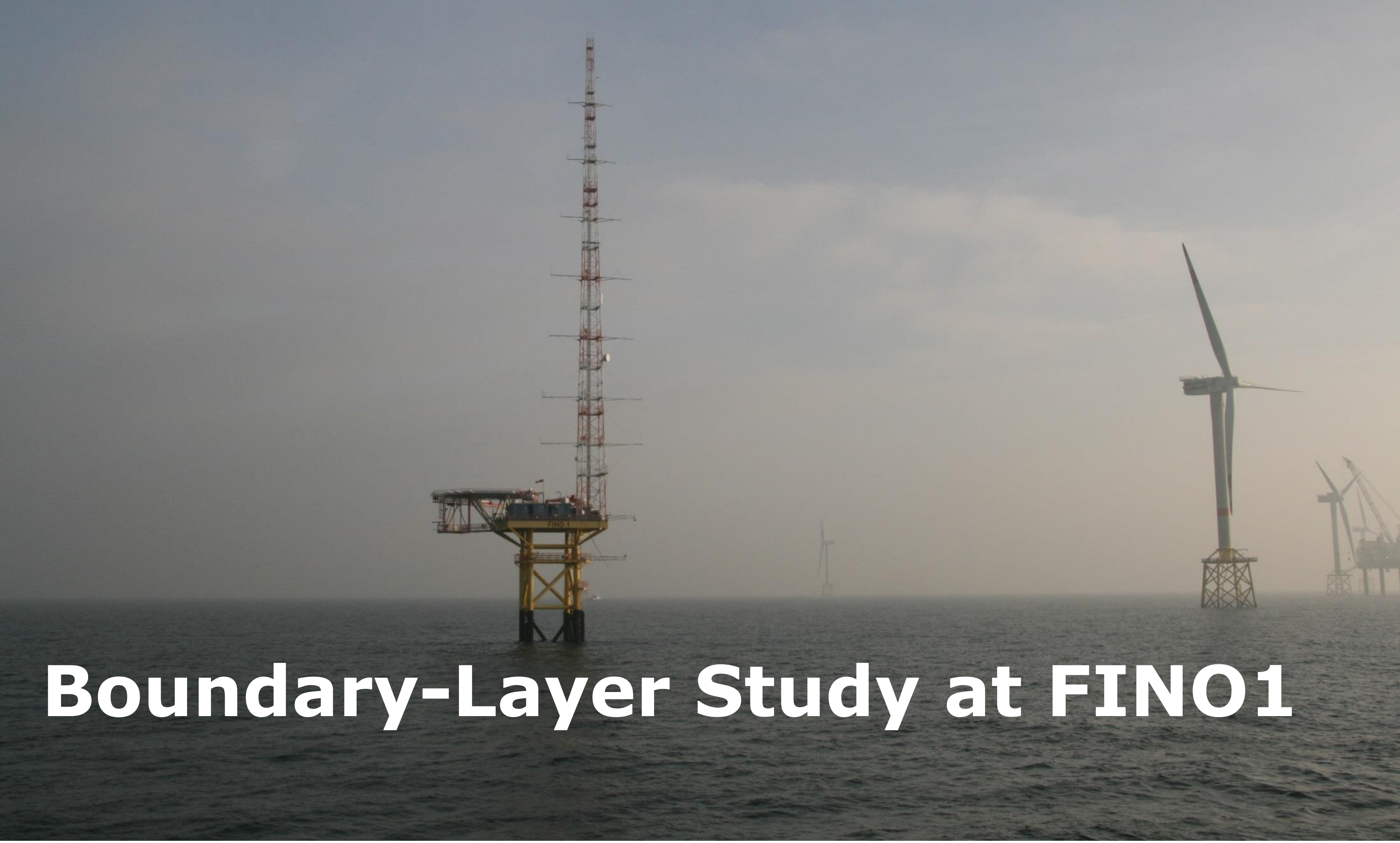
Martin Flügge (CMR), Benny Svardal (CMR), Mostafa Bakhoday Paskyabi (UoB), Ilker Fer (UoB), Stian Stavland (CMR), Joachim Reuder (UoB), Stephan Kral (UoB) and Valerie-Marie Kumer (UoB)



