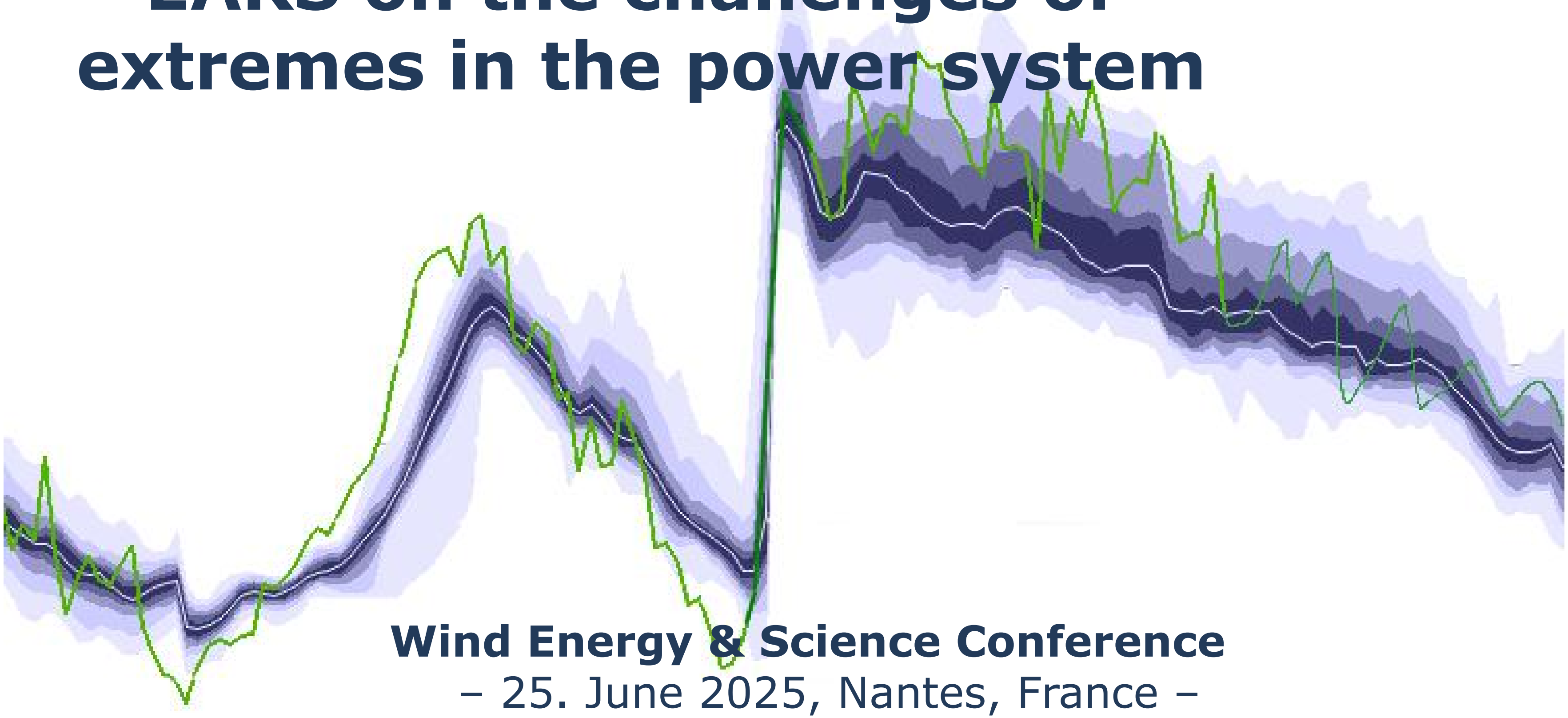
EARS4WindEnergy
Ensemble-based Approach utilizing a Refined SODAR for Wind Energy Applications

EARS on the challenges of extremes in the power system



Wind Energy & Science Conference

– 25. June 2025, Nantes, France –

AQSystem — Remote sensing technique: Pelle Hurtig, Sten-Ove Rodén, André Gräsman

UPPSALA UNIVERSITET: Johan Arnqvist

WEPROG: Corinna Möhrlen (presenting), Jess U. Jørgensen

DTU: Ebba Dellwik

EARS4WindEnergy

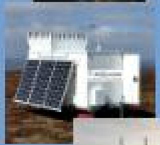
Ensemble-based Approach utilizing a Refined SODAR for Wind Energy Applications

