# Combining short-term lidar measurements and long-term satellite observations for offshore wind resource assessment

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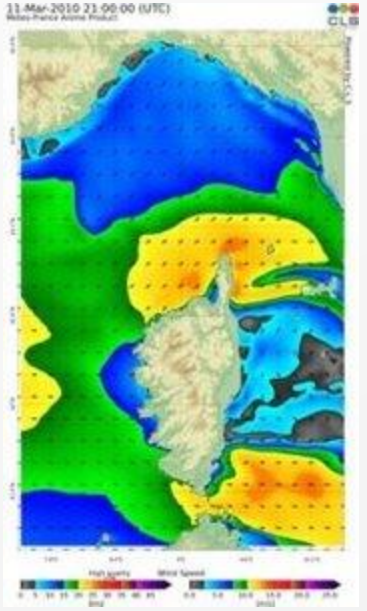
CLS Group

# Wind assessment: state-of-the-art

| | (FLOATING) LIDARS | ATMOSPHERIC MODELS |
|---|---|---|
| + | ▪ High precision<br>▪ High frequency<br>▪ 40-250 m | ▪ Spatial and temporal coverage |
| − | ▪ Single point<br>▪ One- to two-year database | ▪ Strong dependency on numerical parametrisation<br>▪ Flatten extremes<br>▪ Poor coast-to-offshore gradient representation |



Measure-Correlate-Predict (MCP)
methods in IEC 61400-1

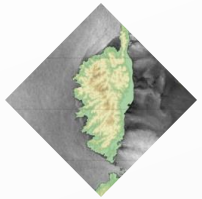
Long-term correction of measured wind data on site, based on correlation with long-term reference data

# Innovative synergy including satellite observations

**Offshore pre-development phase**
**SAR observation available; No lidar**

**When Lidar data available**

## Lev 1 SARWind ATLAS



SAR IMAGERY*

MACHINE LEARNING

METOCEAN BUOYS**

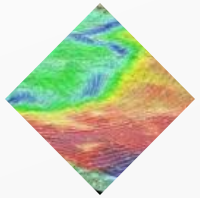
Offshore wind atlas
& Weibull distributions
at surface

*(*)*
*2 European satellites since 2015*

*(**)*
*22,000 co-locations NDBC wave buoys*

## Lev 2 SARWind POWER

EXISTING LIDARS***



HIGH-RESOLUTION ATMOSPHERIC MODEL

MACHINE LEARNING

WIND TURBINE POWER

Offshore wind atlas
& Weibull distributions
& Gross AEP *(without wake effects)*
at 40-250 m

*(***)*
*+30 years*
*12 lidars in North Sea*

## Lev 3 SARWind INSITU

INSITU DATA

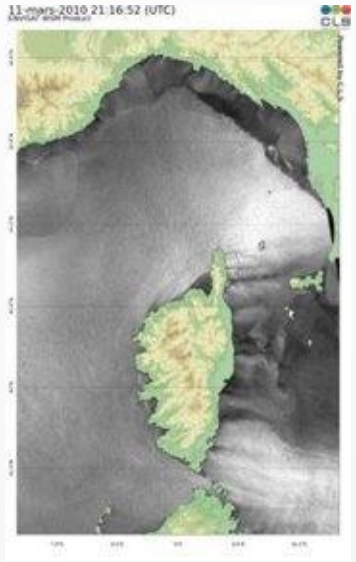
Level 2 +
Incorporating insitu data
Emulation of virtual lidars

1. What are SAR observations?
2. How do we get wind from SAR?
3. And in altitude?
4. Is it validated?
5. How can we use such data?