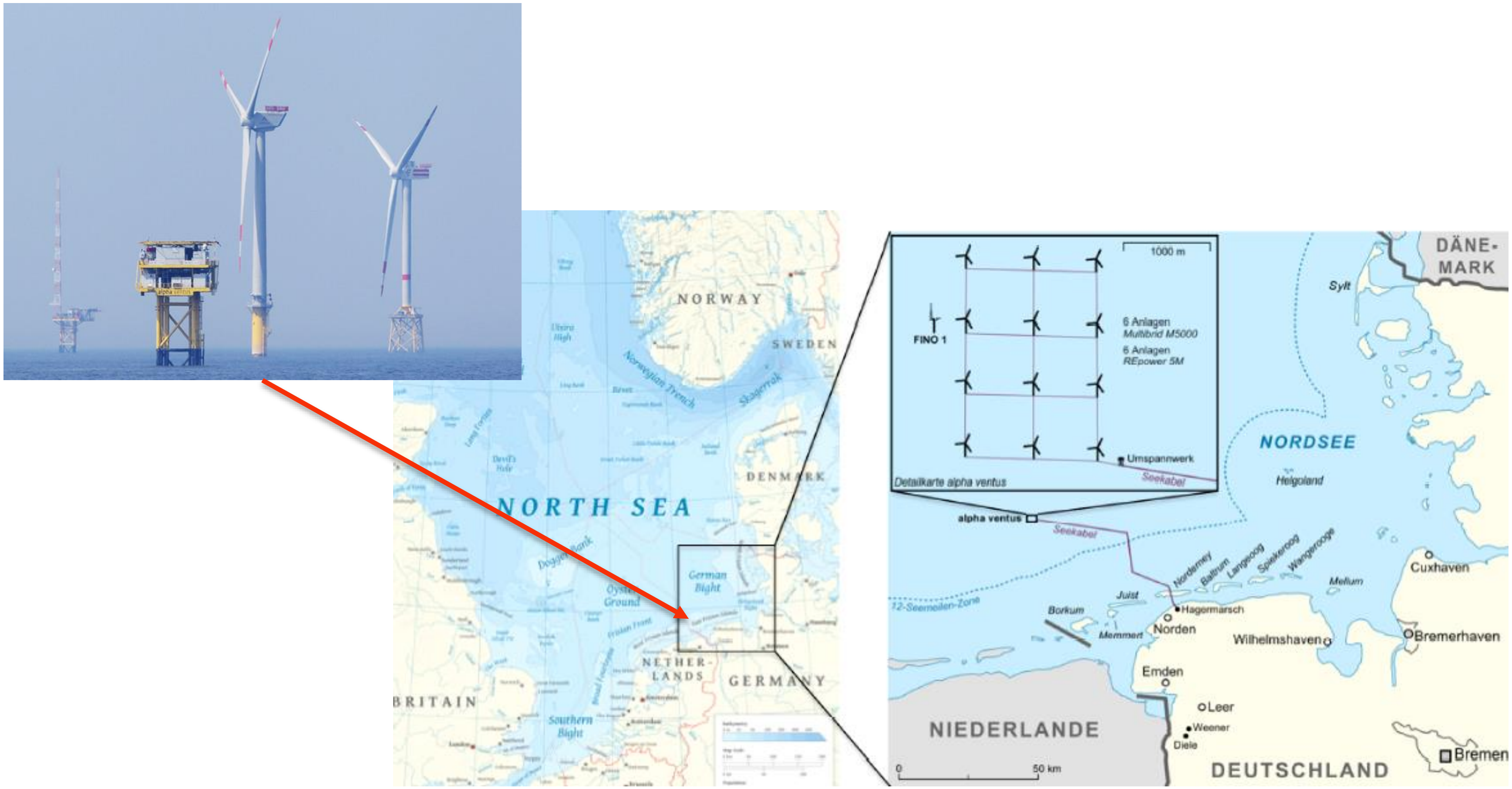
Boundary-Layer Study at FINO1

Christian Michelsen Research

UNIVERSITY OF BERGEN

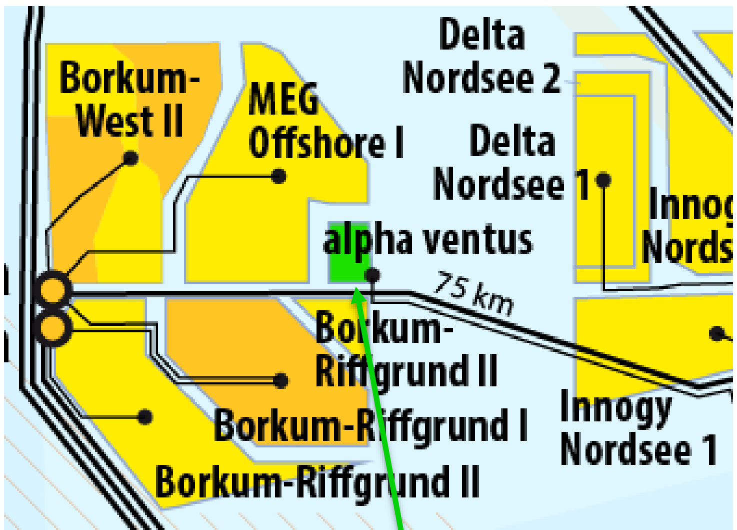
Norwegian Centre for Offshore Wind Energy

FINO1 and Alpha Ventus

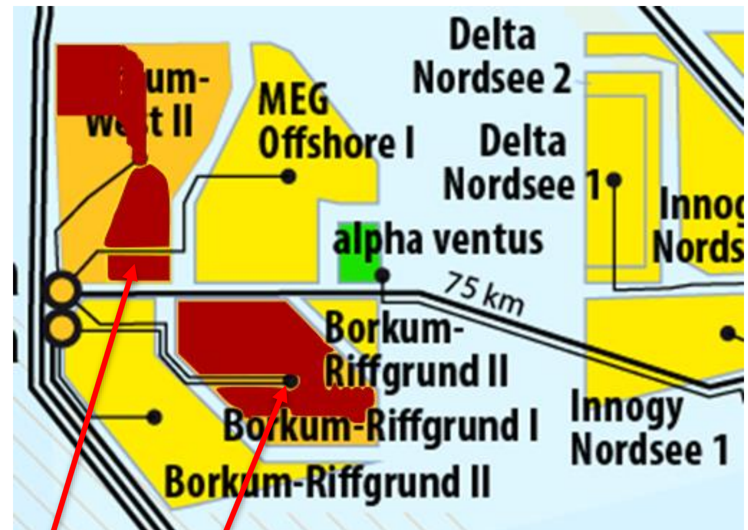


Neighboring wind farms

2013



2015



Alpha Ventus
& FINO1

Trianel

Borkum-Riffgrund 1

OBLEX-F1 motivation

The key purpose of the campaign is to improve our knowledge of the marine atmospheric boundary-layer (MABL) stability, turbulence generation processes in the water column and MABL, and offshore wind turbine wake propagation effects.

- The collected observational data will be used to validate and improve numerical models and tools for e.g. weather forecasting, marine operations and wind farm layout optimization.

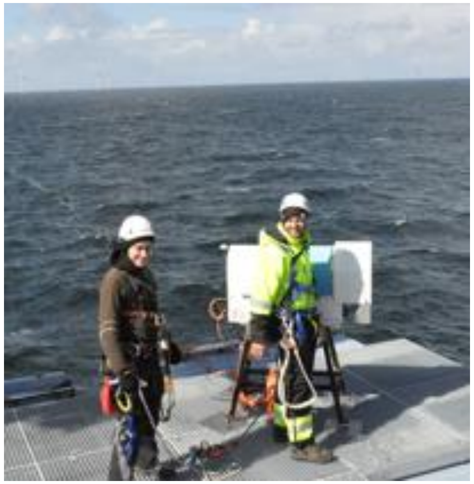
- In order to provide unique datasets for the study of boundary-layer stability in offshore conditions, simultaneous measurements of wind, temperature and humidity profiles in the MABL is performed.

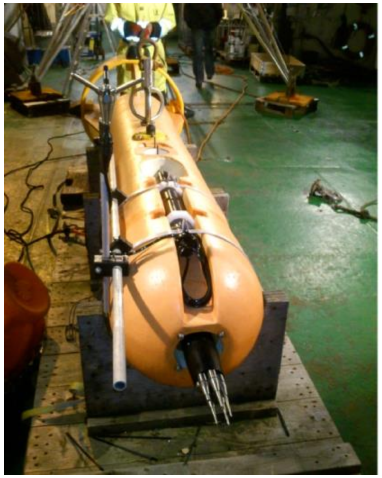
OBLEX-F1

- NORCOWE met-instrumentation: May 2015 – June 2016
- Oceanographic deployment: June – October 2015

<ins>Partners:</ins>

- *DEWI*, *BSH* and *FuE Kiel* – FINO1 reference measurements data
- *AXYS* – LiDAR buoy deployment
- *ForWind Oldenburg* – cooperation on LiDAR measurements



