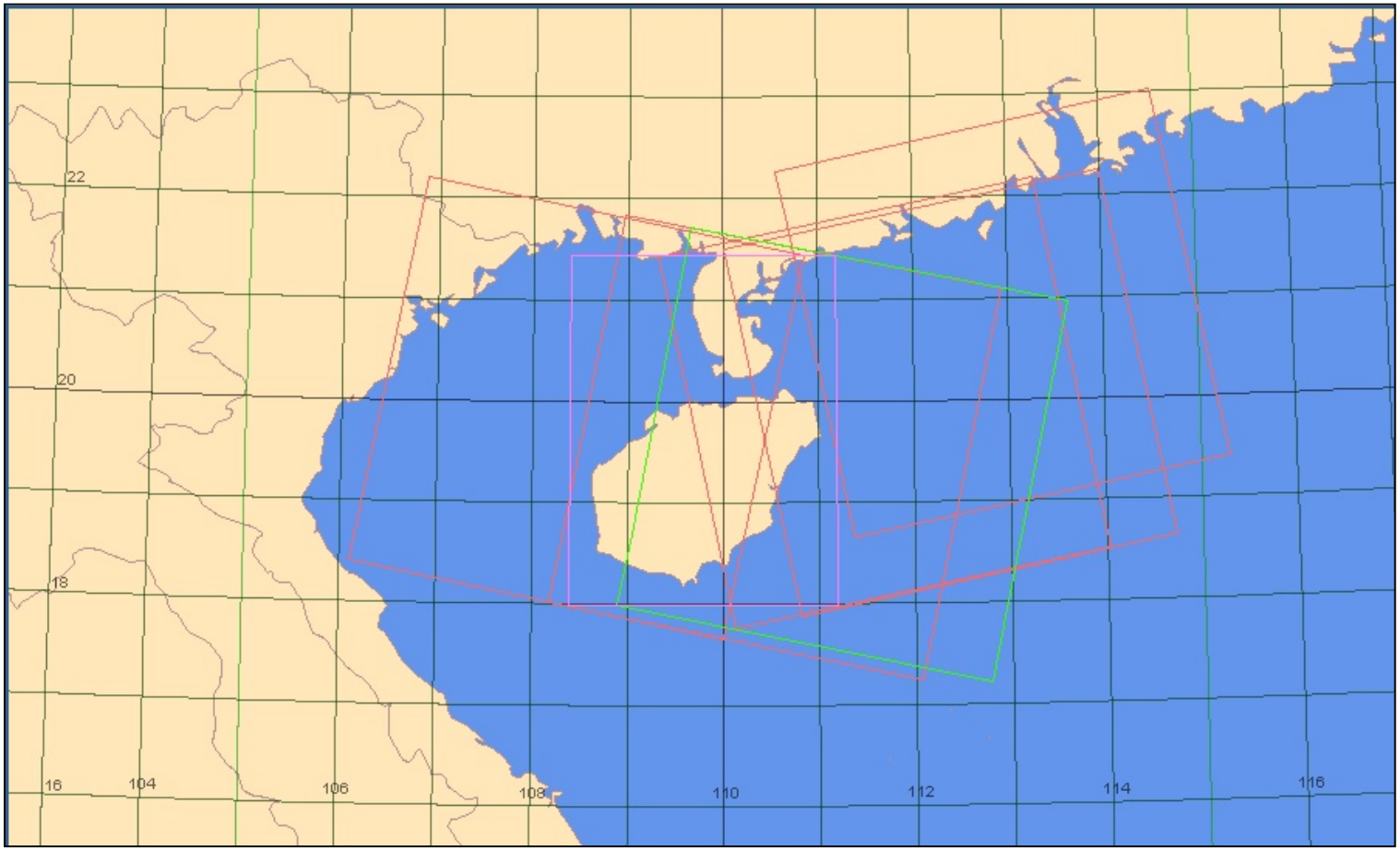
Envisat ASAR

Ocean wind fields from satellites

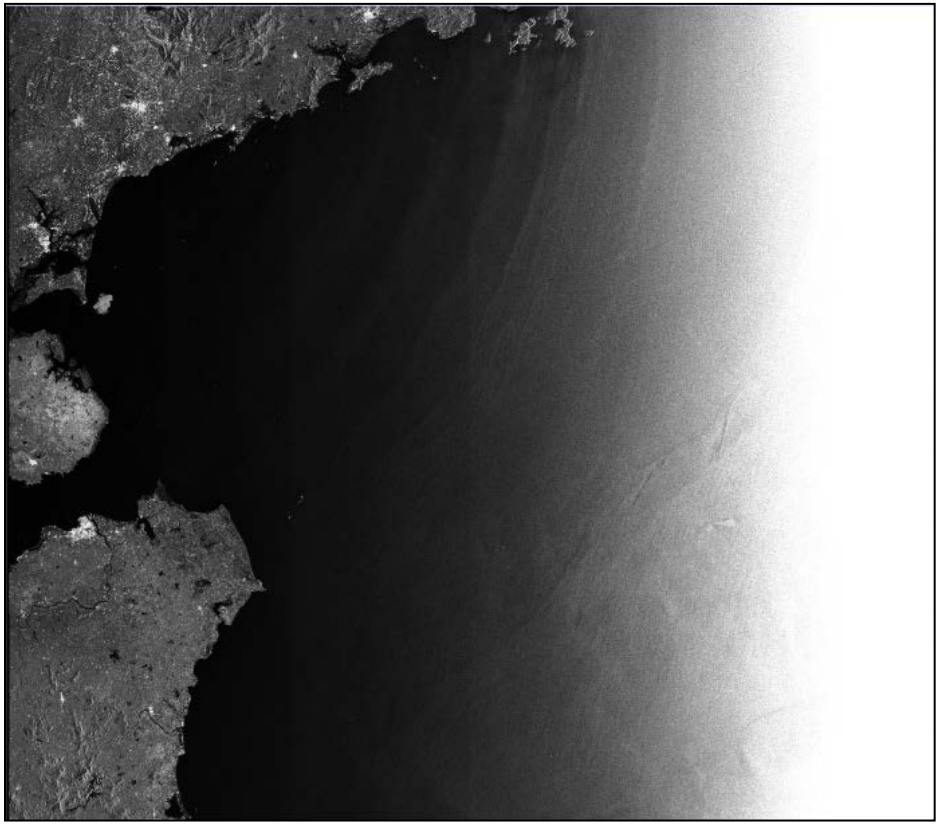
	Radiometer	Scatterometer	Synthetic Aperture Radar (SAR)
Retrieved parameters	Wind speed	Wind speed and direction	Wind speed
Spatial resolution	0.25° lat/lon	0.25° lat/lon	500 m
Spatial coverage	Global	Global	Selected areas
Coastal mask	Cover open oceans only	Up to 70 km from coastline	None
Temporal resolution	4-6 times per day	Twice daily	Variable – less than one per day
Temporal coverage	Systematically since 1987	Systematically since 1991	ScanSAR since 1995
Current sensors	SSM/I (F15, F16, F17)	ASCAT-1/2, HY2A,	Radarsat-1/2, TerraSAR-X, TanDEM-X, COSMO-SkyMed, Sentinel-1
Rain sensitivity	High (rain flags)	Low	Low

SAR image coverage

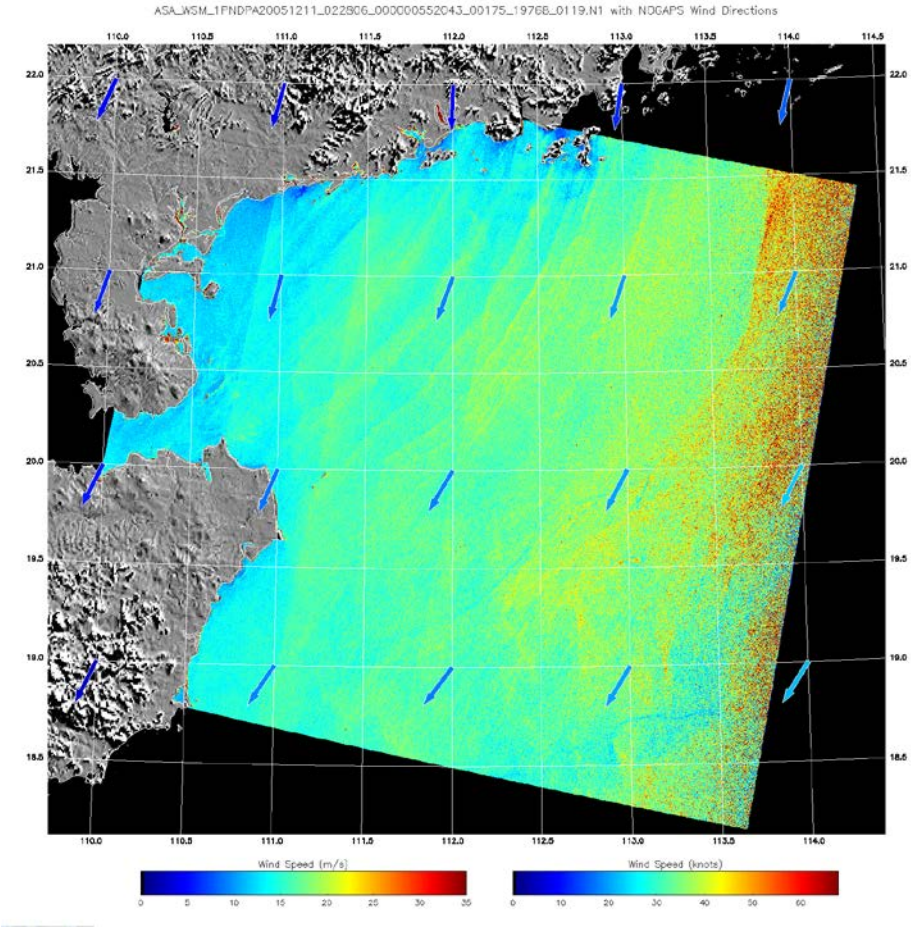
Images frames over a given site have different spatial coverage and orientation



SAR wind retrieval



Original brightness image



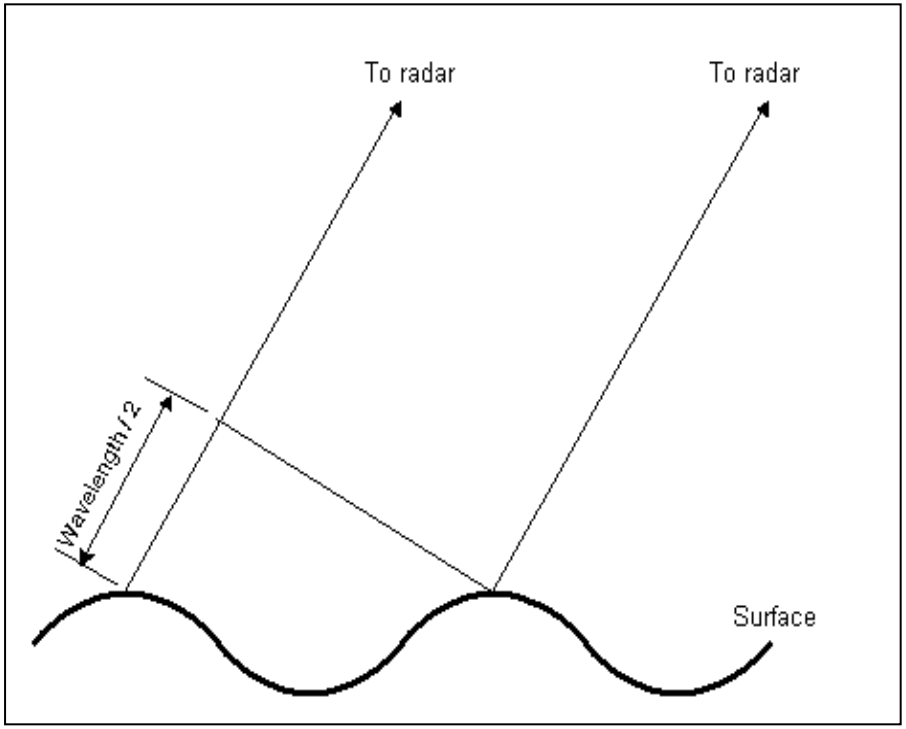
Wind speed map

From wind to radar backscatter

Bragg / resonance scattering:

$$\lambda_{Bragg} = \frac{\lambda_{radar}}{2\sin\theta}$$

θ = incidence angle (15-70°)
λ = wave length



Bragg waves ride on longer-period waves
Random variation occurs (speckle) → Pixel averaging is necessary

From radar backscatter to wind

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]