# SAR observations

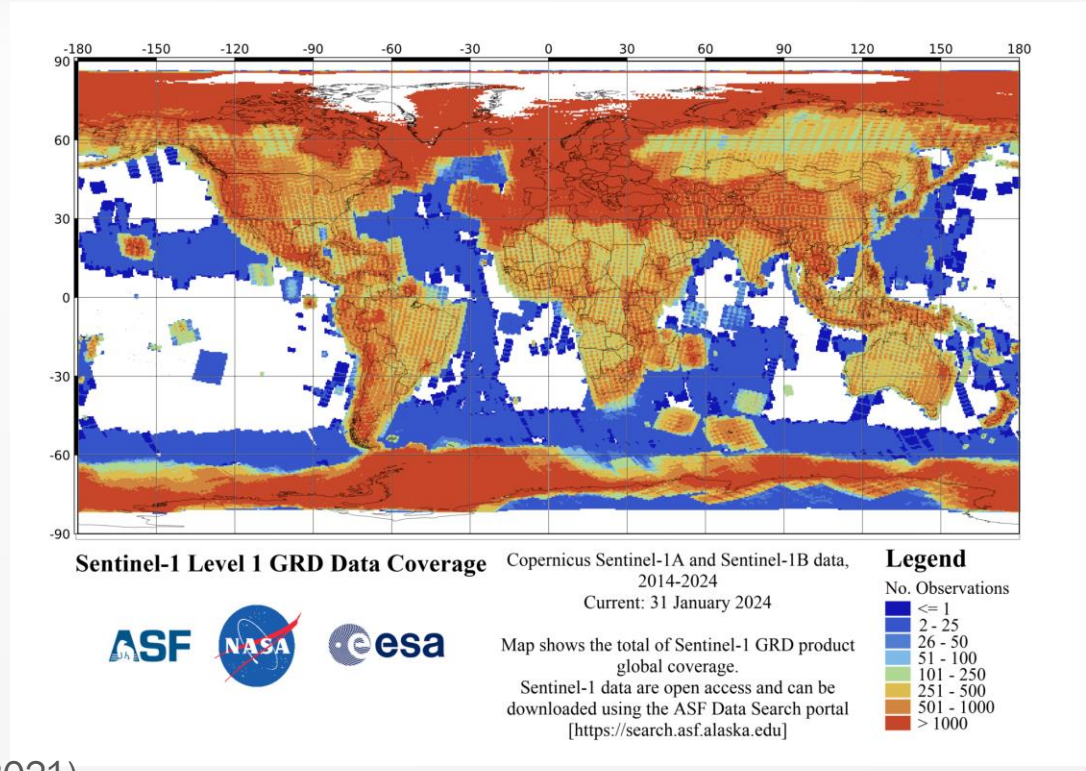
## Synthetic Aperture Radar

- Emission/reception of electromagnetic waves (C-band)
- Interaction with *O*(5 cm) ripples in equilibrium with wind stress
- Backscattered signal
  - Image of normalized radar cross section (NRCS)
- Day and night, no cloud contamination



## Spaceborne system

- Wide coverage (250 to 400 km)