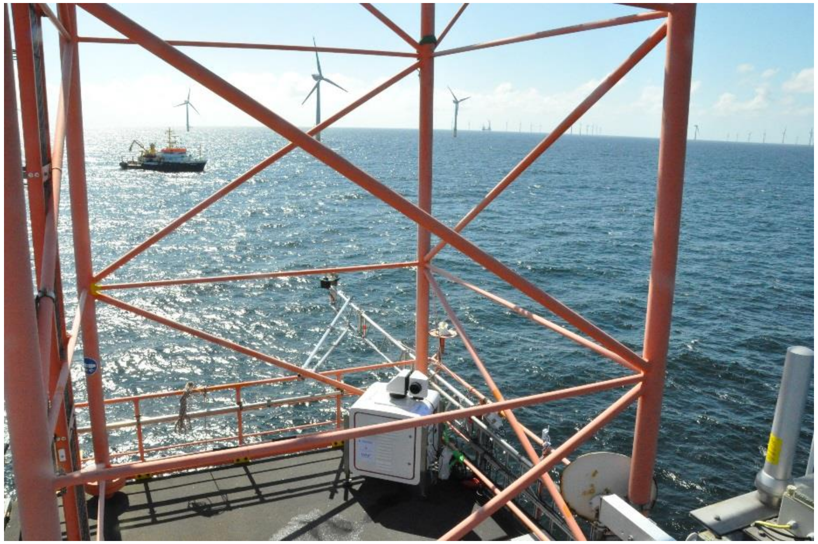



Radiometer
3D scanning LiDAR
Sonic anemometers
FINO 1
ForWind

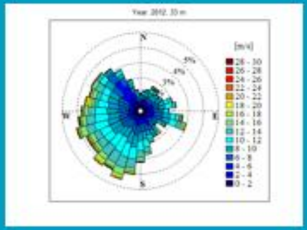
Scanning LiDAR – Leosphere 100s

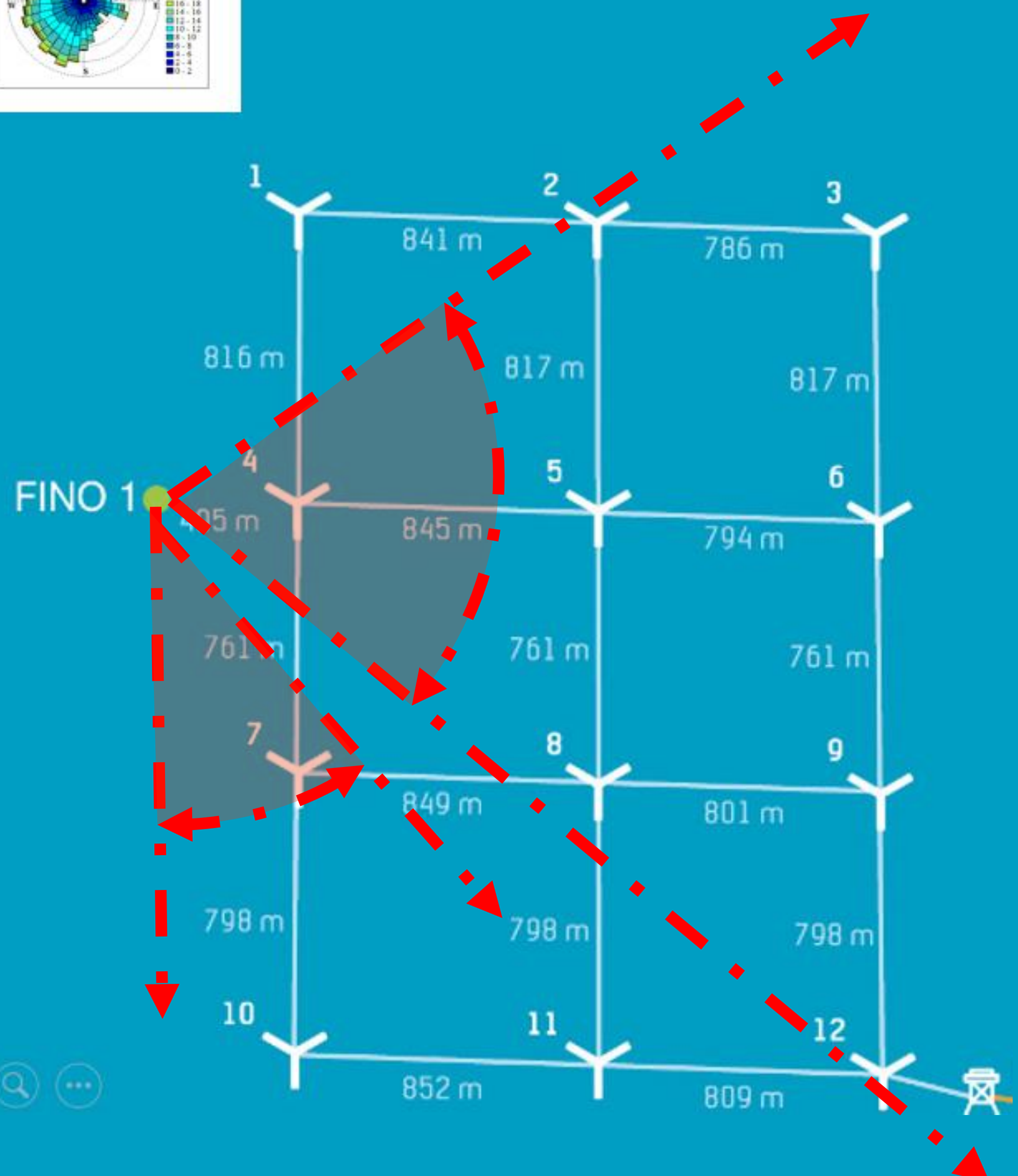
System 1 (WLS100s-37):
- Installed on top of a container platform
- Scanning across Alpha Ventus wind farm + vertical wind profiles

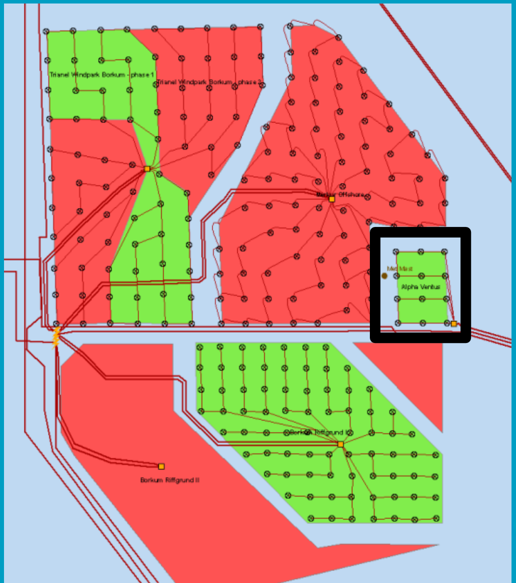
System 2 (WLS100s-34):
- Installed inside the FINO1 100 m mast
- Scanning across the SE – S wind sector