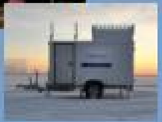
Project Consortium

www.aqsystem.se

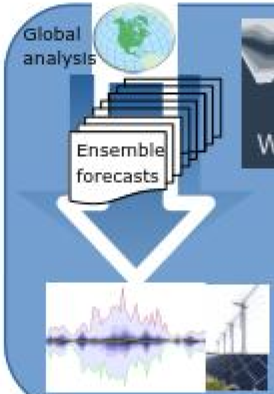
AQSystem

Remote sensing technique





started in 1989 to produce SODARs to monitor wind and turbulence for the wind energy market. Today the AQ510 is a robust self-sufficient life-cycle instrument for all climate conditions...



WEPROG

www.weprog.com

..started in 2003 to generate ensemble weather and energy forecasts for the energy market.

Today, the 75 ensemble member MSEPS system is run world-wide to serve efficient renewables integration and to assist in "dealing with uncertainties"..

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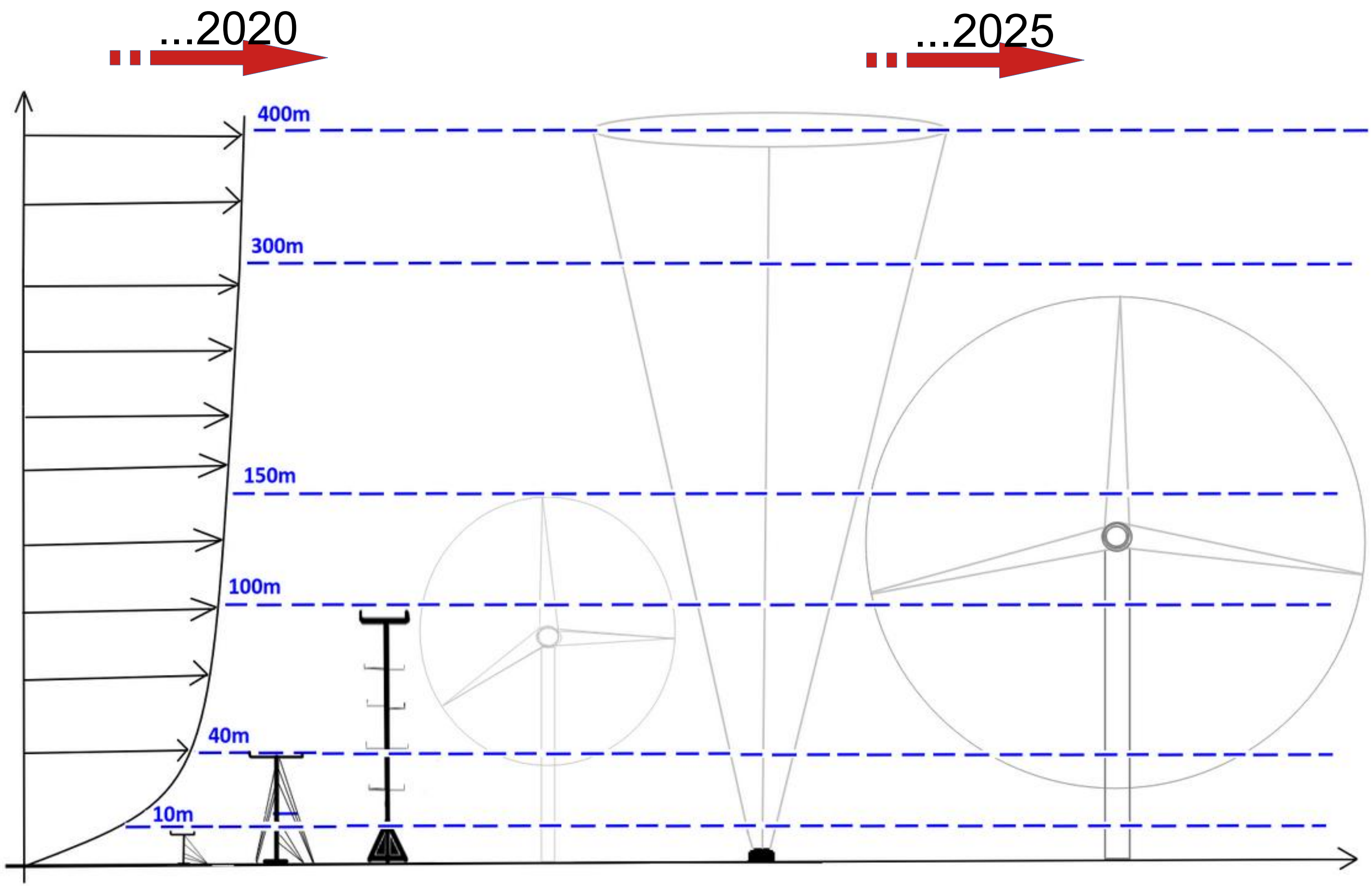
Uppsala University has long experience working with wind power as well as observations and analysis of measurements in the atmospheric boundary layer.