- 20-year database
  - ENVISAT (2004-2012)
  - Sentinel-1A & -1B (2014-ongoing & 2016-2021)
  - Others (Radarsat-2, etc.)
- Quasi worldwide coverage
- Low-temporal sampling, always at the same time
  - ~ one passage every two days at 6AM/6PM in Europe



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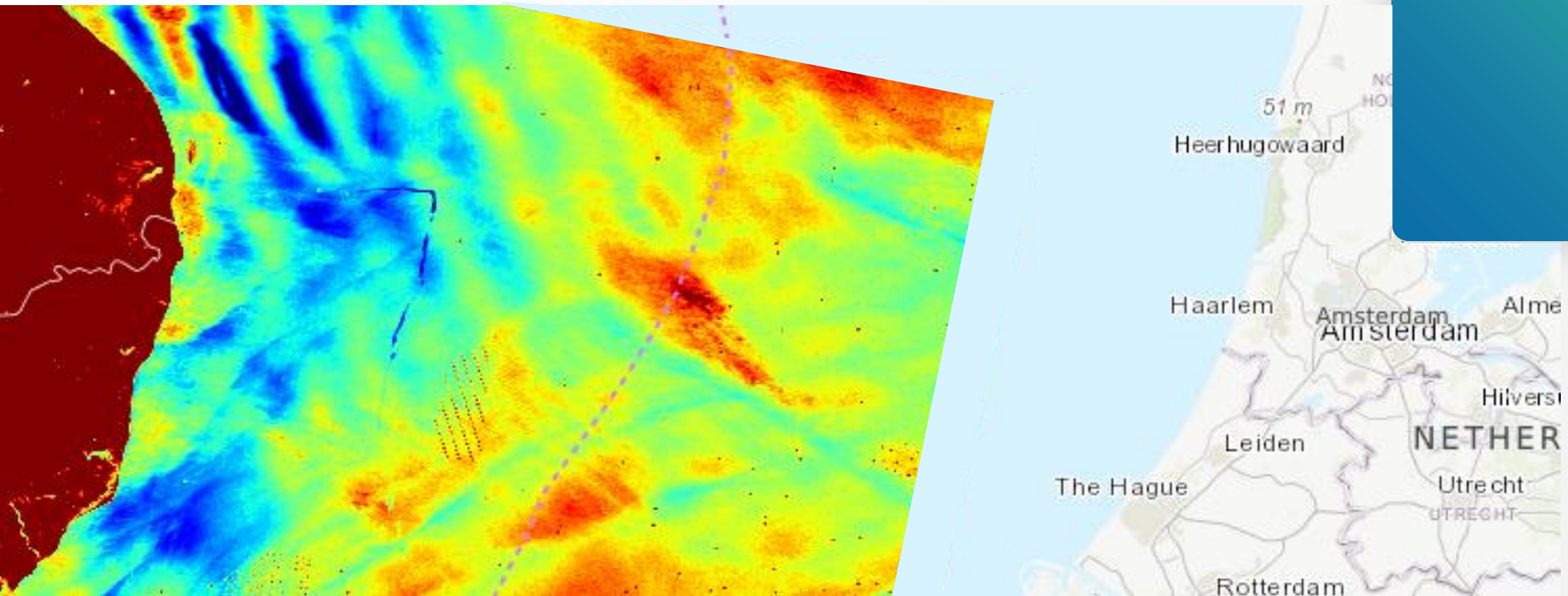
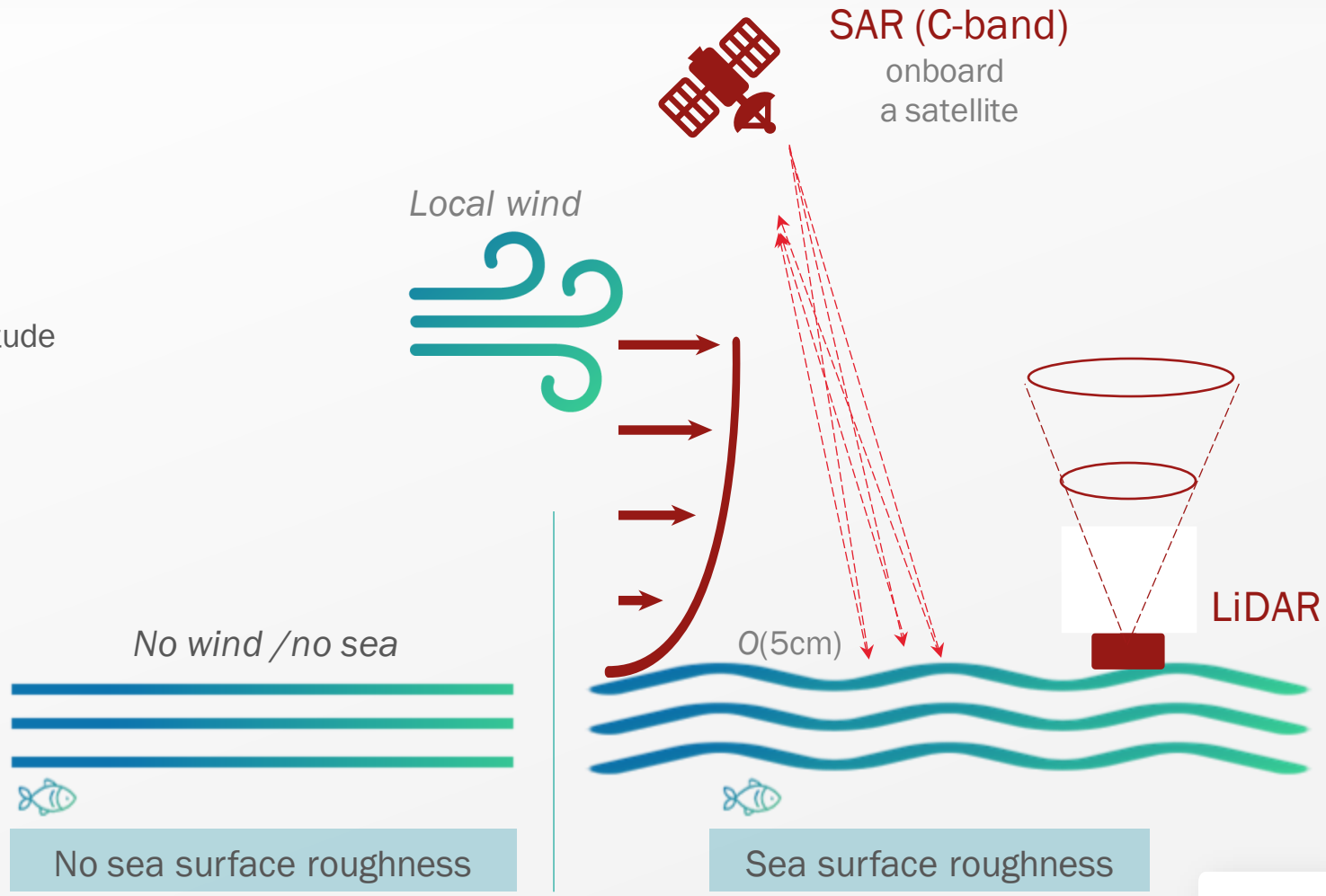