Lidar coverage



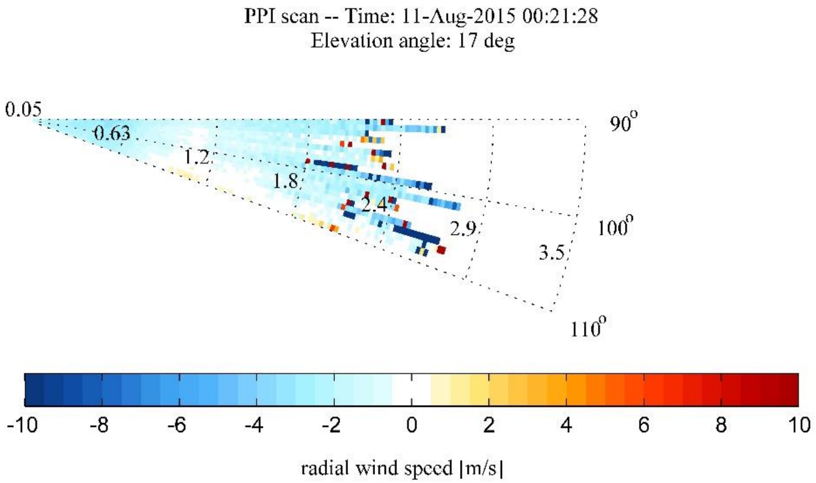




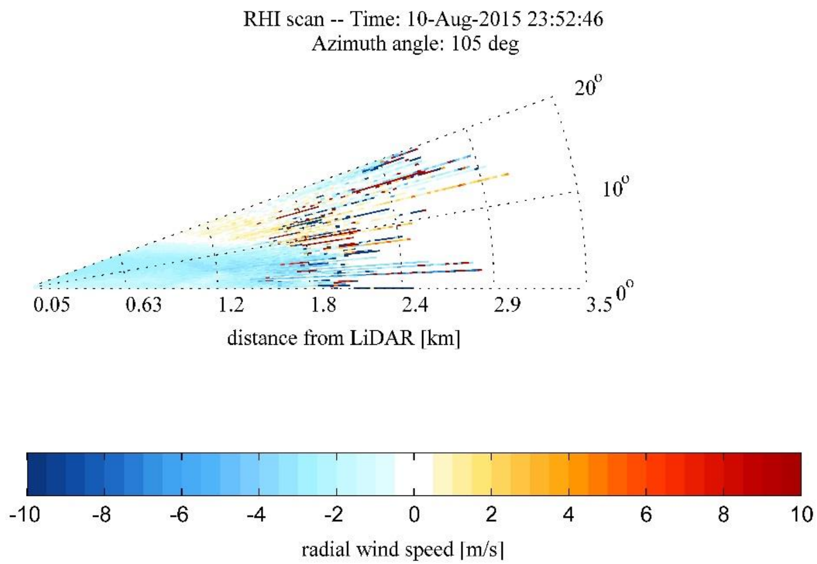
Source: http://www.4coffshore.com/windfarms/

Example of LiDAR scans – PPI and RHI mode

Plan Position Indicator (PPI) mode – constant elevation angle



Range Height Indicator (RHI) mode – constant azimuth angle

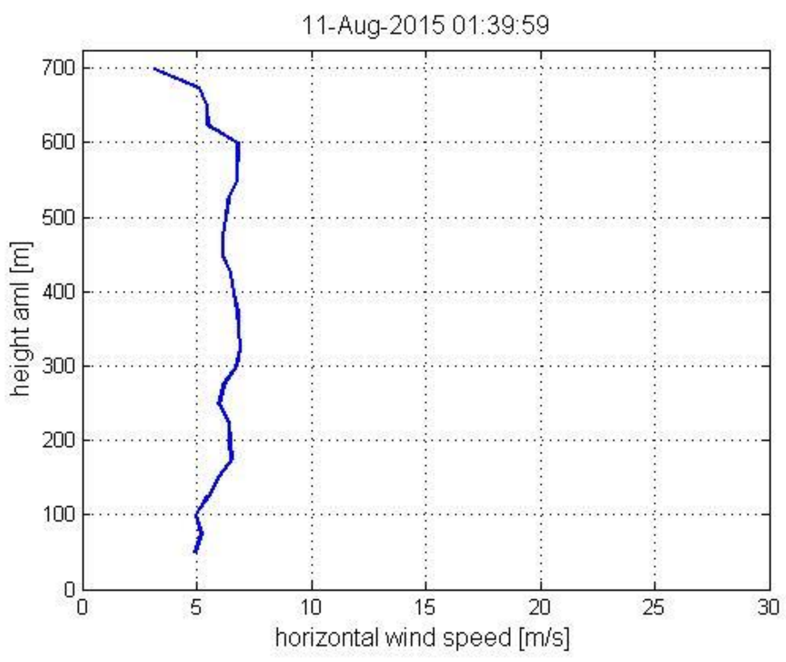


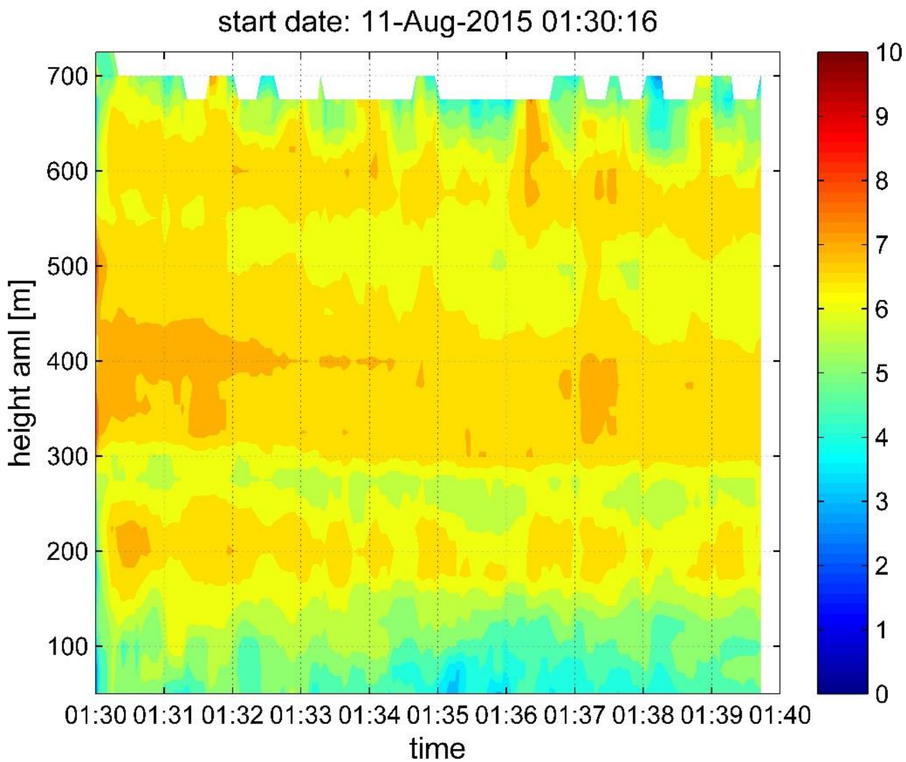
Figures showing an example of a PPI and RHI measurement, pointing towards wind turbine AV5.