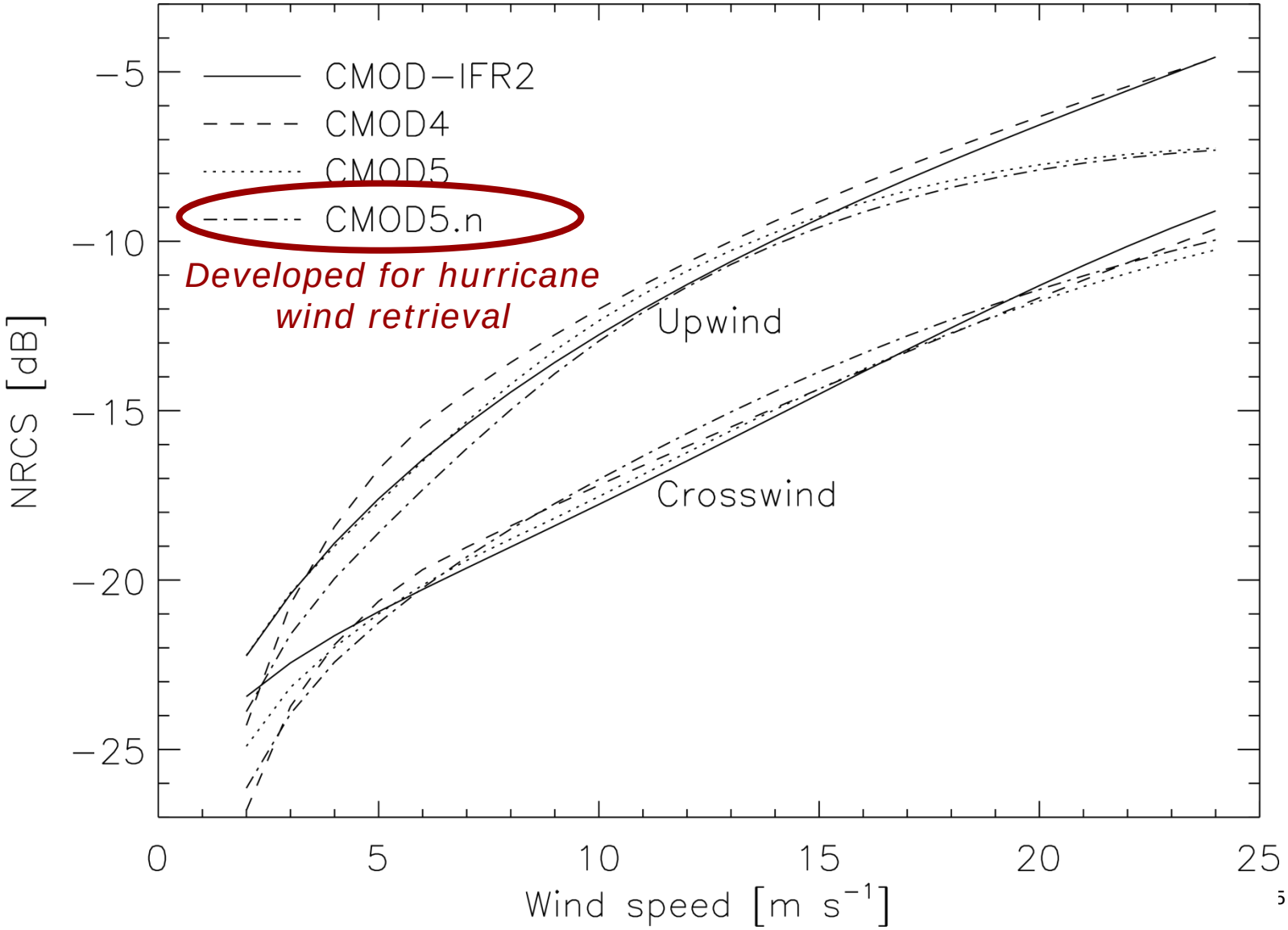
θ = incidence angle [degrees]

U = wind speed at 10 m [m/s]

Φ = relative wind direction [degrees]

Model functions apply to open oceans and neutral atmospheric stability
The nominal accuracy on wind speed is +/- 2 m/s

Geophysical model functions



APL / NOAA SAR Wind Retrieval Software

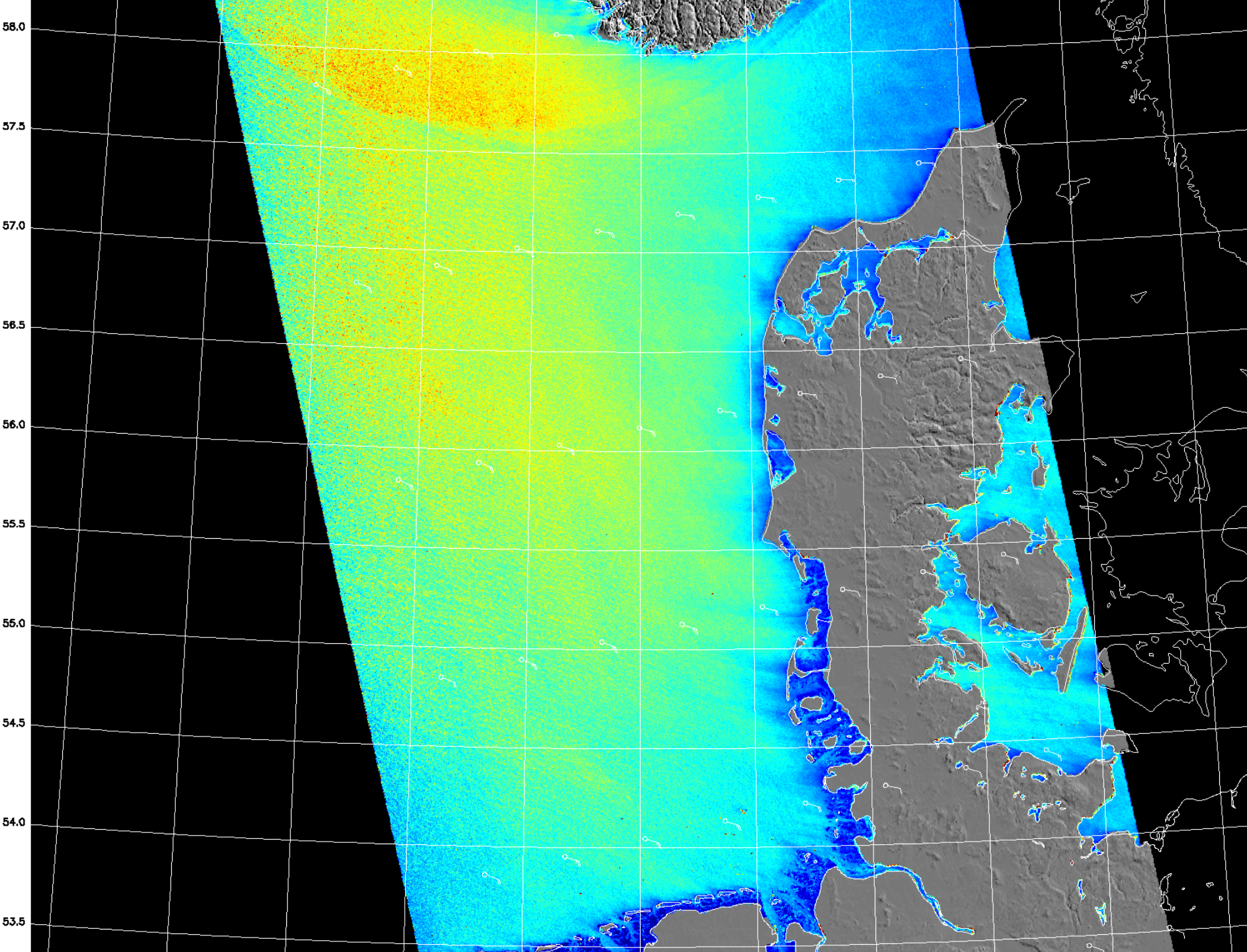
- Developed by the Johns Hopins University, Applied Physics Laboratory (JHU/APL), USA (http://fermi.jhuapl.edu/)

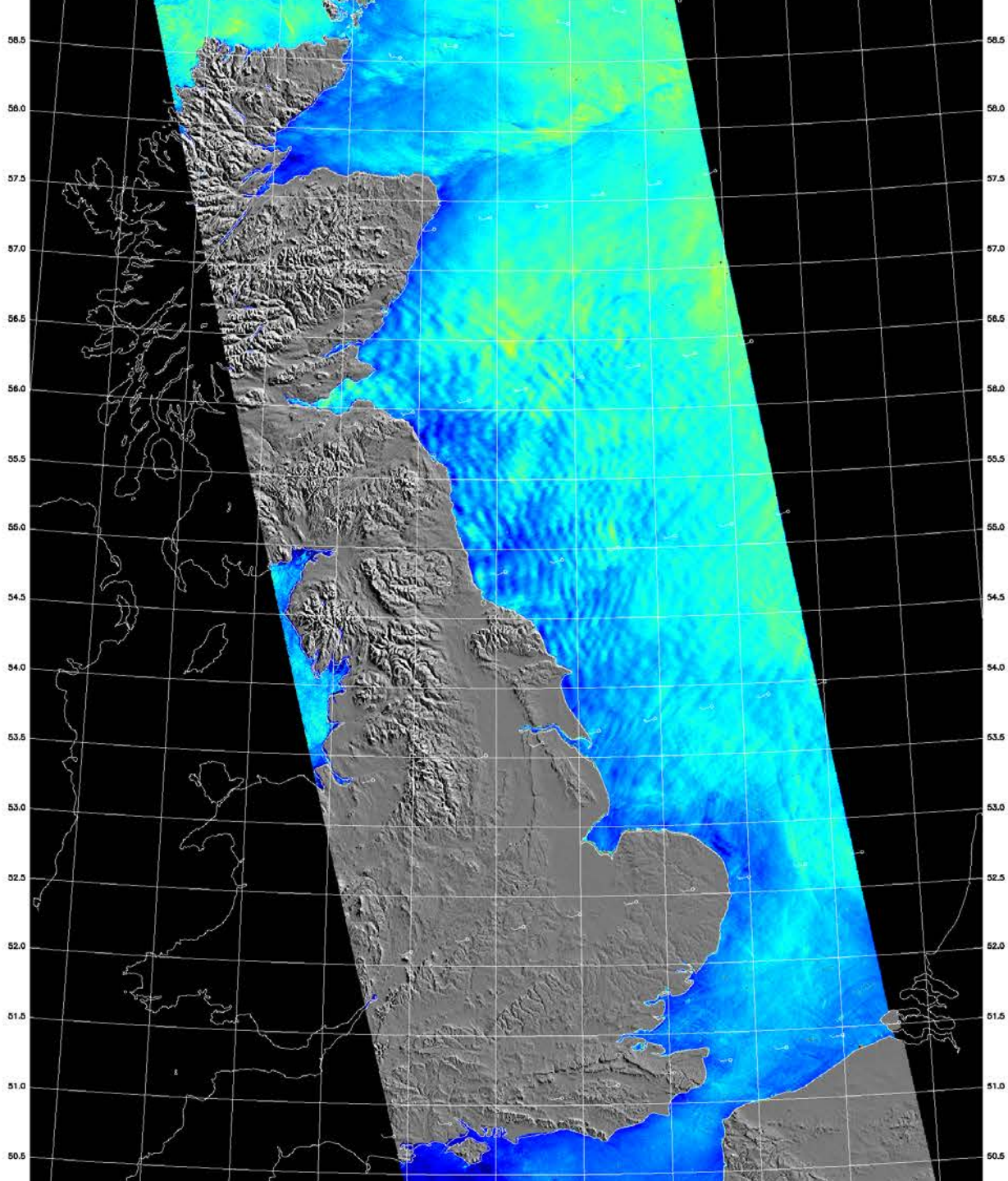
- Implemented at DTU, NOAA, the Alaska SAR Facility, …

- Performs SAR wind mapping in near-real-time (when satellite data is available)

- Default wind directions from the Navy Operational Global Atmospheric Prediction System (NOGAPS):

  - *Spatial resolution: 1° latitude/longitude*
  - *Temporal resolution: 6 hours*


58.0
57.5
57.0
56.5
56.0
55.5
55.0
54.5
54.0
53.5


58.5
58.0
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56.5
56.0
55.5
55.0
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54.0
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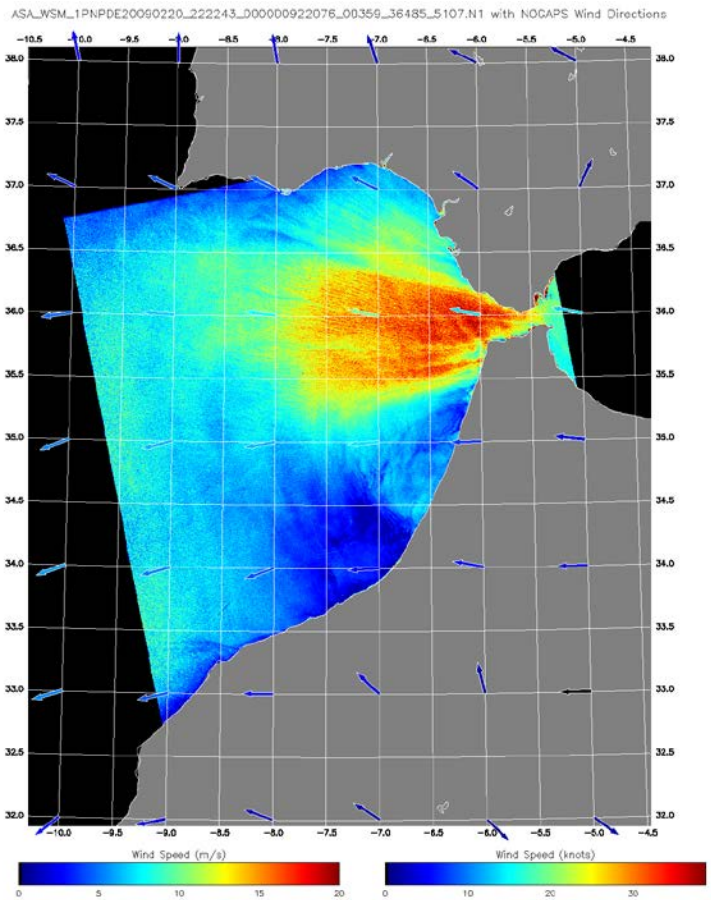
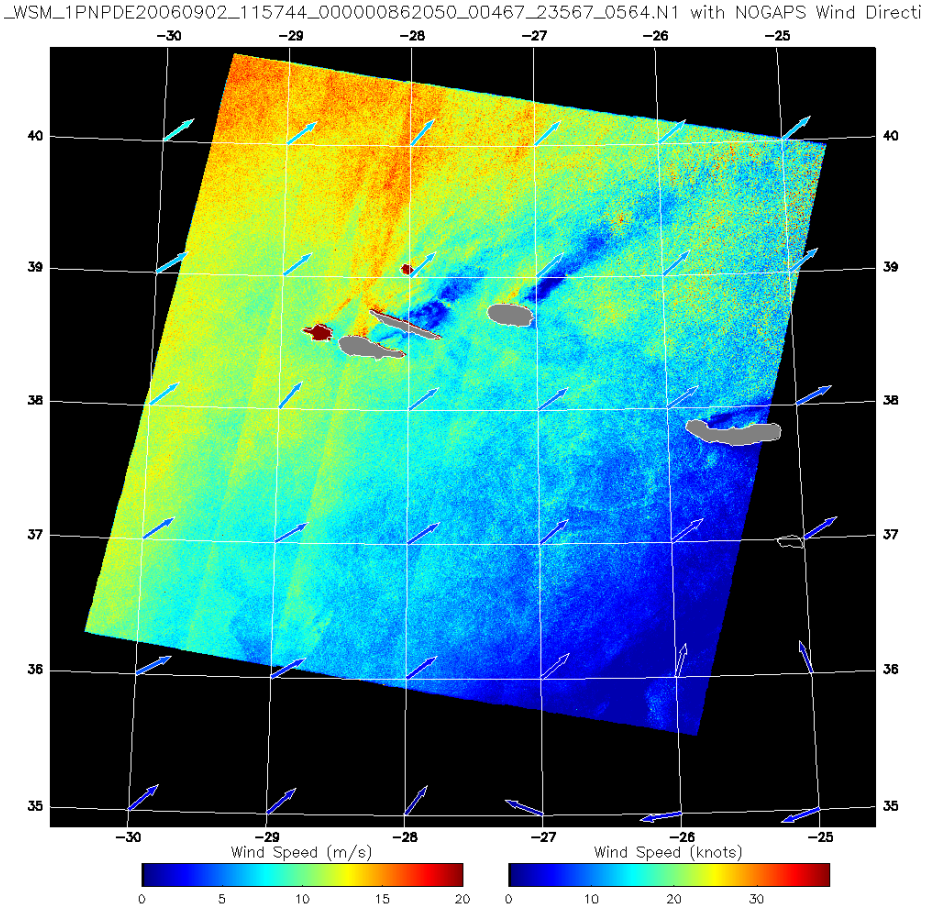
53.0
52.5
52.0
51.5
51.0
50.5