# Wind measurements from space

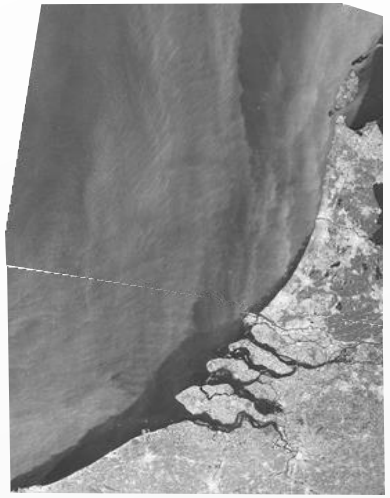
## Remote wind measurement

- Doppler LiDAR
  - Aerosol-scattered radiation
  - Intensity and phase of backscattered signal
  - Needs reconstruction to get wind speed in altitude
- FLiDAR
  - Same + motion correction algorithm
- SAR
  - Backscatter from sea surface ripples
  - Intensity and phase of backscattered signal
  - Needs reconstruction to get sea state
  - And to get wind speed?



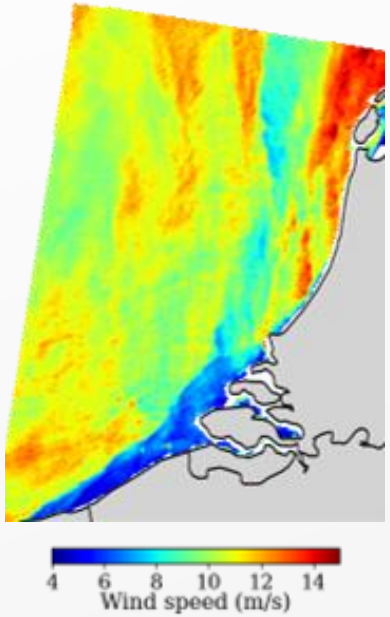
# Step 1. Surface wind speed retrieval

**SAR L-1 product**



SAR observation
2019-09-11 at 05:57 UTC
North Sea off the Netherlands

**SAR L-2B product**



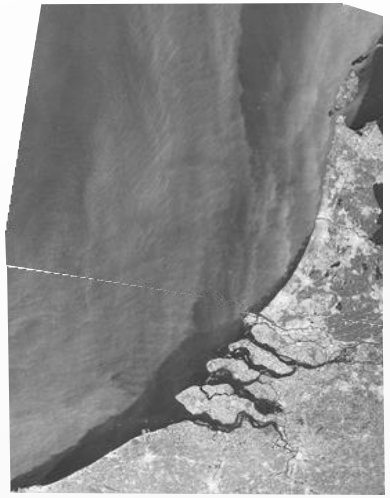

## Sea state is a direct reflection of surface wind field

- Relationship between sea roughness and wind speed and direction
- Advanced and quality-controlled process
  - CLS official provider of geophysical fields (L-2B) from post-processed SAR observations to European Space Agency
    - S-1 Annual Performance Report for 2022 SAR-MPC-0588 – Issue 1.2 –13/03/2023
  - SAR L-1 retrieved from the Copernicus Data Space Ecosystem
  - Here, newer version of processing with advanced features compared to opensource SAR products distributed by Copernicus.

✓ *South-westerly winds flowing off the Channel*
✓ *Blockage effect from the Cap Gris-Nez in France*

# Step 2. Enhanced surface wind processing

**SAR L-1 product**



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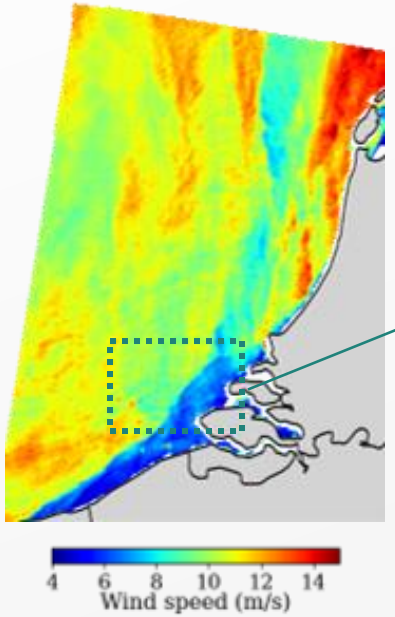
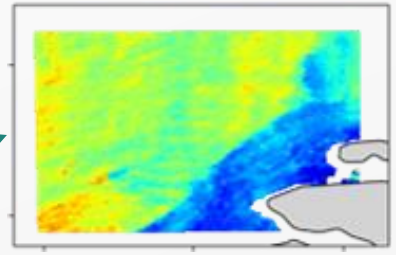
**SAR L-2B product**




**SARWind at 10 m**

10-min wind speed at 500m resolution



## Processing dedicated to offshore wind applications

- Selection of an area of interest
- Removal of bright targets (e.g. ships, wind turbines) and non-related wind phenomena (e.g. marine pollution, etc.)
- Improvement of the wind speed over the area with a **surface recalibration model**
  - Site-independent
  - Correction of biases inherent to SAR sensor
  - Based on a machine-learning algorithm trained on 22,000 buoys measurements
    - **Reduced bias** from -0.57 m/s to 0.01 m/s
    - **Reduced std** from -1.24 m/s to 0.85 m/s

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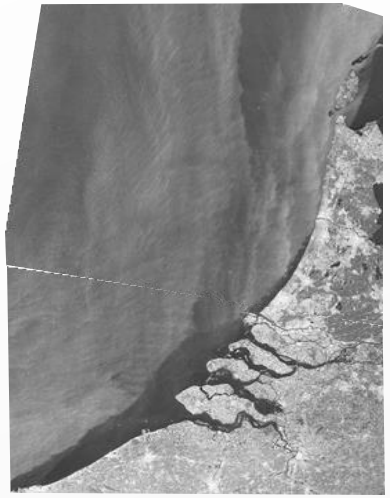
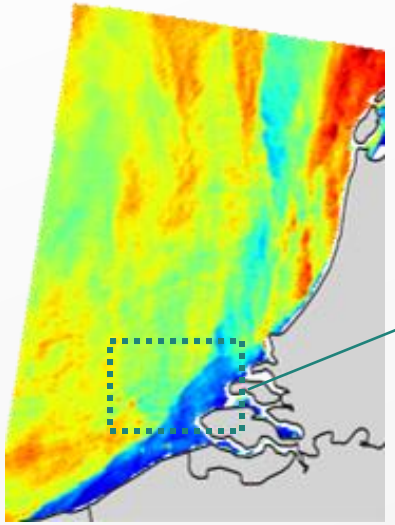
# Step 3. Vertical extrapolation