- Azimuth angle: 0 – 360 deg, Elevation angle: -10 – 190 deg, Angular resolution: 0.1 deg
- Maximum rotation speed: 0.5 – 8 deg/s while acquiring data
- Measurement resolution: from 50 m up to 3500 m, 25 m intervals

Example of LiDAR scans – 3D wind vector reconstruction in DBS mode

- Radial wind speed accuracy: <0.5 m/s
- Radial wind speed range: -30 to 30 m/s





Figures showing an example of a DBS measurement.

HATPRO-R4 passive microwave radiometer

- Installed on top of container platform
- Provides vertical profiles of temperature and humidity up to an altitude of at least 1000 m
- These measurements are combined with the LiDAR wind measurements to obtain information on dynamic stability conditions at FINO1
- First time such measurements are performed continuously nearby an offshore wind farm

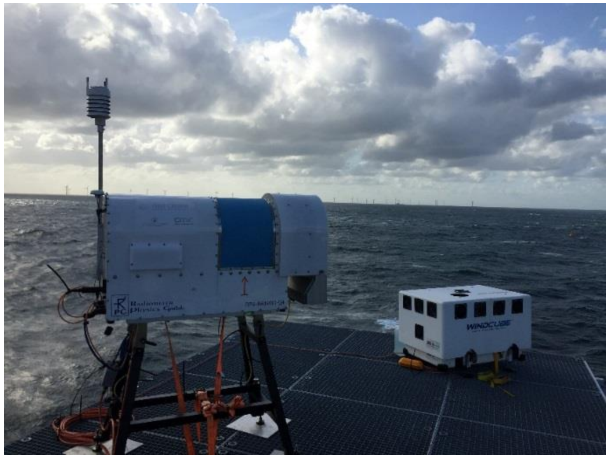
Height Range	Vertical Resolution	Accuracy
0-1200 m	30-50 m (BLM)	0.25 K RMS
0-1000 m	100 m (ZM), 30-50	0.25 K RMS
1000-2000 m	200 m	0.35 K RMS
2000-5000 m	200 m	0.50 K RMS
5000-10000 m	400 m	0.50 K RMS

***Table 6**:Typical characteristics of RPG-HATPRO-G4 temperature profiles.*

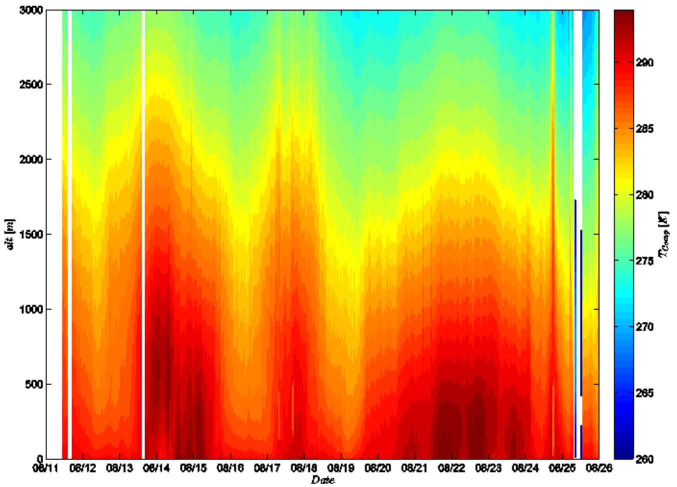
Height Range	Vertical Resolution	Accuracy (Abs Hum.)	Accuracy (Rel. Hum.)
0-1000 m	100 m	0.4 g/m³ K RMS	5% RMS
1000-2000 m	100 m	0.4 g/m³ K RMS	5% RMS
2000-5000 m	250 m	0.4 g/m³ K RMS	5% RMS
5000-10000 m	400 m	0.4 g/m³ K RMS	5% RMS

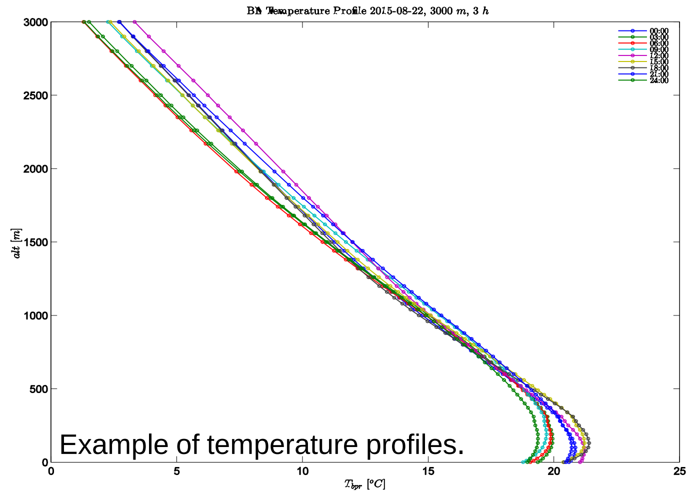
***Table 7:** Typical characteristics of RPG-HATPRO-G4 humidity profiles.*