Risø Campus & Test facilities

DTU

Why are Remote Sensing instruments important ?

-- Background --



The development of wind turbines leads to the need for measurements being able to reach up to higher altitudes...

Where are we today ?

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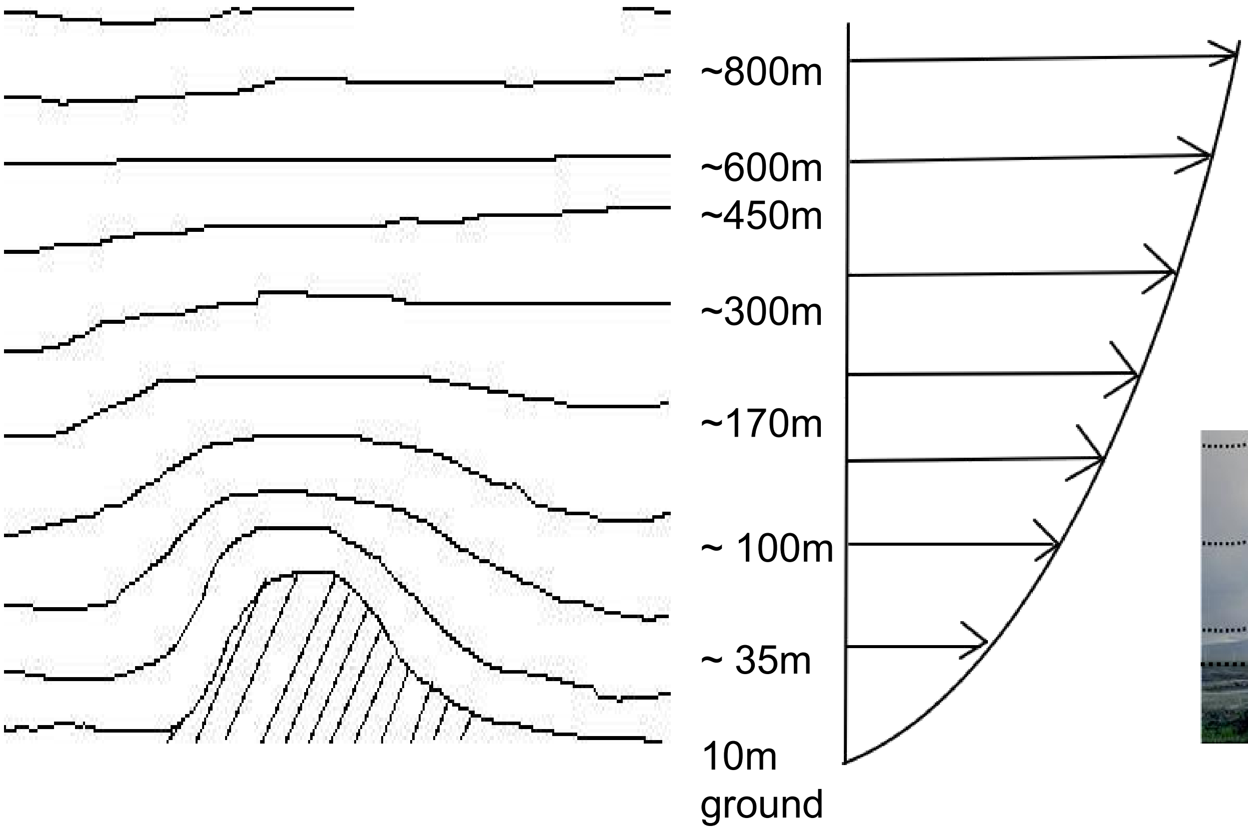
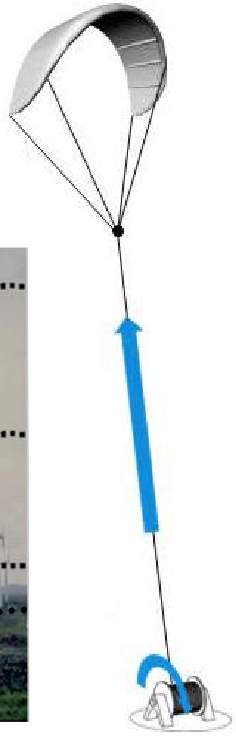
- Many met towers only measure up to hub height or lower
- Wind turbines increase in size – 15MW turbines reach up to ~300m
- airborne wind energy in 400-800m above ground is developping
- Large uncertainty and possibly bias from using the hub height wind speed only
- Remote sensing is sometimes not accepted by third party consultants
- Distrust in turbulence measurements from remote sensing