**SAR L-1 product**

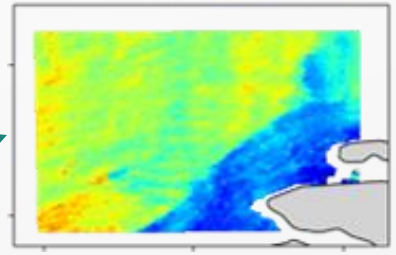


SAR observation
2019-09-11 at 05:57 UTC
North Sea off the Netherlands

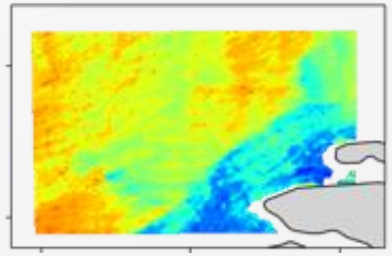
**SAR L-2B product**




**SARWind at 10 m**
10-min wind speed
at 500m resolution



**SARWind at 140 m**
10-min wind speed
at 500m resolution



Same post-processing for all satellite passages (~1500 since December 2015)

- Wind atlas derived from observations

# Advanced methodology

Wind Energ. Sci., 7, 1441–1453, 2022
https://doi.org/10.5194/wes-7-1441-2022

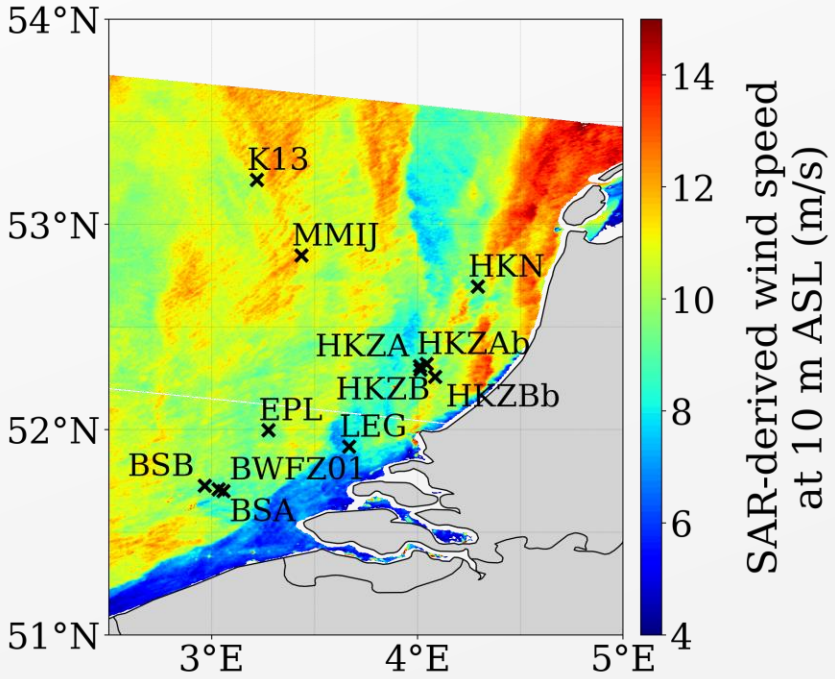

eawe european academy of wind energy
Open Access WIND ENERGY SCIENCE

**High-resolution offshore wind resource assessment at turbine hub height with Sentinel-1 synthetic aperture radar (SAR) data and machine learning**

Louis de Montera[1], Henrick Berger[1], Romain Husson[1], Pascal Appelghem[2], Laurent Guerlou[1], and Mauricio Fragoso[1]
[1]CLS Collecte Localisation Satellites, Ramonville-Saint-Agne, France
[2]Atmosky, Talence, France

## Learning the wind extrapolation from the surface

- From 40 m up to 250 m
- Based on machine learning
  - Trained on real data (12 lidars, 2-yr campaigns, 30 yr in total, North Sea)
  - To come: 40+ lidars in Europe, US, China, etc.
- Input parameters
  - Calibrated SAR surface wind speed from Step 2
  - Stability-related parameters from high-resolution atmospheric model
- Methodology published in peer-reviewed scientific journal (Wind Energy Science, 2022)
- Machine-learning model dependent to its training dataset
  - Has learnt features related to wind regimes
  - Is able to deal with similar wind regimes in other areas
  - The training dataset can be increased to deal with very specific regions.