SAR showing meso-scale wind phenomena

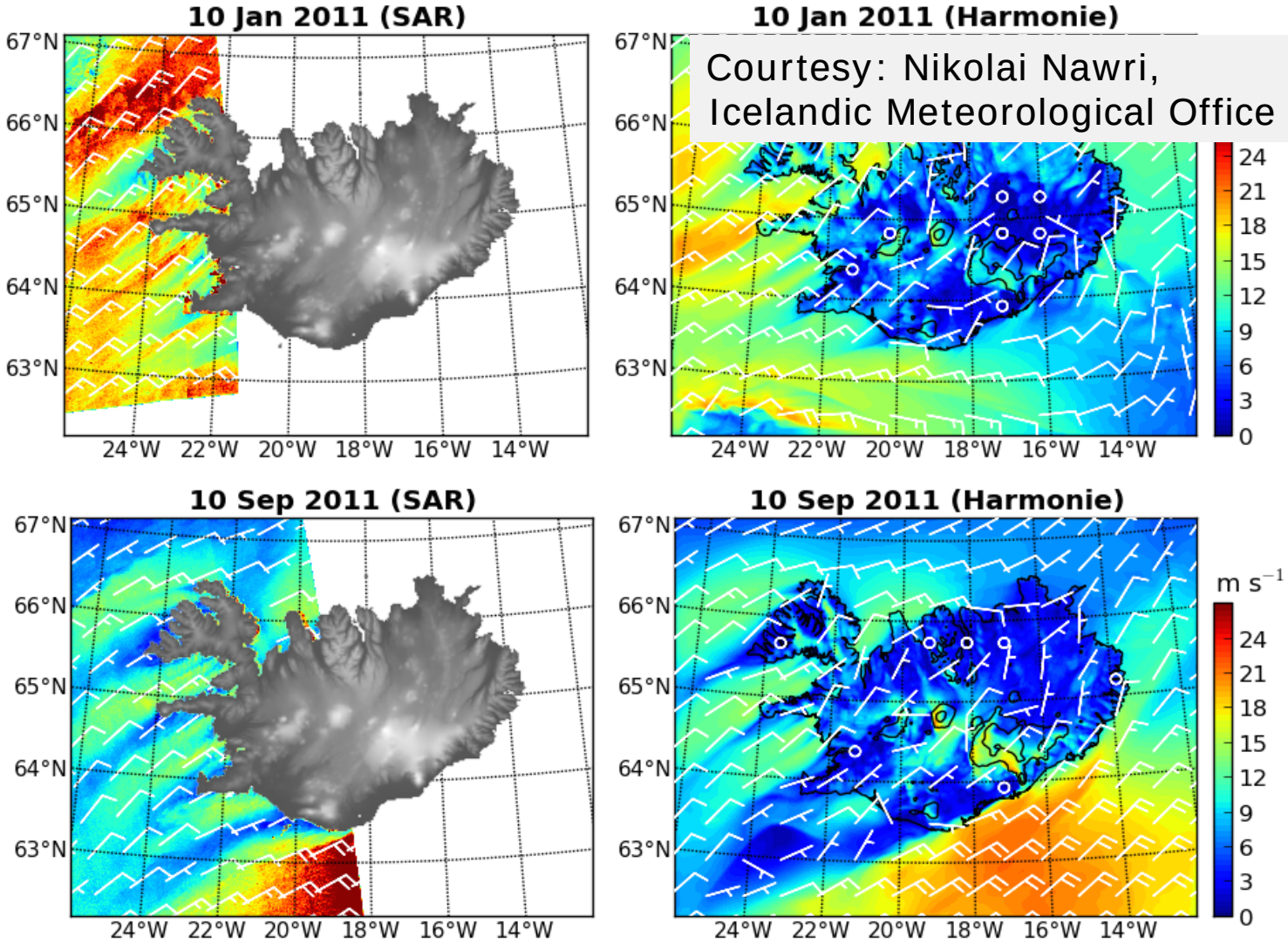


Strait of Gibraltar



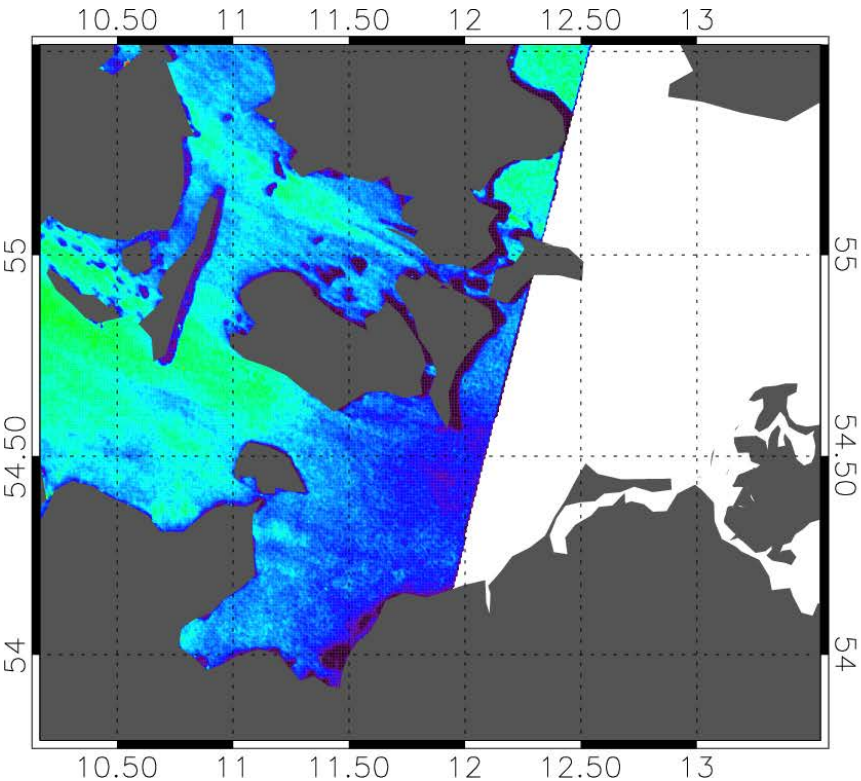
The Azores

Case-by-case comparison SAR and model: Iceland

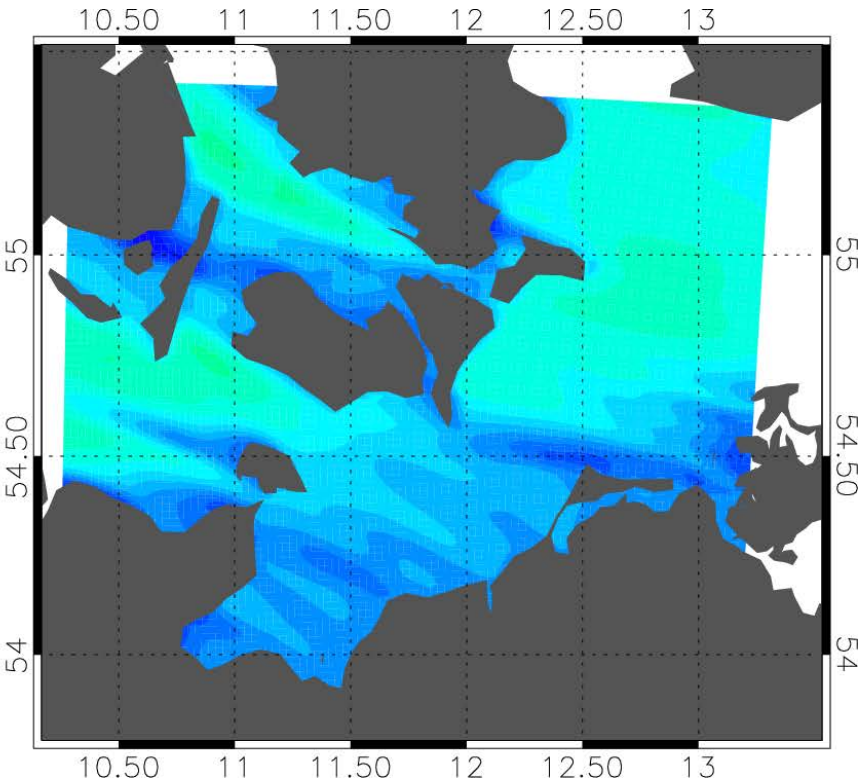


Courtesy: Nikolai Nawri, Icelandic Meteorological Office

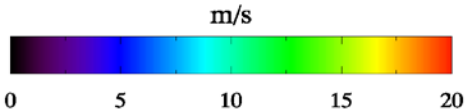
Case-by-case comparison SAR and model: Denmark