Representativeness of measurements and fit to NWP Forecasting models

Background information about the relevance of measurement heights for NWP models





Wind profile looks quite different in 300m than in 100m !

Why do we want to use a profiler for forecast assistance?

- Profilers (both sodars and lidars) are today used predominately for wind resource estimation
- They target minimum MAE and/or maximum correlation with a hub height cup anemometer

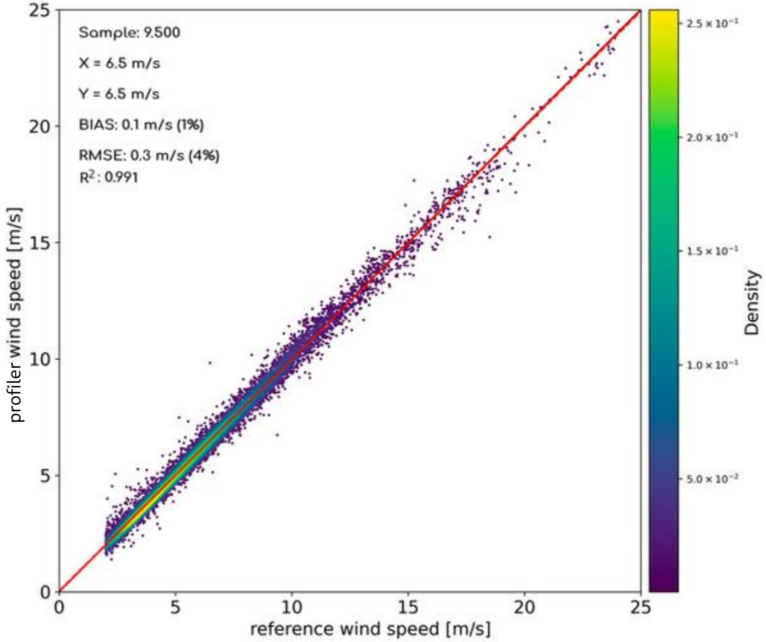
This leads to:

- Standard output that mimics a point measurement
- Accuracy is prioritized over availability

Why do we want to use a profiler for forecast assistance?

- Accurate long term wind speed distribution (accuracy of u ~1%)
- Accurate long term wind direction distribution
- Accurate long term turbulence distribution (or at least p_{90} of σ_u)

In practice, many consultants apply an arbitrary number - such as availablity of more than 90% or r^2>0.97



Important to consider random errors when comparing measurements from two positions

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$$u = u_a + \epsilon_a$$

$$r^2 = \frac{\overline{u_a u_b} + \overline{\epsilon_a \epsilon_b}}{\overline{u_a^2}^{1/2}\,\overline{u_b^2}^{1/2}}$$

➔If sensors are close, their random errors are higly correlated
--> r^2 close to 1 can be acheived.

➔If they are further apart and turbulence is high,
--> a lower r^2 must be expected, even when they measure correctly

Distance does matter !!!

Why do we want to use a profiler for forecast assistance?

- Nacelle mounted lidars are nice, but typically have too short vision to assist many relevant lead times
- Wind power estimates from wind turbines are important but
  - Provide no information on wind conditions when in full production (>12m/s)
  - unreliable signal at or around cut-out
- Profilers are <u>independent</u> from the turbines
- <u>Profilers can be maintained from ground level</u> (a real benefit in practice)

How to get velocity estimates from the doppler effect?