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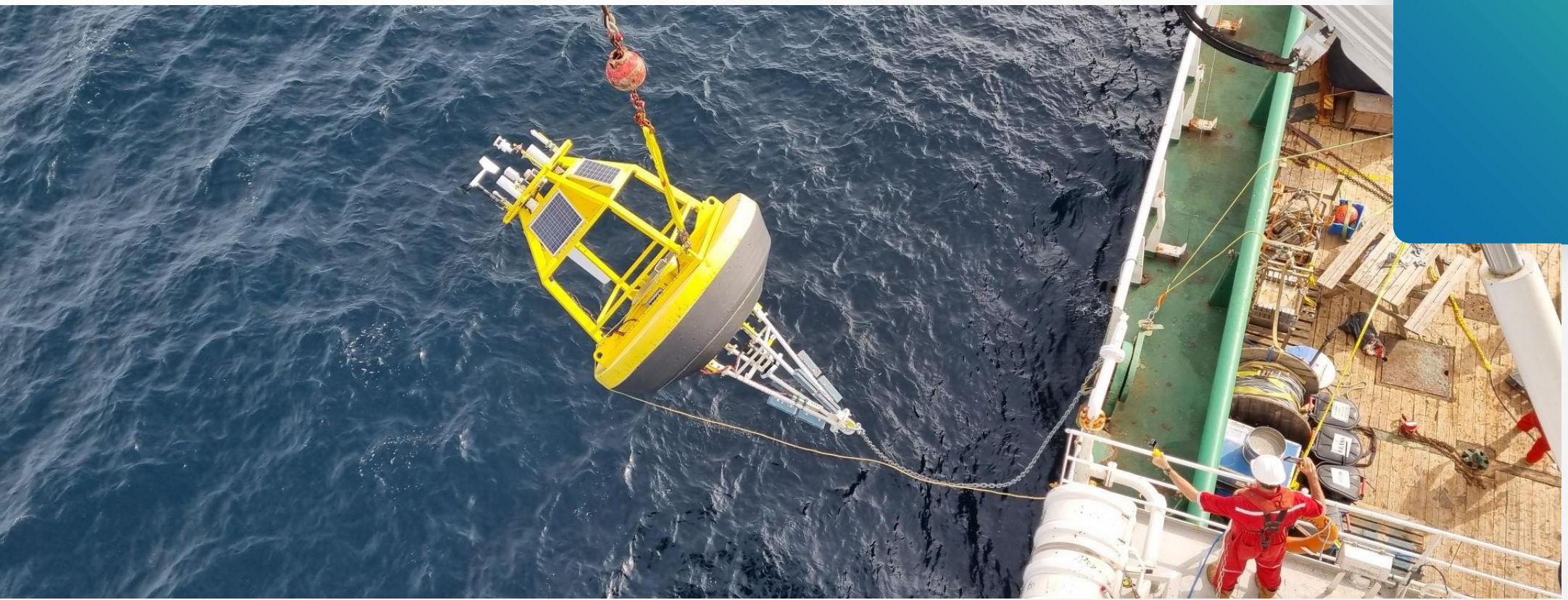


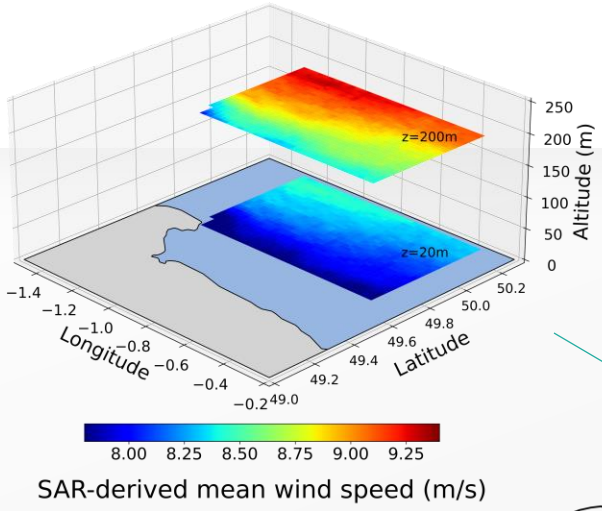
# Validation against insitu data

## 8 validation projects in Europe, North America, Asia

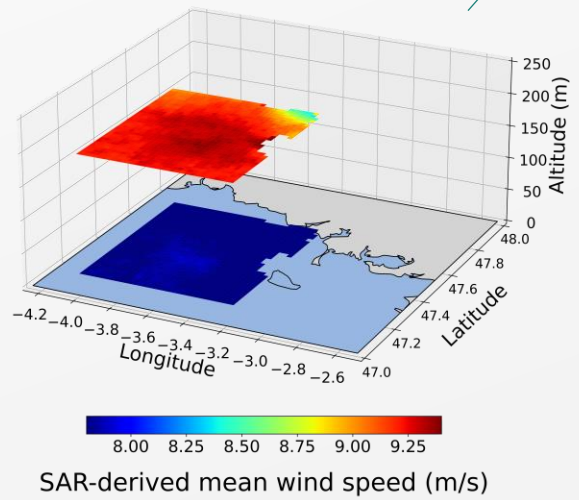
- Against anemometers on buoys, met masts, floating lidars
- Here, focus in France
  - Contract with French Directorate General for Energy and Climate from the Ministry of Energetical Transition
  - SARWind provided as data to bidders (A04 and A05)
  - Post-validation with A05 lidar measurements
    - Higher accuracy of SAR-derived winds compared to mesoscale model

| | Measurement | 1-km WRF | 500-m SARWind |
|---|---|---|---|
| Bias (m/s) | | -0.10 | 0.05 |
| Abs. bias (m/s) | 2 lidars | 1.15 | 0.98 |
| STD (m/s) | | 1.40 | 1.27 |

- Publications in conference




A04+A08 – Normandy
(1000MW + 1500MW)




A05 – South Brittany
(floating 250MW)