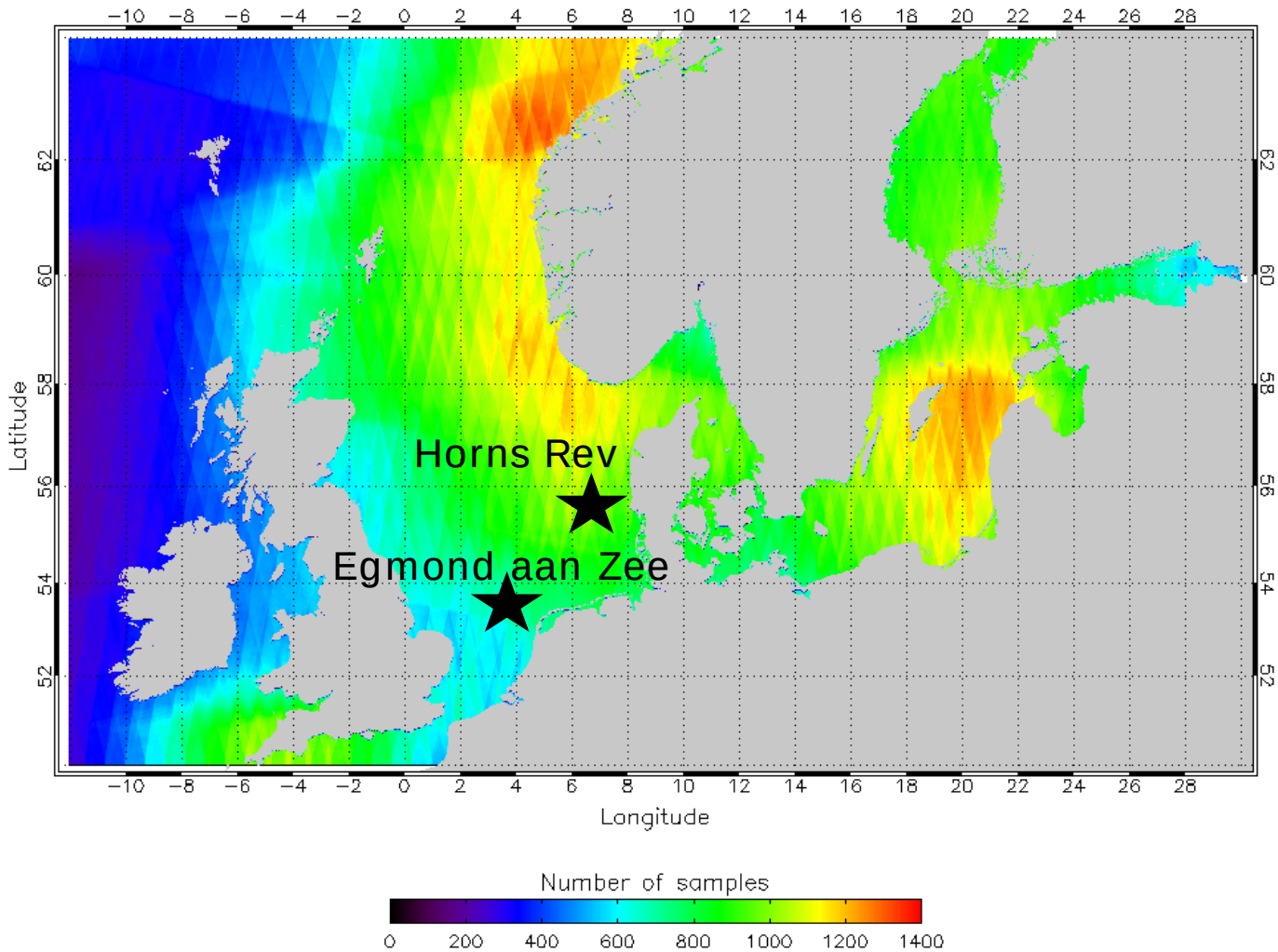
Satellite wind map



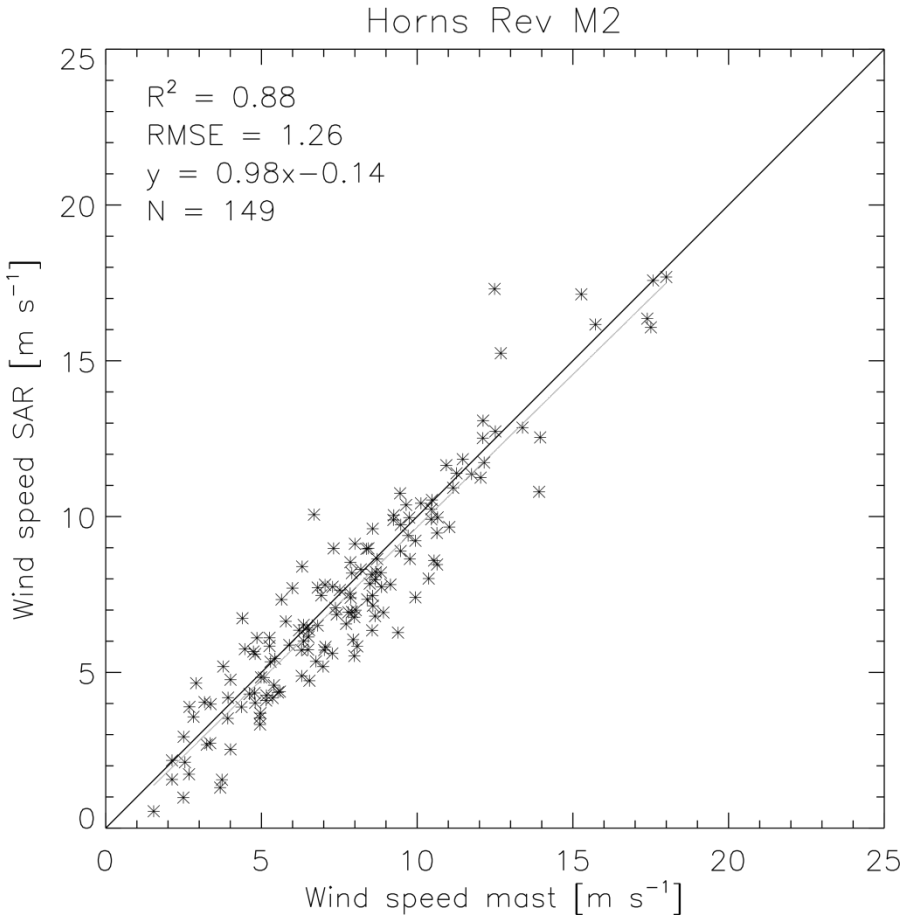
KAMM model

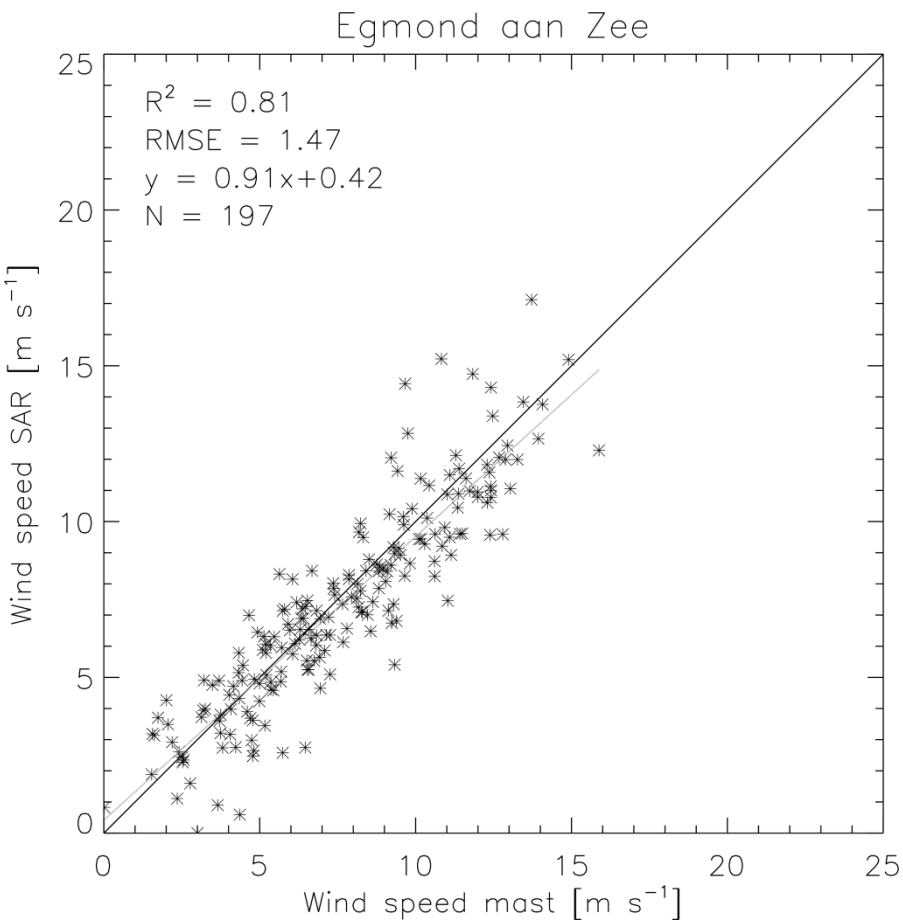


NORSEWInD: SAR data

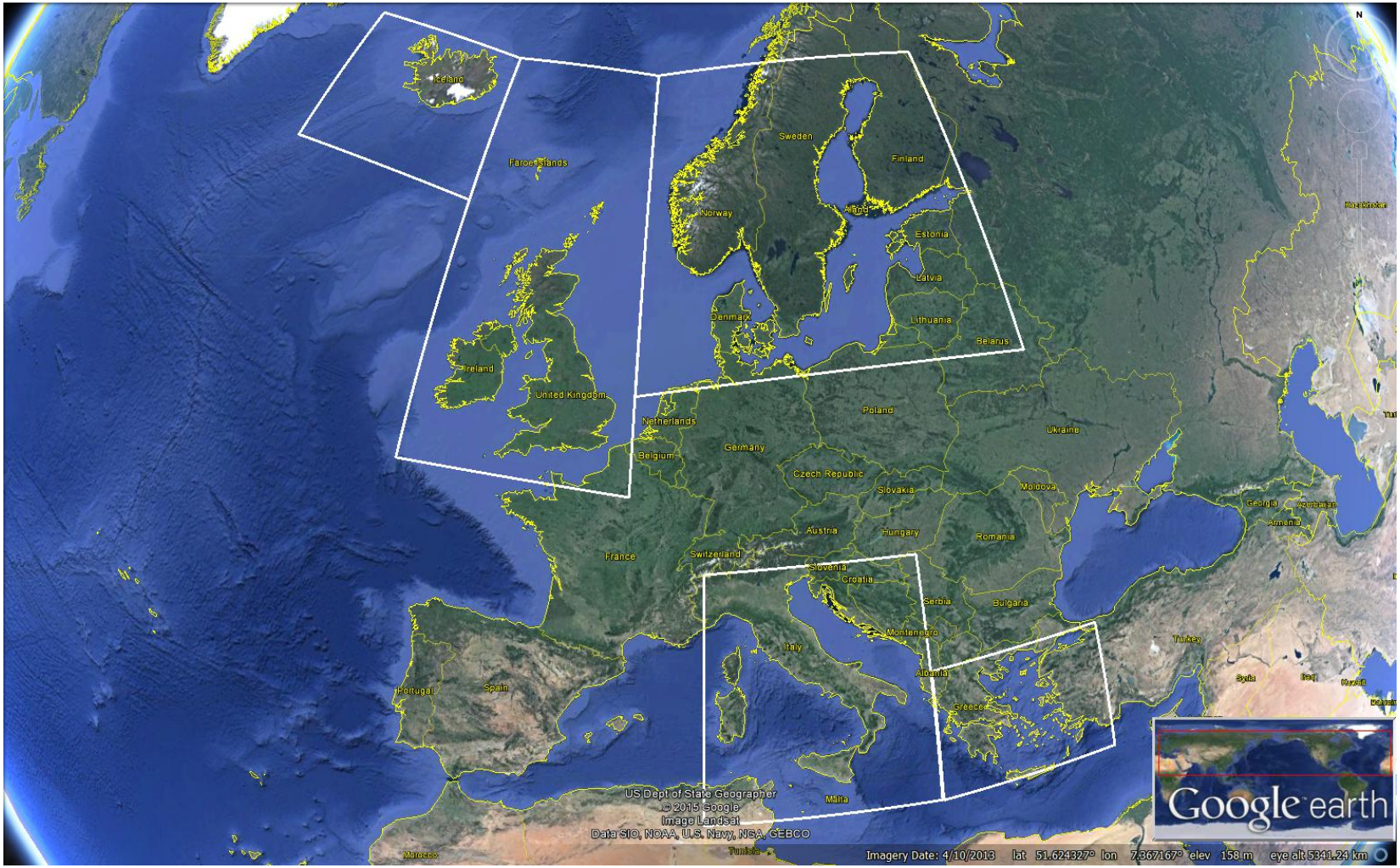


Comparison of SAR and mast winds at 10 m

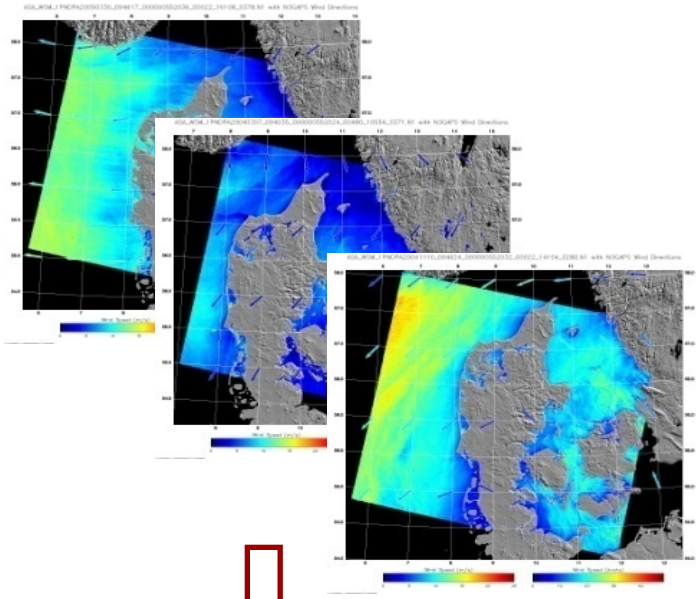


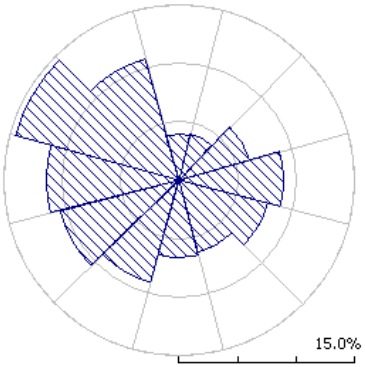


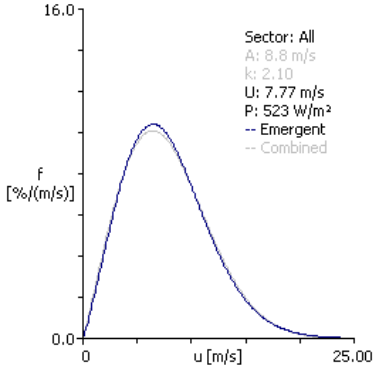
Archived SAR scenes over Europe (~15,000)