Source: Radiometer Physics GmbH

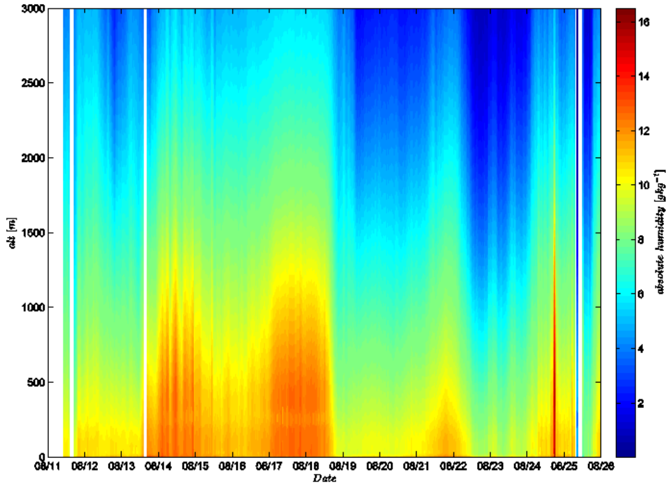


HATPRO-R4 passive microwave radiometer

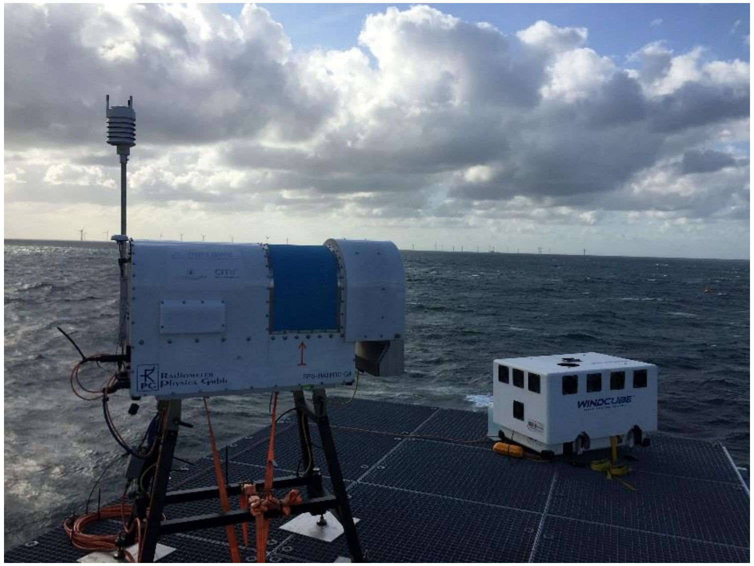




Example of temperature profiles.



Figures showing an example of temperature (upper panel) and humidity (lower panel) Hovmøller diagrams.



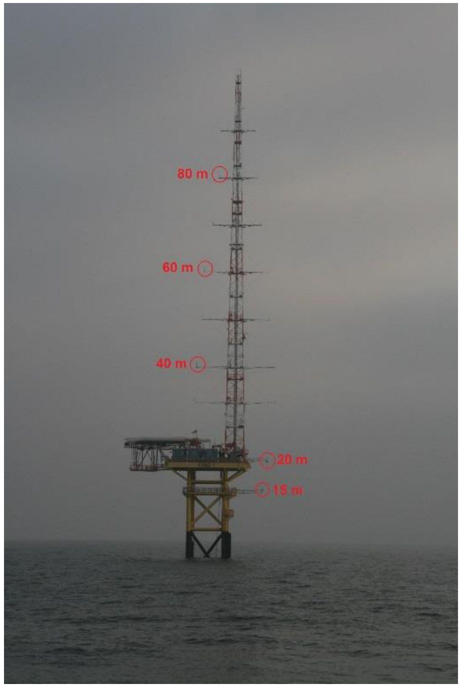
Ultra sonic anemometer (USA) measurements

- Two additional Gill R3-100 anemometers installed on outward facing booms at 15 and 20 masl
- FINO1 USA installed at 40, 60 and 80 masl – NW site of 100 m mast
- High frequency (25 Hz) measurement of the 3D wind vector (U,V,W)
- Provides information about turbulent fluxes at the measurement height

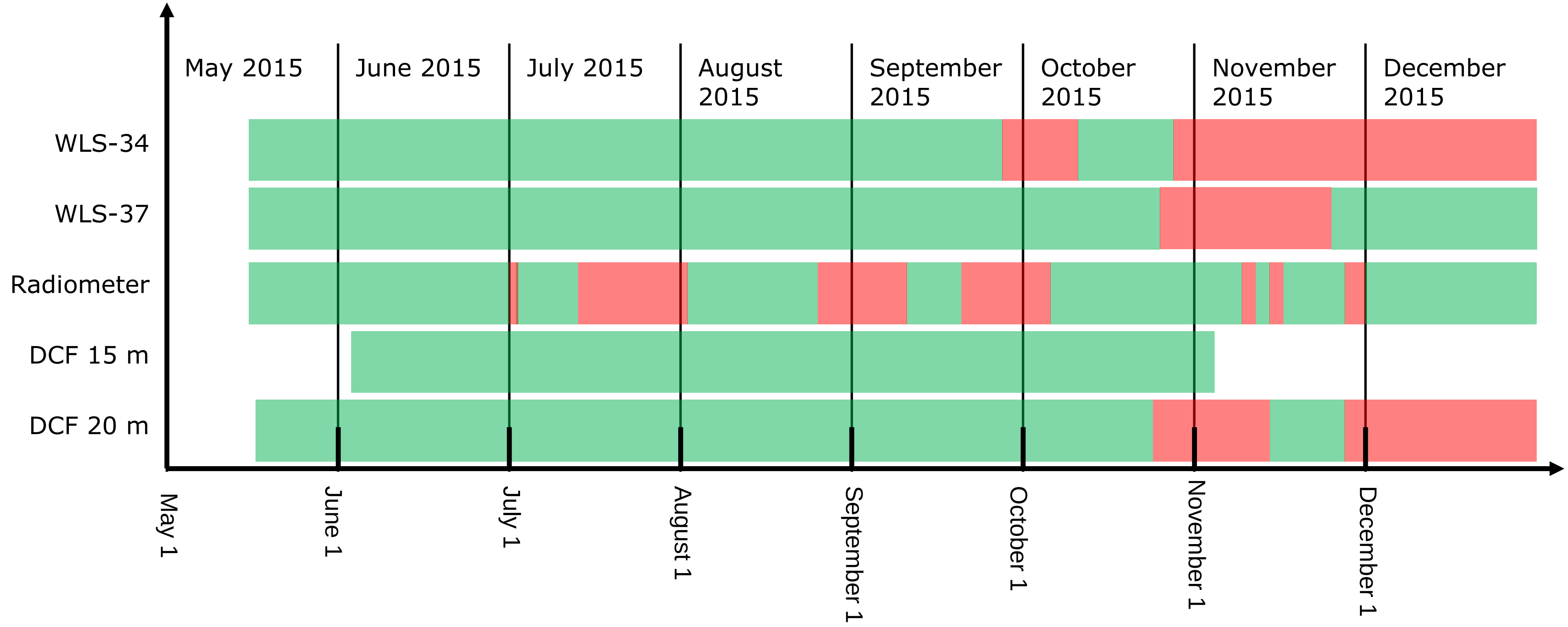
The array of USA provides independent information about the vertical wind profile and the turbulence intensity between 15 – 80 masl.

It also provides information about heat and momentum fluxes which is highly needed for the characterization of the MABL.

Together with the ocean equipment, the lowest measurement level (15 m) provides flux measurements for air-sea interaction.



Availability of met-data



Oceanographic measurements

The overall aim is to gain a better understanding of the interactions between the atmosphere, the ocean and offshore wind farms, such as single turbine and wind farm wake characteristics in the presence of combined wind and wake effects.

⇩

How does the wind field around offshore wind farms influence the ocean and vice versa?