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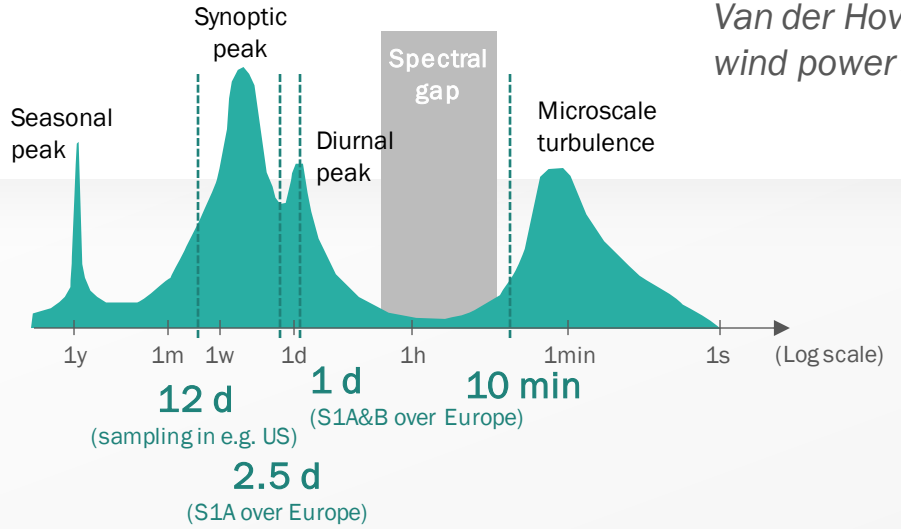
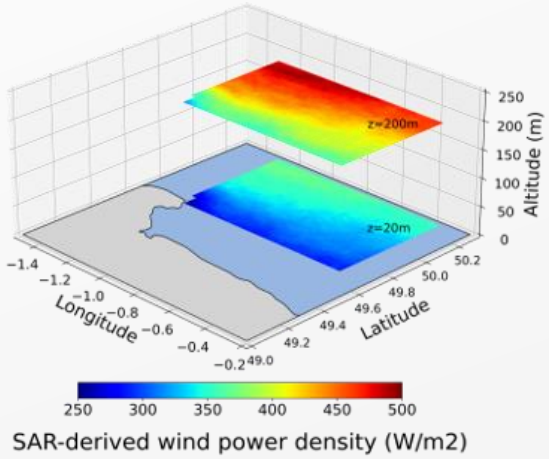
# Wind atlas




*Van der Hoven wind power spectrum*

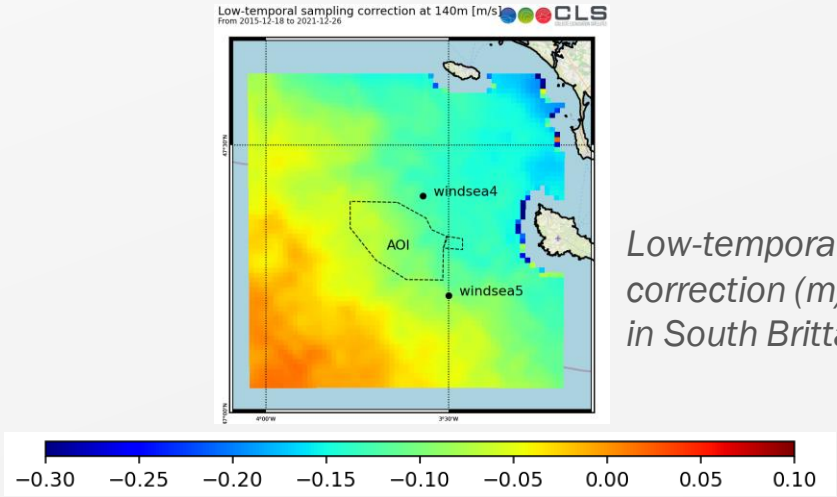
## Processing of all the SAR images available over an area

- Mean / statistics over a time period
  - Mean wind speed, standard deviation
  - Weibull distributions
  - Wind power density (W/m²)
  - Gross annual energy production (including turbine power curve, without wake losses)
- With horizontal variations: at 500-m resolution
- In altitude: 10m and 40-250m




*Normandy*

- Super-sampling
  - Need to compensate for low-temporal sampling effect
  - Mimic the satellite passages in the 1-h timeseries of a model
    - Compute bias between 1-h sampled and SAR-sampled timeseries of the model: for AO5 → -0.08 m/s
    - Correct the SAR-derived Weibull distribution

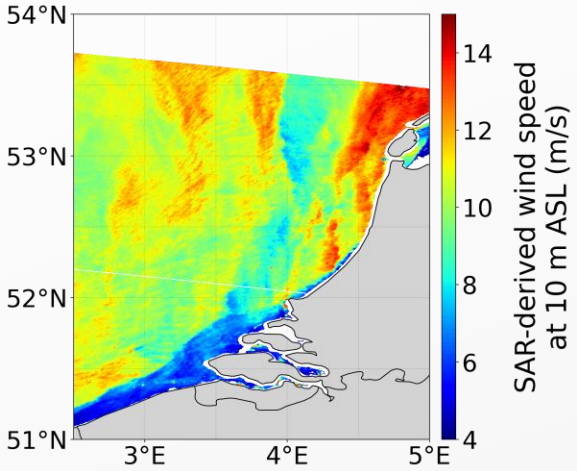



*Low-temporal sampling correction (m/s) in South Brittany*

# Dedicated nearshore observations

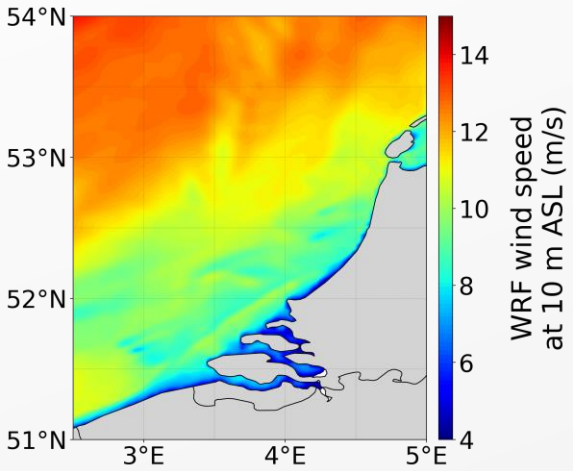
## High-resolution observations with spatial heterogeneities