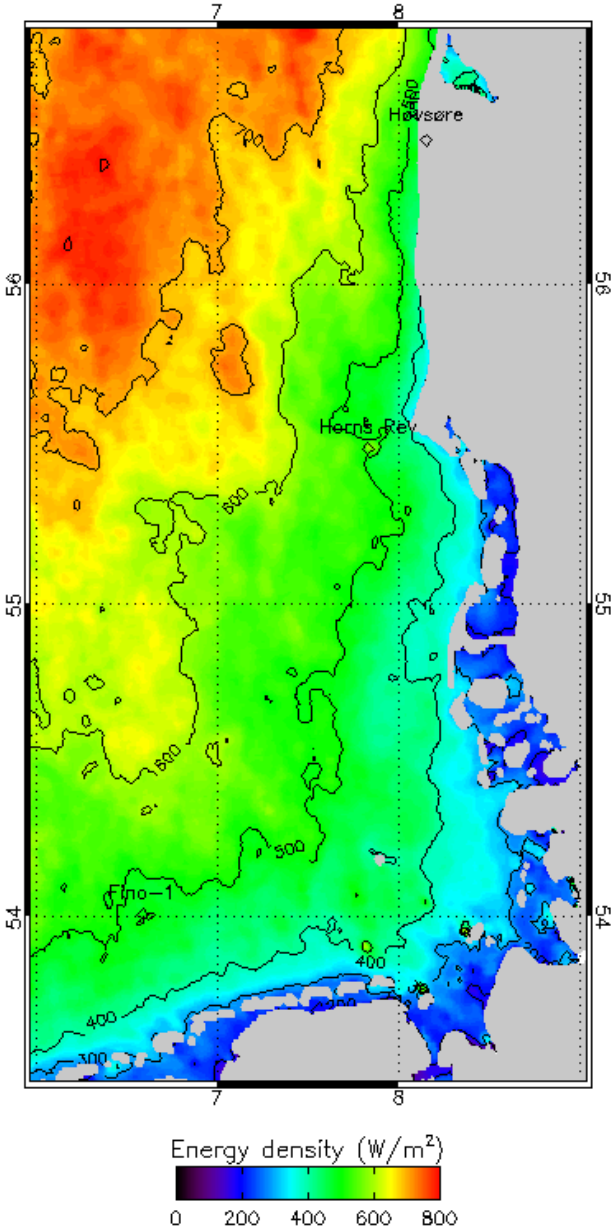


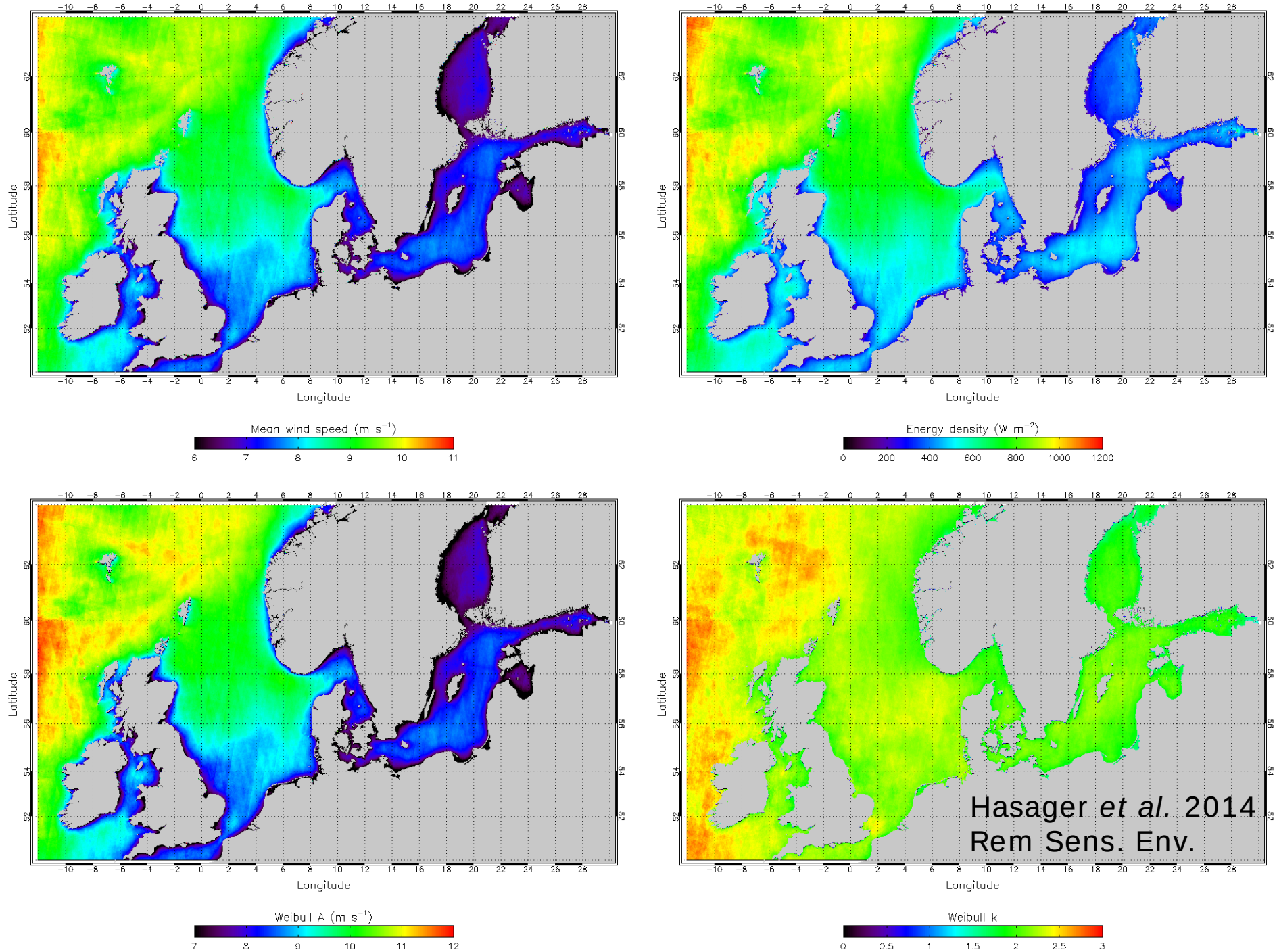
Wind resource mapping from SAR



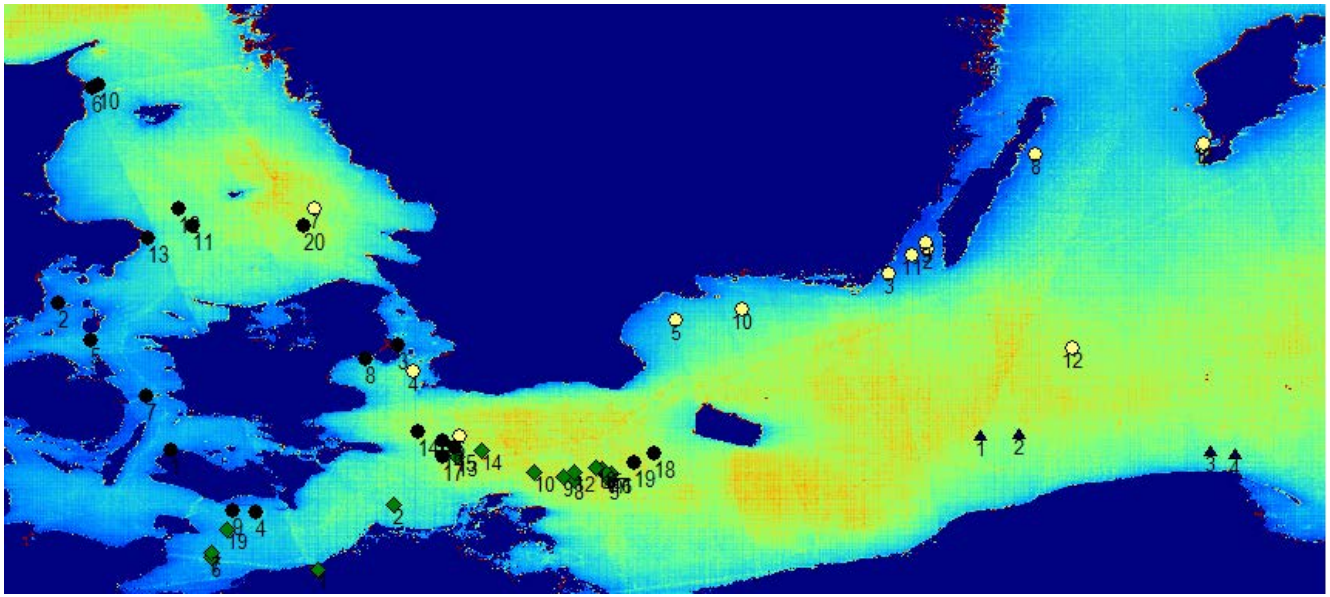


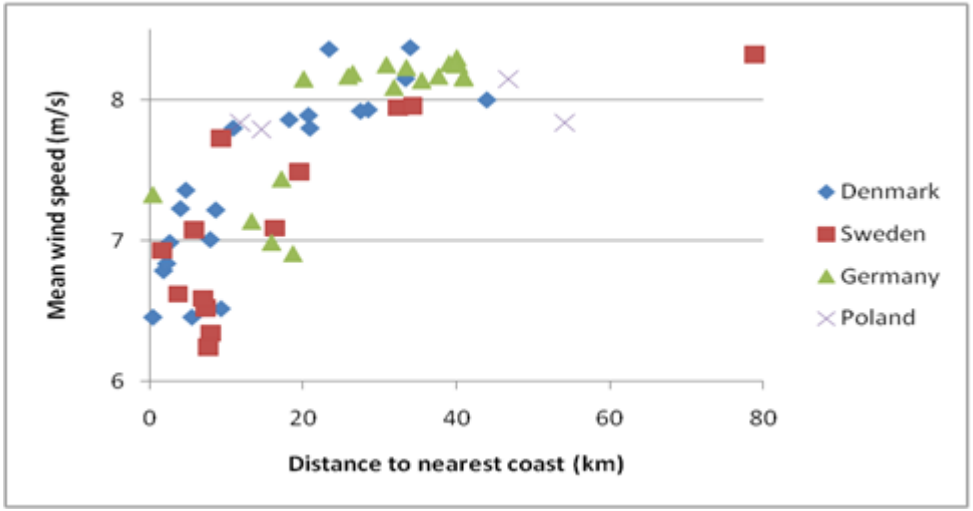





Latitude
Longitude
Mean wind speed (m s^{-1})
6 7 8 9 10 11
Energy density (W m^{-2})
0 200 400 600 800 1000 1200
Weibull A (m s^{-1})
7 8 9 10 11 12
Weibull k
0 0.5 1 1.5 2 2.5 3
Hasager *et al.* 2014
Rem Sens. Env.

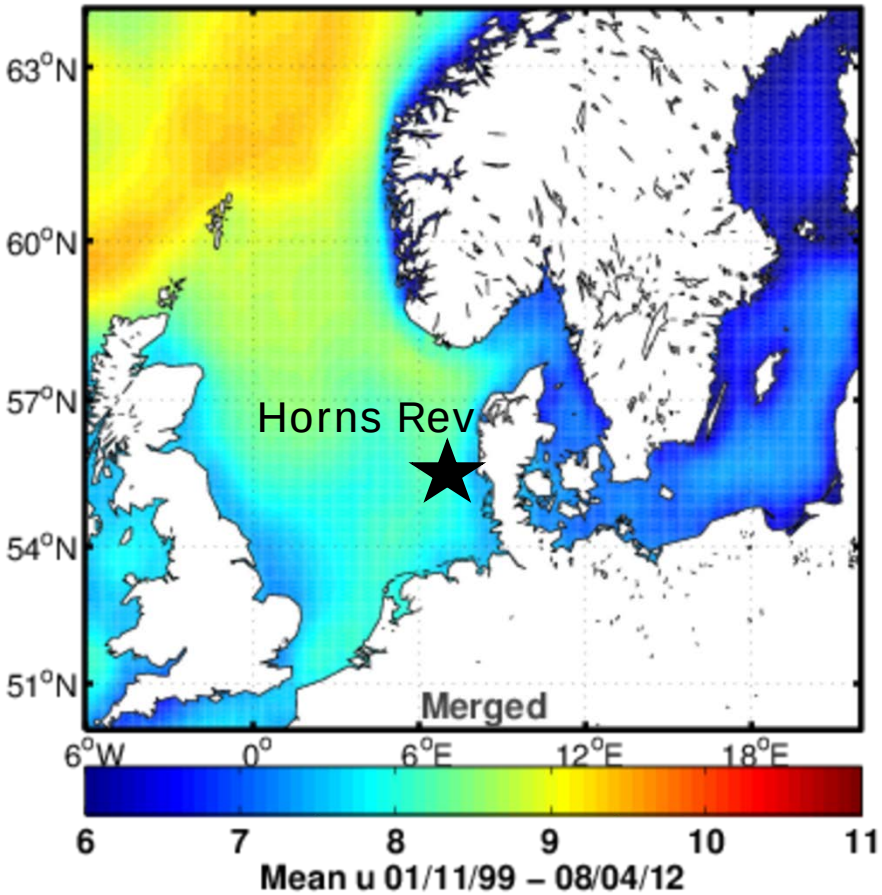
Baltic Sea existing and planned offshore wind farms



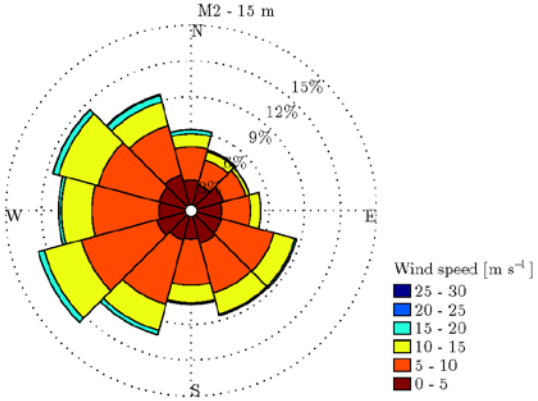


Hasager et al. 2011, SAR-Based Wind Resource Statistics in the Baltic Sea. *Remote Sens., 3*(1), 117-144.