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Pulsed

- All sodars
- Most lidars and doppler radars
- A pulse is sent, then the response is sampled. Since the speed of the wave is known, the time of arrival can be transformed to distance

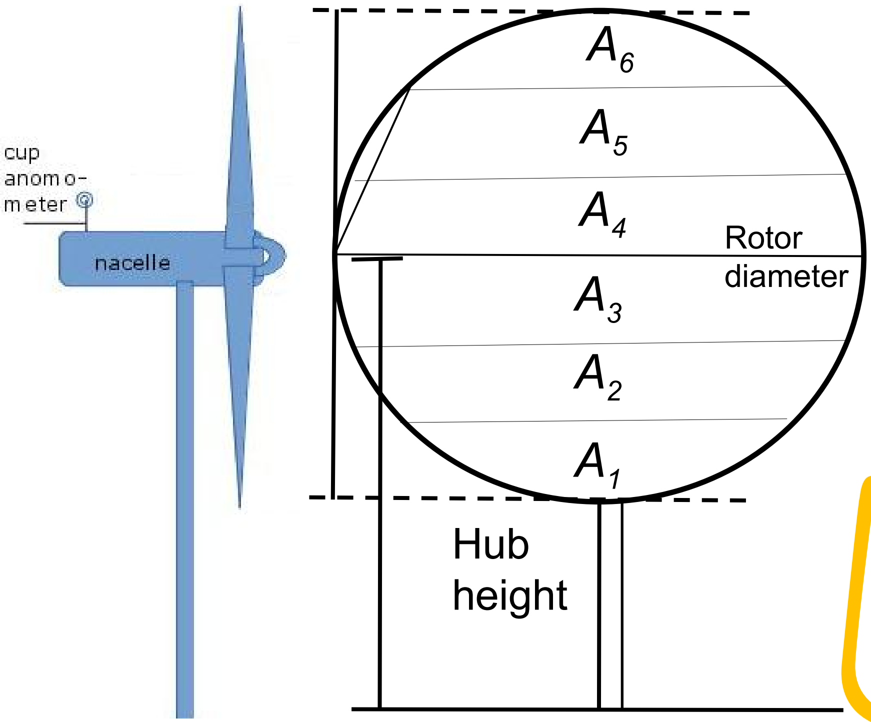
Continous wave

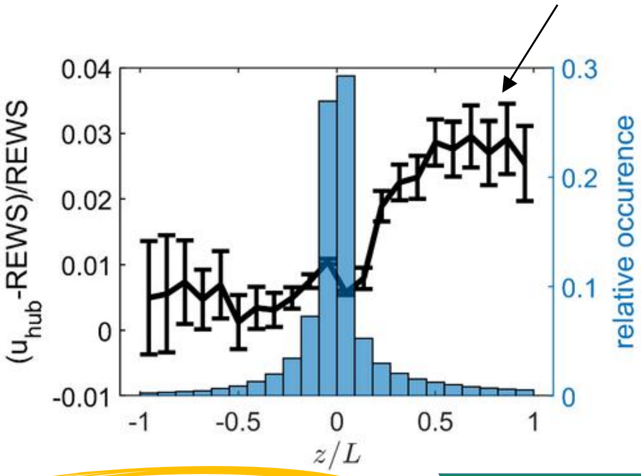
- Some lidars
- The waves are sent continously, but focused on the height of interest.
- Most, but not all, of the returning signal willcome from the height of interest

Background for Remote Sensing

Nacelle or mast anemometer at hub heights fail to measure over entire rotor area → leads to **overestimation of the wind speed,** especially in stable conditions

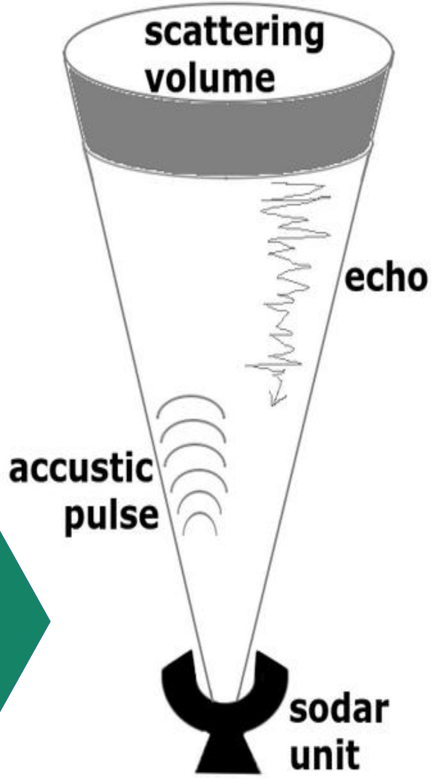
$$REWS = \left(\sum_{i=1}^{N} u_i^3 \frac{A_i}{A} \right)^{1/3}$$