10-min SAR at 10 m
(2019-09-11 at 05:57)

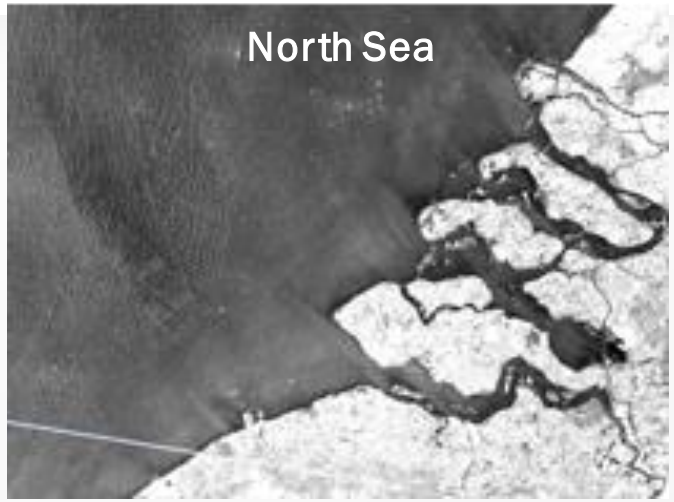



*Very detailed flow, strongly heterogeneous, coastal effects*

10-min WRF at 10 m
(2019-09-11 at 06:00)

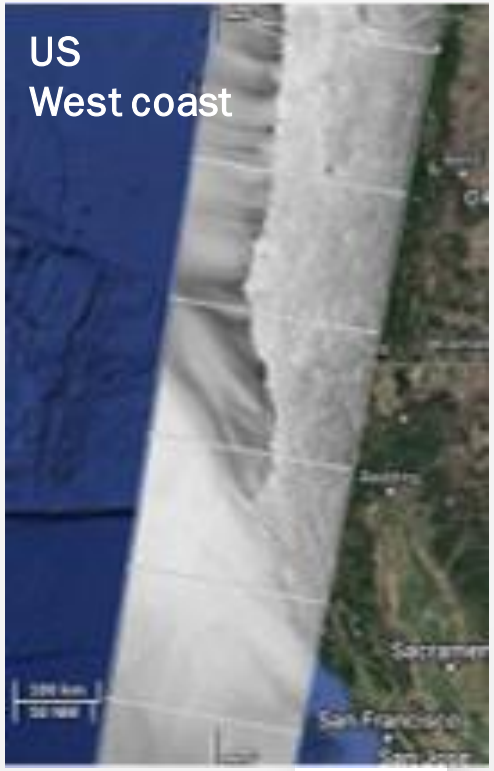



*Smoother flow, limited coastal effects*




## Observations of coastal effects

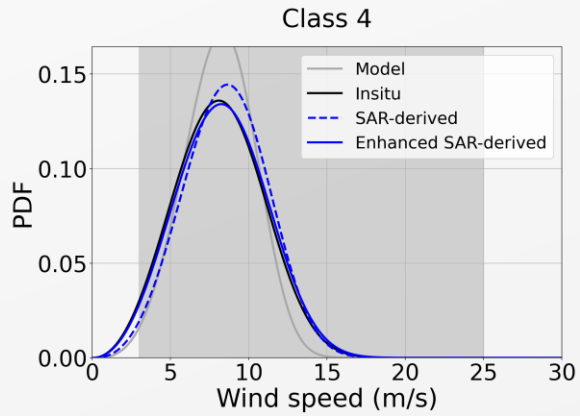
- Orography effects
- Land-sea transition, air-sea interactions
- Wakes of existing wind farms



# And more!

- Combination with Lidar data to improve SARWind statistics with short-term high-frequency dataset (similar to Measure-Correlate-Predict (MCP) methods in IEC 61400-1)
  - Improve SARWind accuracy in altitude in areas with unique/specific wind regimes or with few SAR observations
  - Methodology based on clustering algorithm with corrections derived by wind regimes
  - Validation against lidar:

| | Commercial WRF | SARWind |
|---|---|---|
| Wind power | -7.7% | -0.8% |
| Gross AEP (based on a 15MW wind turbine | -8.7% | -3.7% |




- Ongoing development to provide 1-h timeseries and not only statistics
- Future development: investigate wake effects with SAR imagery to provide P90

# SARWind for offshore wind assessment

- SARWind, a dedicated tool for all the stages of offshore projects
  - Allows to significantly reduce cost of offshore assessment
  - Provides high-definition data, all over a selected zone
  - Is available before LiDAR installation or in complement of measurement campaigns
- The team:

**Mauricio Fragoso, PhD**
Head of Energy & Infrastructure Division of CLS Group

**Marie Cathelain, PhD**
Offshore wind expert
Marine atmosphere modelling and interactions with wind farms

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# Thank you

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