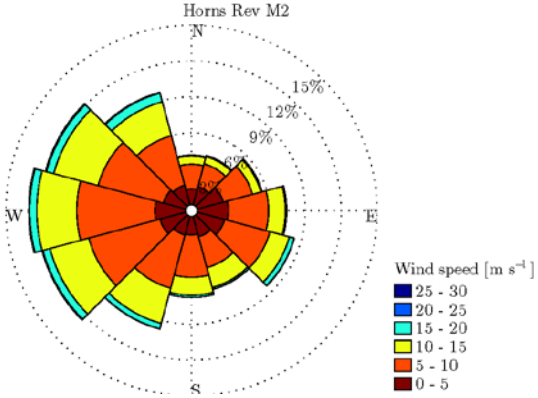
Synergetic use of satellite wind products



Mean wind speed map from Envisat ASAR, QuikScat, and ASCAT



Wind rose from the mast Horns Rev M2



Wind rose from the merged satellite data set

Hasager *et al.* 2014, Rem Sens. Env.

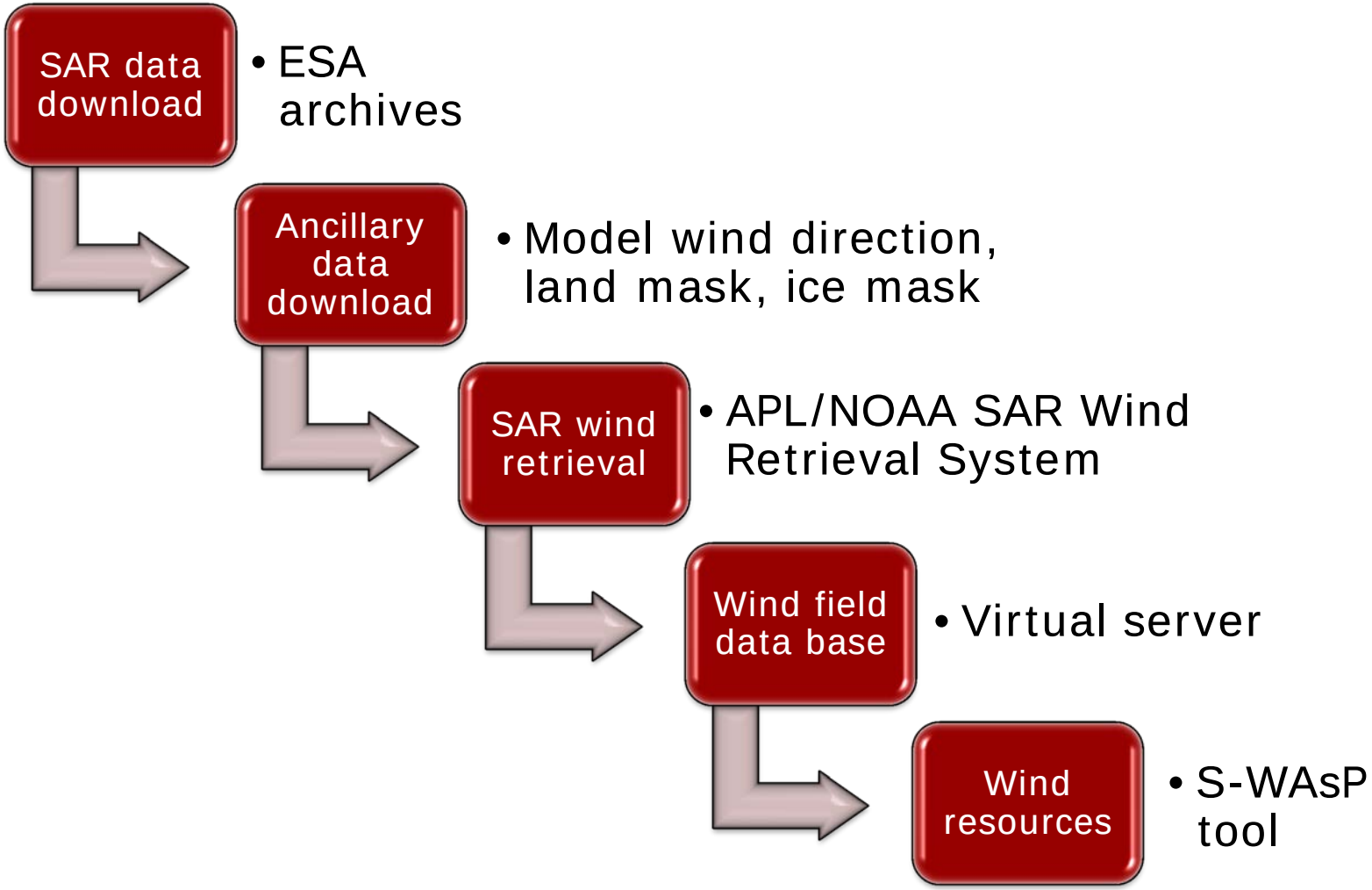
The SAR data archive at DTU Wind Energy

- Our data archive is based on ENVISAT ASAR 2002-12
  – *freely available from ESA*

- Continuation of the data supply is secured with the Sentinel-1 mission (2014 ->)

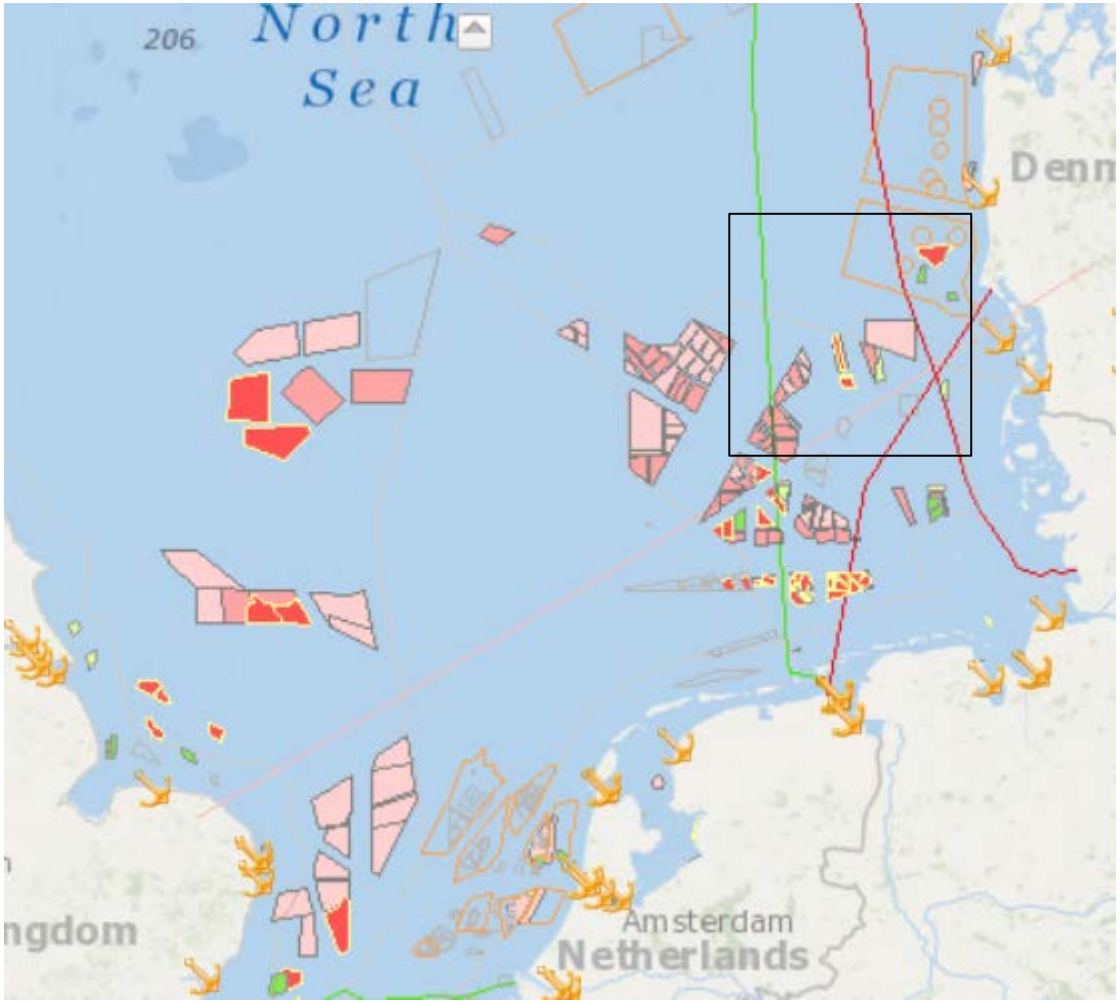
- Sentinel-1 sets new requirements for data processing
  – *much more data, rolling archive (no permanent storage)*