Sullivan et al, 2008

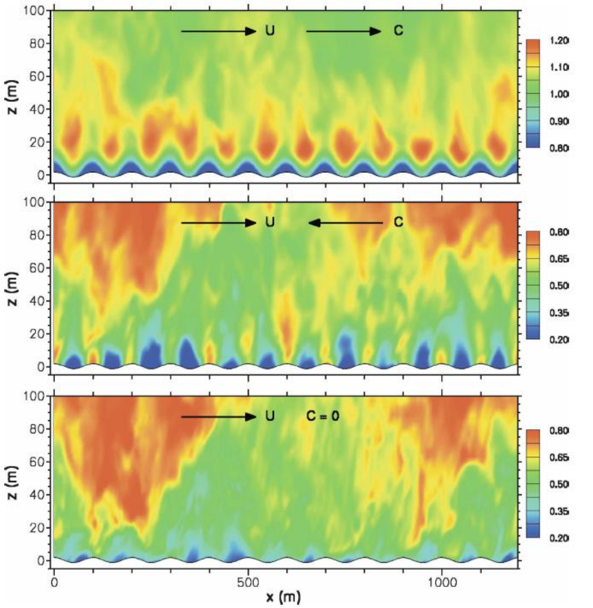


FIG. 5. Contours of the u component of the horizontal wind field for cases with moving and stationary surface waves. The nondimensional field shown is $\overline{u}/U_g$. (top) Wind following waves; (middle) wind opposing waves; and (bottom) stationary bumps. For each case the geostrophic wind $(U_g, V_g) = (5, 0)$ m s^{-1} and the wave slope $ak = 0.1$ where the wave amplitude $a = 1.6$ m. In the top and middle panels the wave phase speed $c = 12.5$ m s^{-1}. The color bar changes between the top and middle panels. Note the supergeostrophic winds near the surface in the top panel.

Sullivan et al, 2014

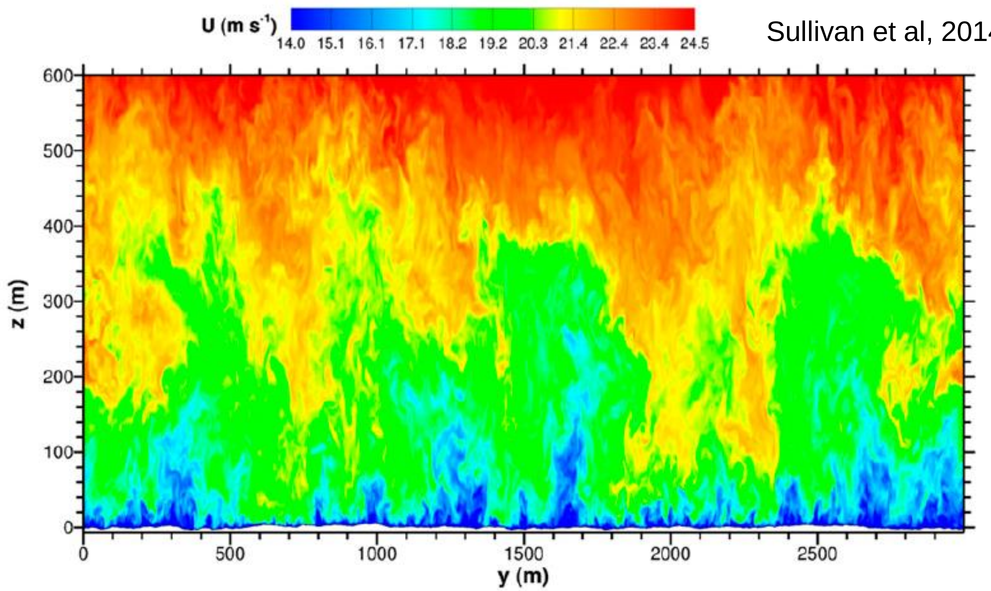
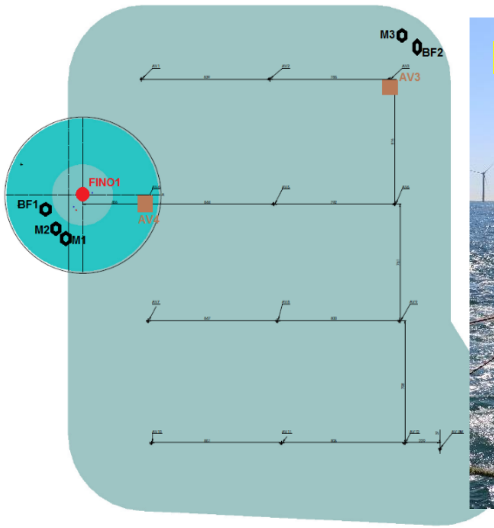
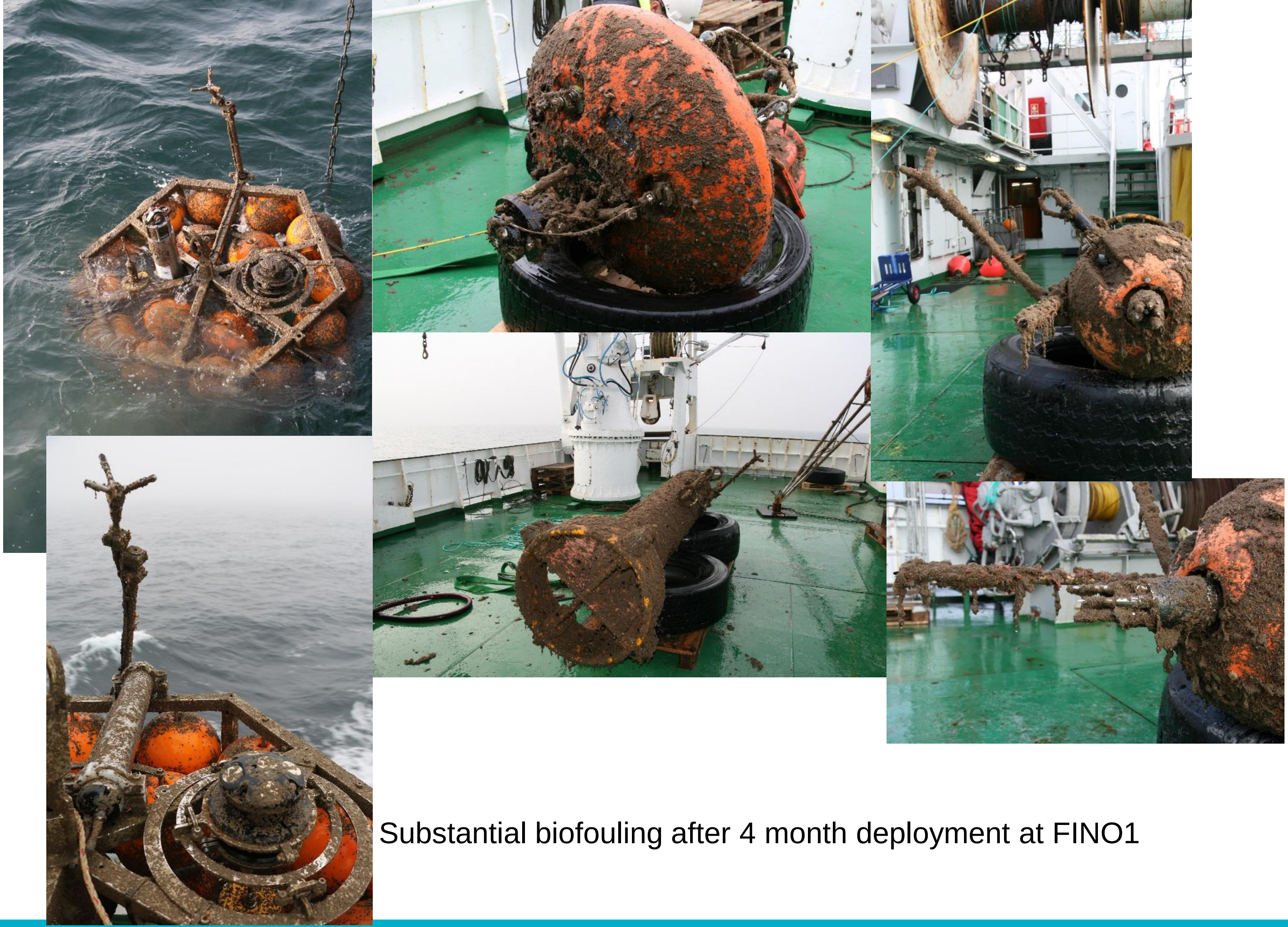