Processing chain for SAR wind atlas

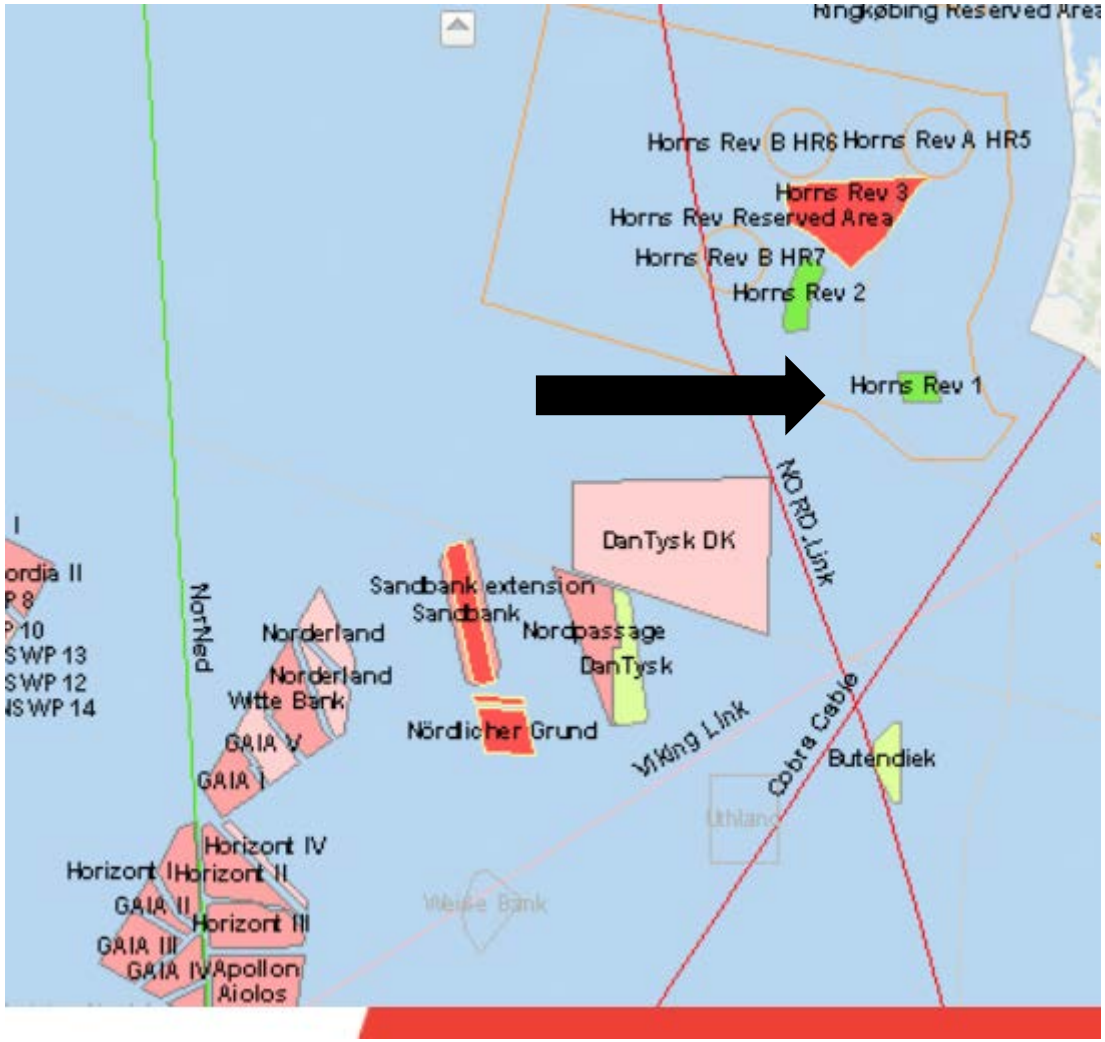


Wind farm wake

Offshore wind farm status: Source C4Offshore

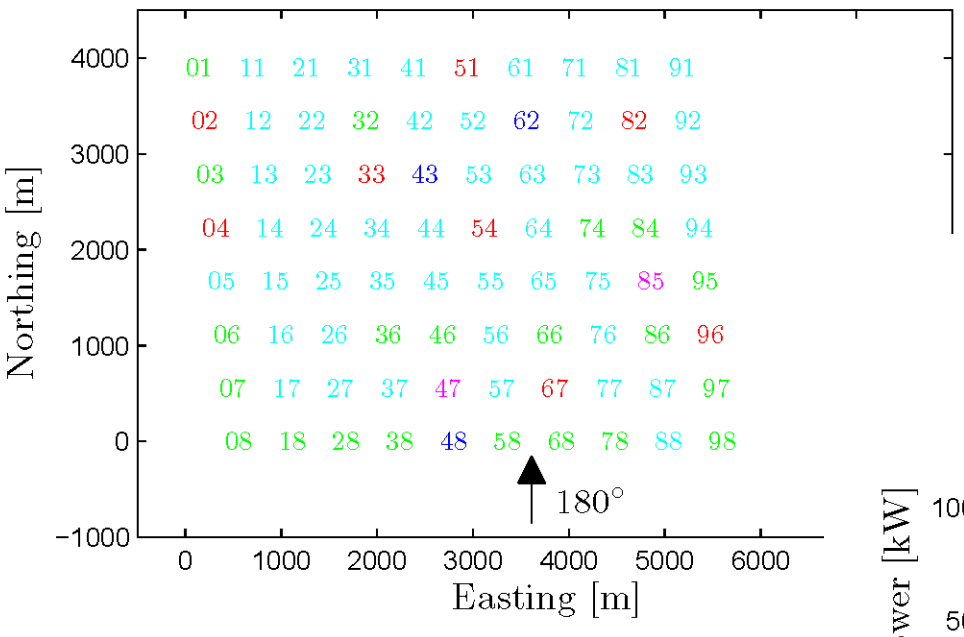


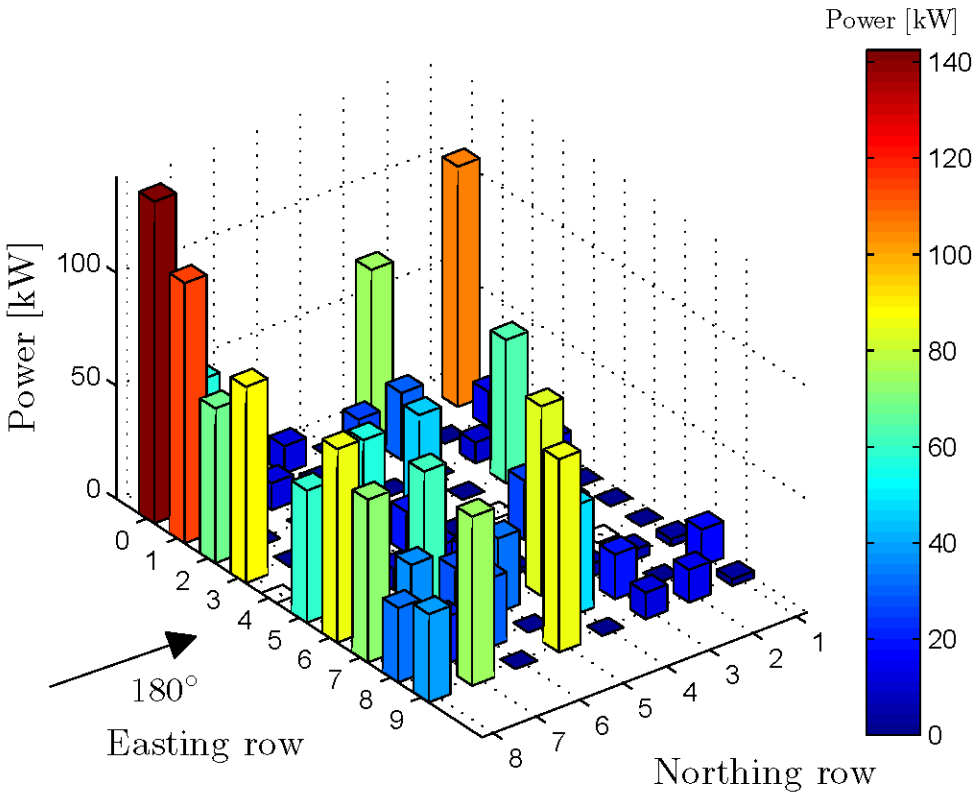
Offshore wind farm status: Source C4Offshore



Horns Rev 1

Horns Rev 1


01 11 21 31 41 51 61 71 81 91
02 12 22 32 42 52 62 72 82 92
03 13 23 33 43 53 63 73 83 93
04 14 24 34 44 54 64 74 84 94
05 15 25 35 45 55 65 75 85 95
06 16 26 36 46 56 66 76 86 96
07 17 27 37 47 57 67 77 87 97
08 18 28 38 48 58 68 78 88 98
180°
Northing [m]
Easting [m]
4000
3000
2000
1000
0
−1000
0 1000 2000 3000 4000 5000 6000


Power [kW]
140
120
100
80
60
40
20
0
Power [kW]
100
50
0
180°
Easting row
Northing row
0 1 2 3 4 5 6 7 8 9
8 7 6 5 4 3 2 1

Horns Rev 1 offshore wake photo study case

The special atmospheric conditions are characterized by a layer of cold humid supersaturated air that re-condensates to fog in the wake of the turbines. The process is fed by humid warm air up-drafted from below and adiabatic cooled air down-drafted from above by the counter-rotating swirl generated by the rotors.

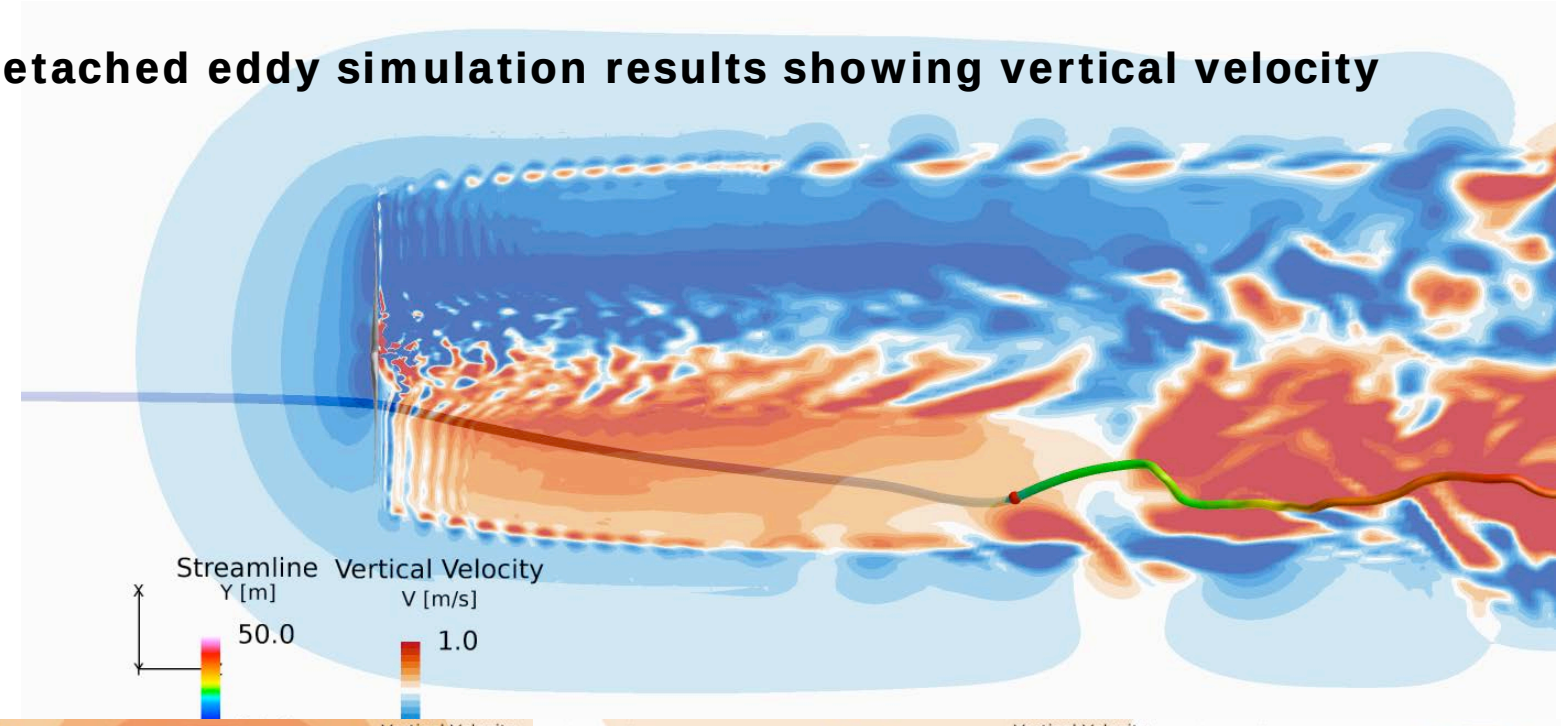
The large-scale structure of the fog has an imprint of rotational spiraling bands similar to wake flow characteristics deduced from CFD DES modeling.

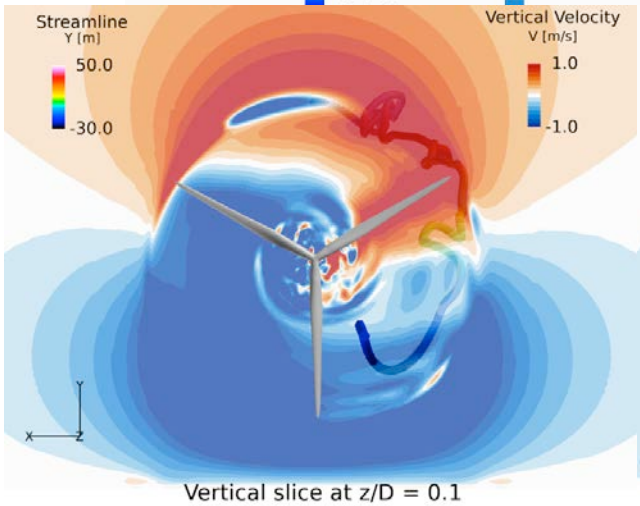
Wind speed near cut-in.

Hasager, C.B., Rasmussen, L., Peña, A., Jensen, L.E., Réthoré, P.-E., 2013, Wind farm wake: The Horns Rev photo case, *Energies*, *6*(2), 696-716