FIG. 6. (top) The instantaneous streamwise velocity contours in a y–z plane. Notice the large-scale shear-convective rolls and the eruption of low-speed fluid near the lower wavy boundary.

Oceanographic measurements

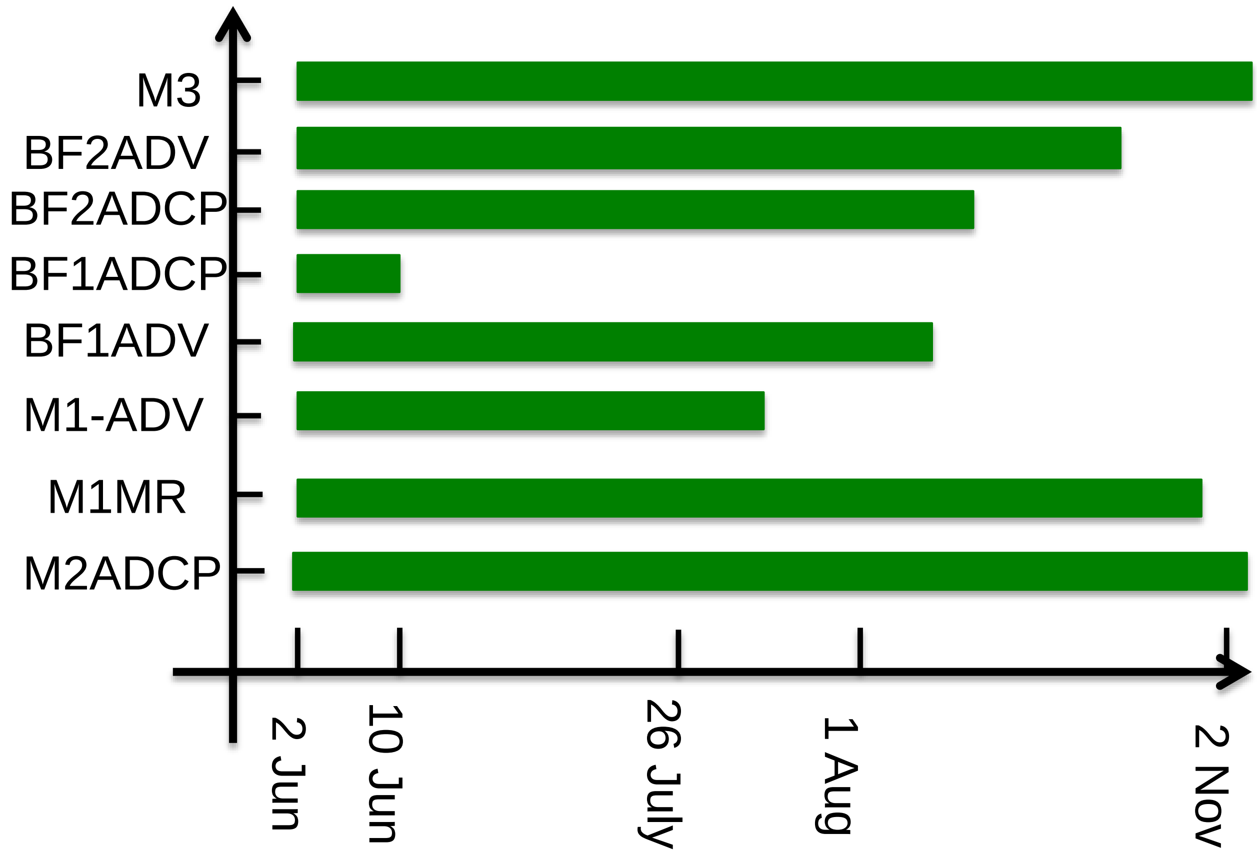
- Several moorings deployed in close vicinity to FINO1 and the North-East-corner of Alpha Ventus
- Moorings equipped with ADCP and ADV which provide current profiles and directional wave properties
- Mooring M1 equipped with airfoil shear probes and fast response thermistors in order to assess the Reynolds stress

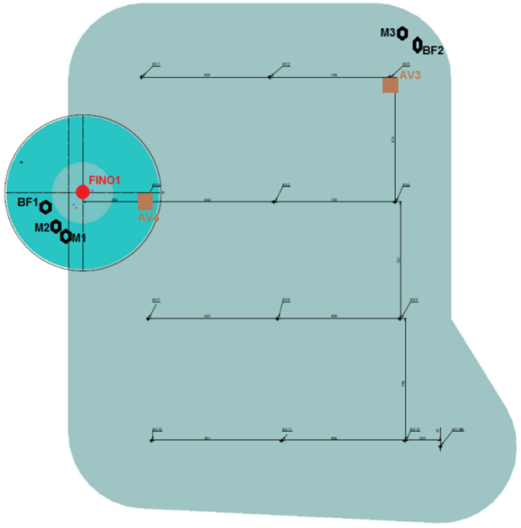




Substantial biofouling after 4 month deployment at FINO1

Availability of ocean data





The availability of datasets depends on the quality control criteria which are used.

Thank you for your attention!

References

- Sullivan, P. P., et al. (2008). "Large-eddy simulations and observations of atmospheric marine boundary layers above nonequilibrium surface waves." Journal of the Atmospheric Sciences **65**(4): 1225-1245.

- Sullivan, P. P., et al. (2014). "Large-Eddy Simulation of Marine Atmospheric Boundary Layers above a Spectrum of Moving Waves." Journal of the Atmospheric Sciences **71**(11): 4001-4027.