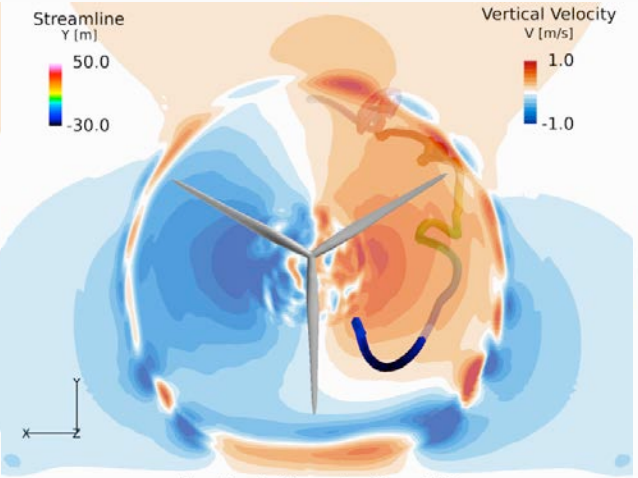
Horns Rev 1

Detached eddy simulation results showing vertical velocity

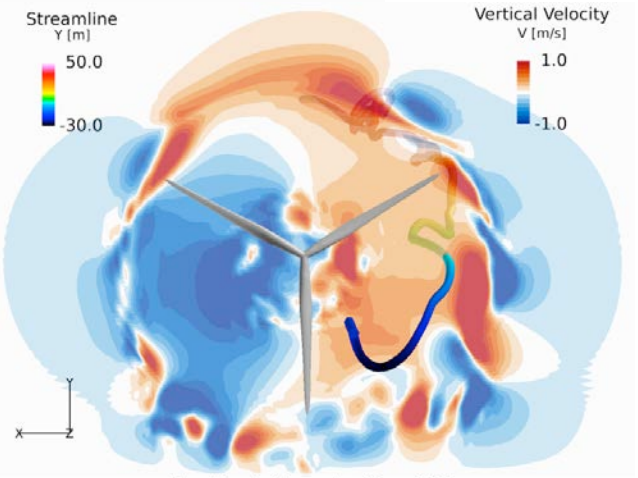




Vertical slice at z/D = 0.1



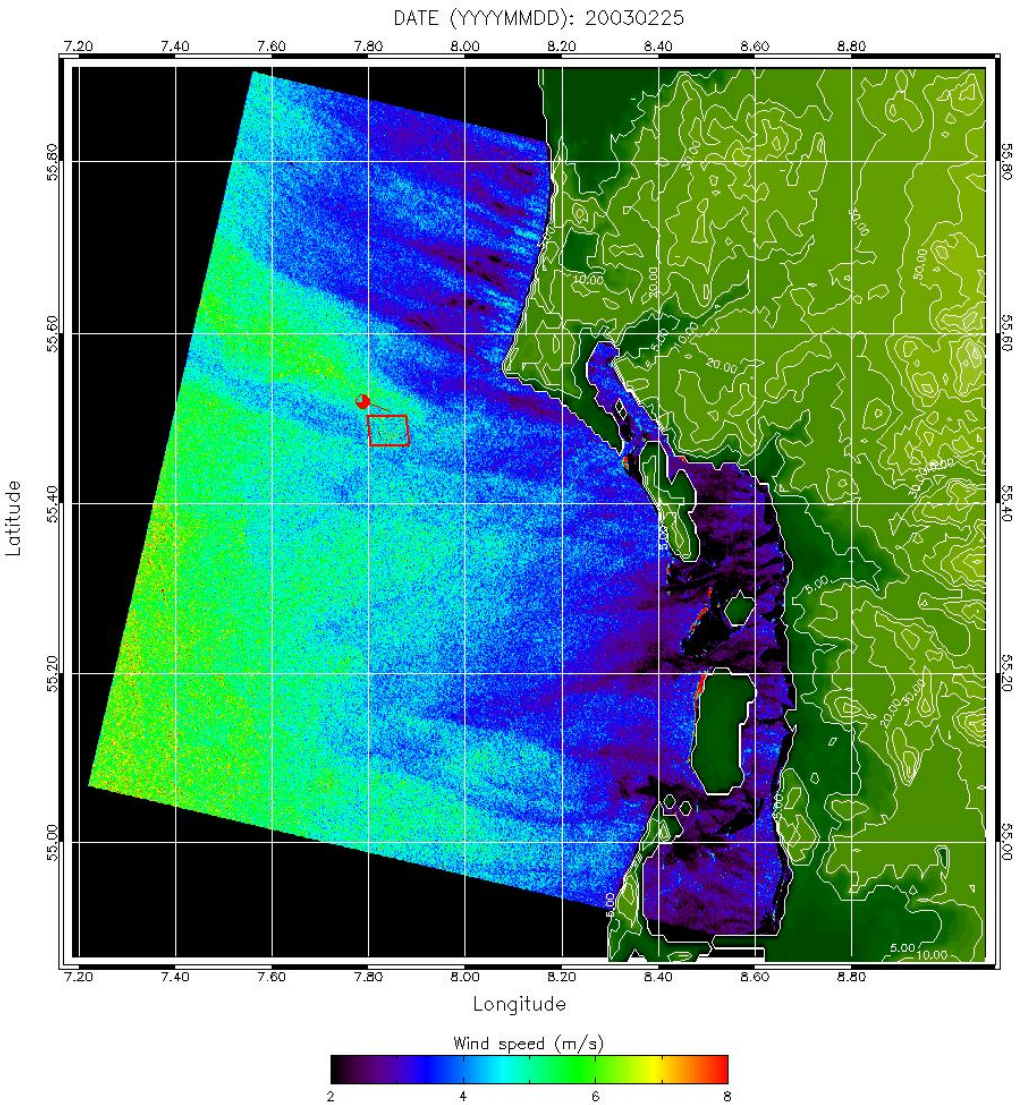
Vertical slice at z/D = 1.0



Vertical slice at z/D = 2.0

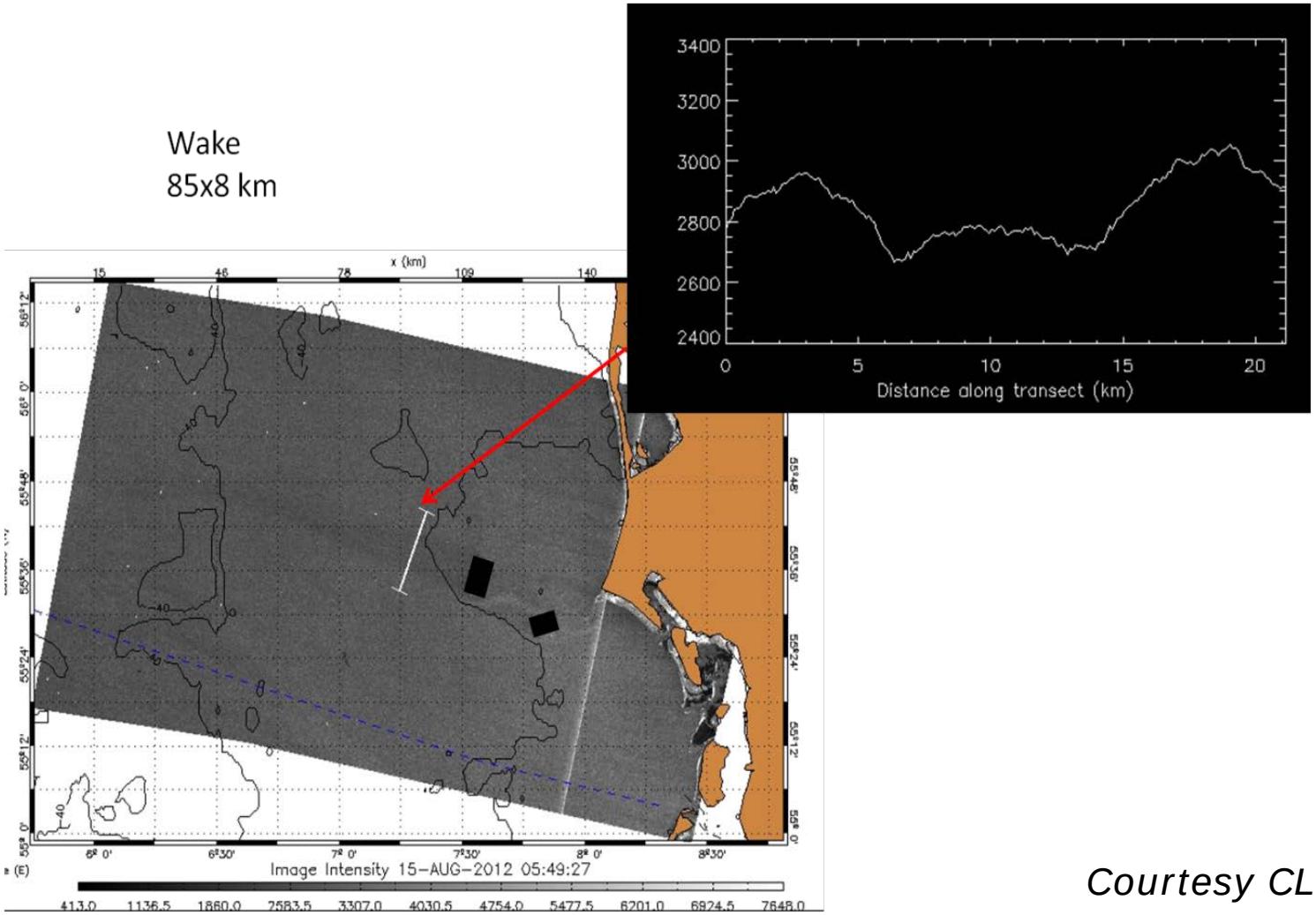
Horns Rev 1

Wind farm wake analysis



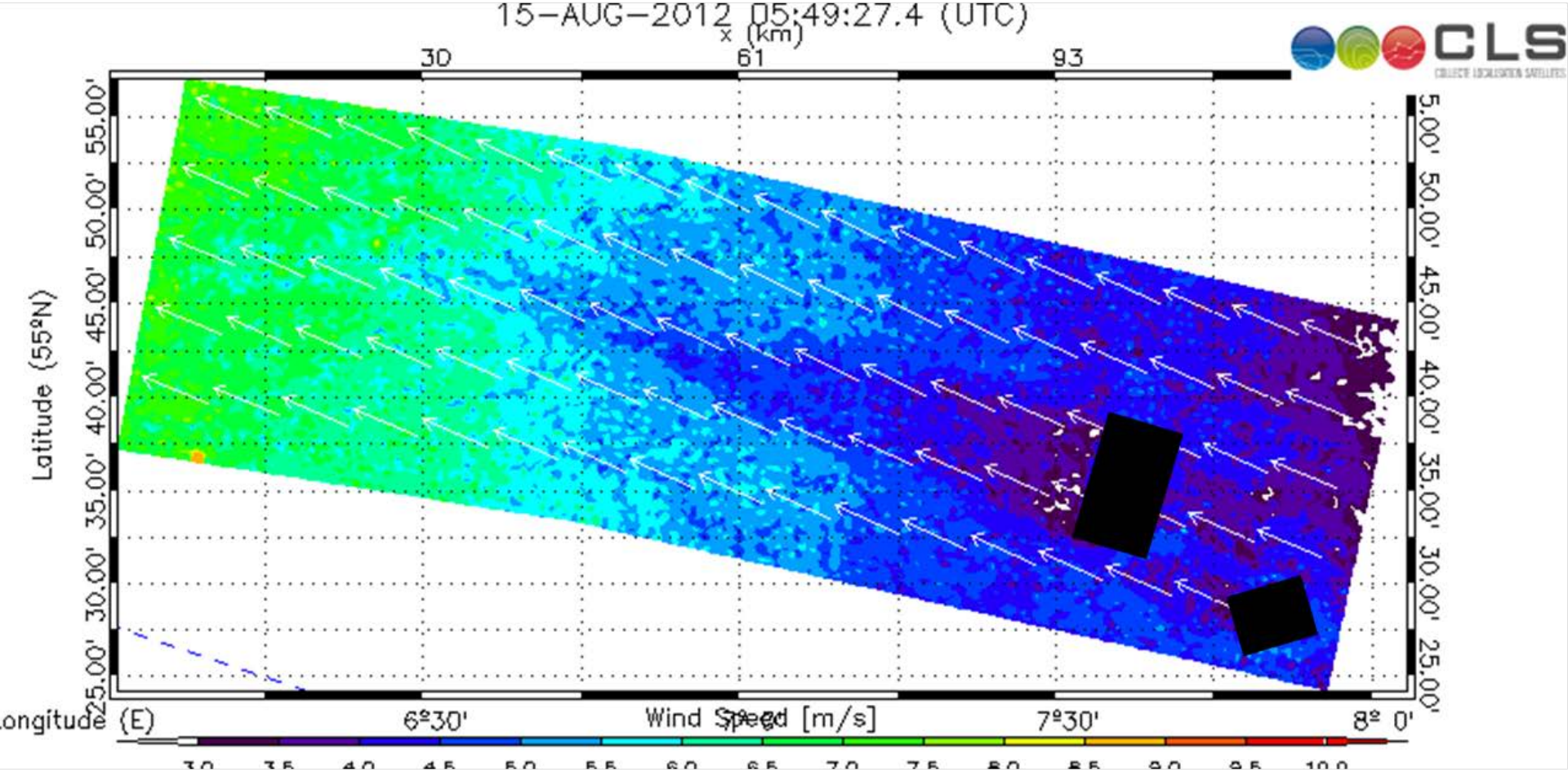
Wind field from ERS-2 SAR, Horns Rev, Denmark

Wakes in the EERA-DTOC project (2012-15)



Courtesy CLS, France

Wakes in the EERA-DTOC project (2012-15)

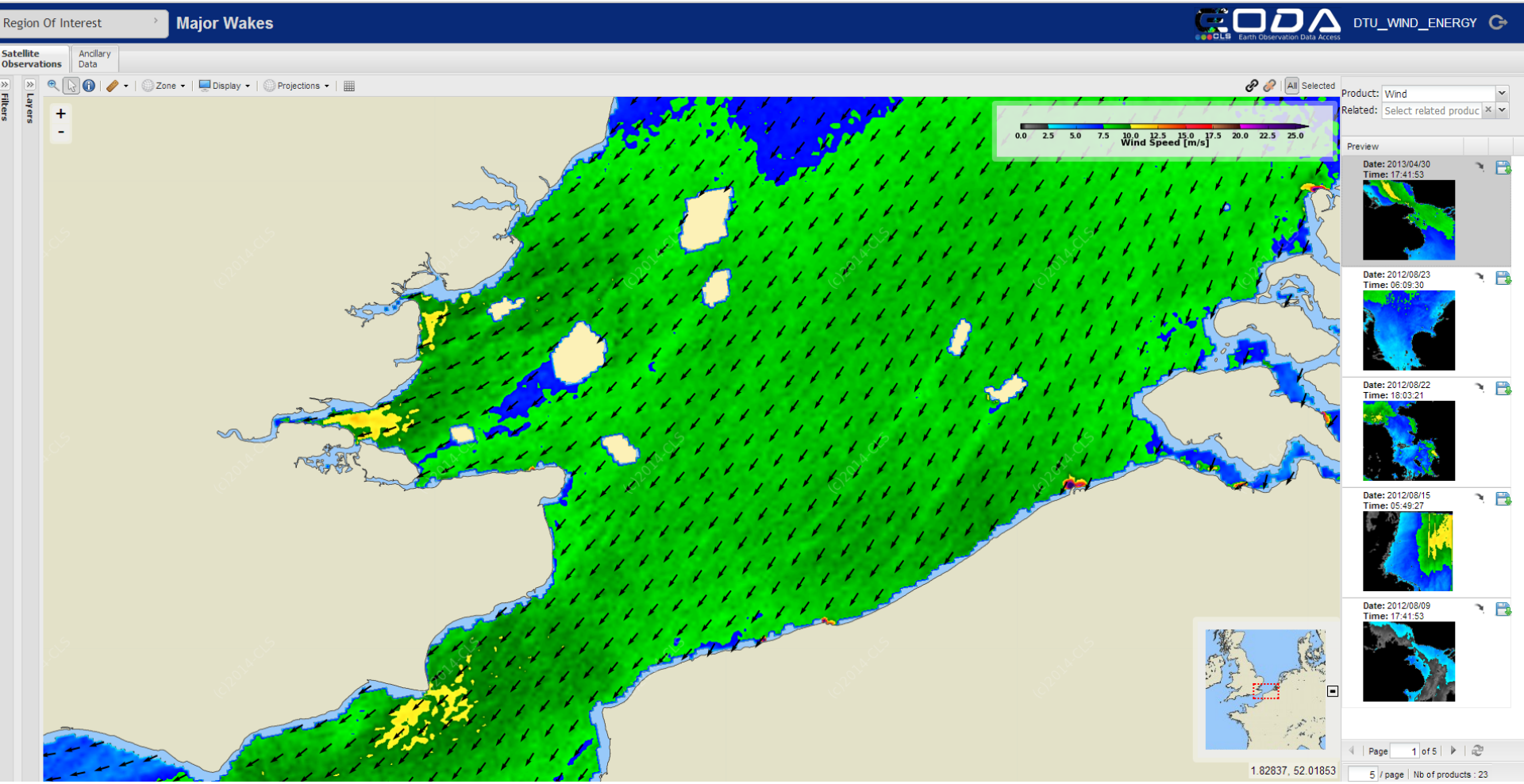


Courtesy CLS, France

Example from Radarsat-2 2013/04/30 - radar backscatter

Courtesy CLS, France

Example from Radarsat-2 2013/04/30 - wind speed



Courtesy CLS, France

Summary of SAR advantages and limitations

Advantages:

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

Coastal seas are covered (very important for wind energy applications)

Limitations:

Wind retrievals are valid for the height 10 m

A limited number of samples for statistical analyses

Acknowledgements

Satellite data:

The European Space Agency (ESA)

EUMETSAT Ocean and Sea Ice Satellite Application Facility

Remote Sensing Systems (RSS)

SAR wind field retrieval:

Collecte Localisation Satellites (CLS)

The Johns Hopkins University, Applied Physics Laboratory (JHU/APL)

Mast observations:

All mast data accessed through the NORSEWInD project. Horns Rev: DONG energy and Vattenfall, Egmond an Zee: NoordZeewind.

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