Using hub height wind speed only, generates large un-certainty & possibly bias …

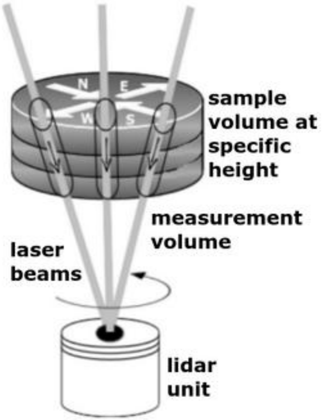
Remote sensing Instruments Include by default entire rotor area

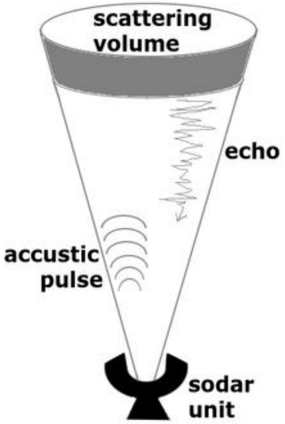


*Annual Energy Production

For live operation, what can the profilers provide?

- Wind speed
  - Direction
- Shear
- Turbulence
- Precipitation
- Boundary layer height proxies

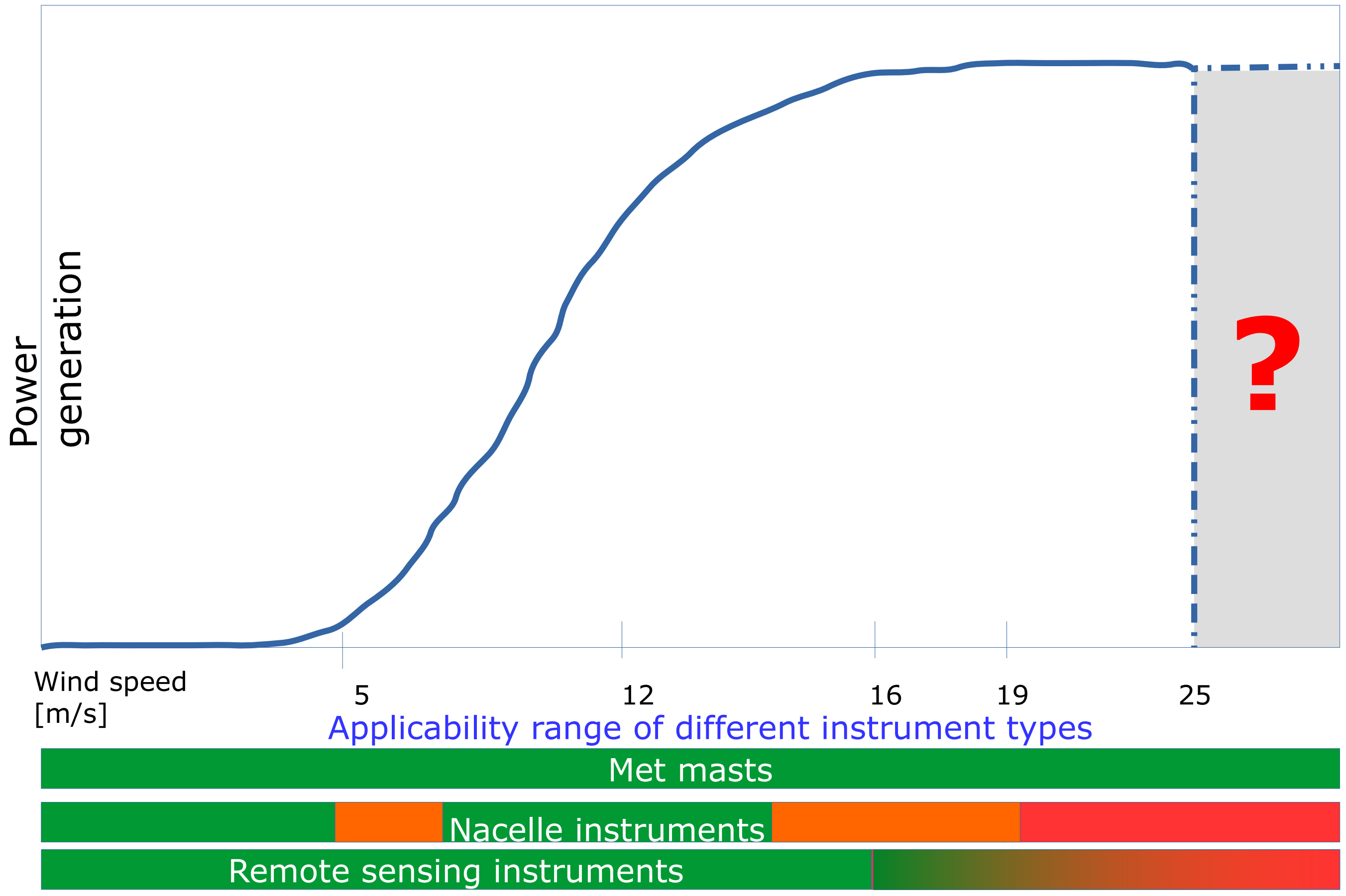


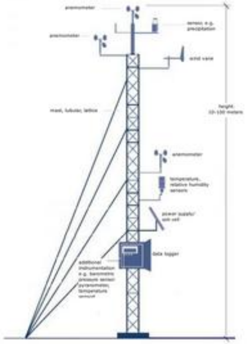


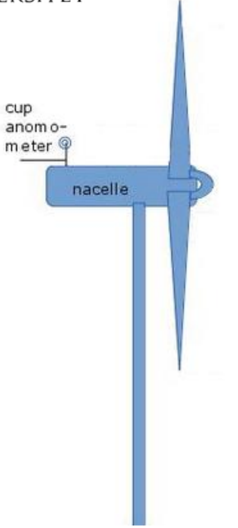
For live operation the data is useful as long as it is:

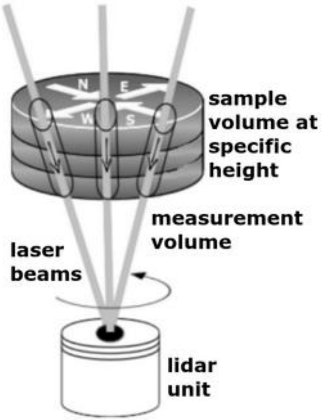
- *more accurate than the forecast error (u ~10% ok)*
- *reliable in strong wind and heavy precipitation*
- *an independent measurement*

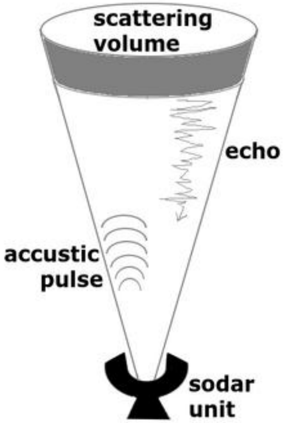
For live operation, what can the profilers provide in comparison to traditional instruments?











What is the challenge with Remote Sensing Instrumentation in real-time applications ?

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Typical errors in measurements:

- power failure or other complete failures
- meteorological conditions
  - Signal to noise ratio of lidars is sensitive to fog and dirt
  - Lidars show backscatter problems in clean air / low boundary layer heights
  - Sodars can have problems in very high/low wind speed / stable|neutral conditions
  - Sodars have a sensitivity to sensible heat flux
- random errors due to distance from target (see talk by J. Mann, E. Dellwik et al., *Instrument validation at a distance: an analysis of a sodar - mast comparison,* WESC2025 27.06.2025 RS#1.09)
- icing or snow at a non-snow compatible instruments
- outliers
- signal processing quality control with too strong filters
- Availability BIASES

In-situ measurement campaigns

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Flat terrain

Site 1: AQ test site Fimmerstad, Mohol, Souther Sweden, 300m mast

Coastal sites:

Site 2: Østerild – DTU Test center
Northwest Jutland, Denmark, 200m masts

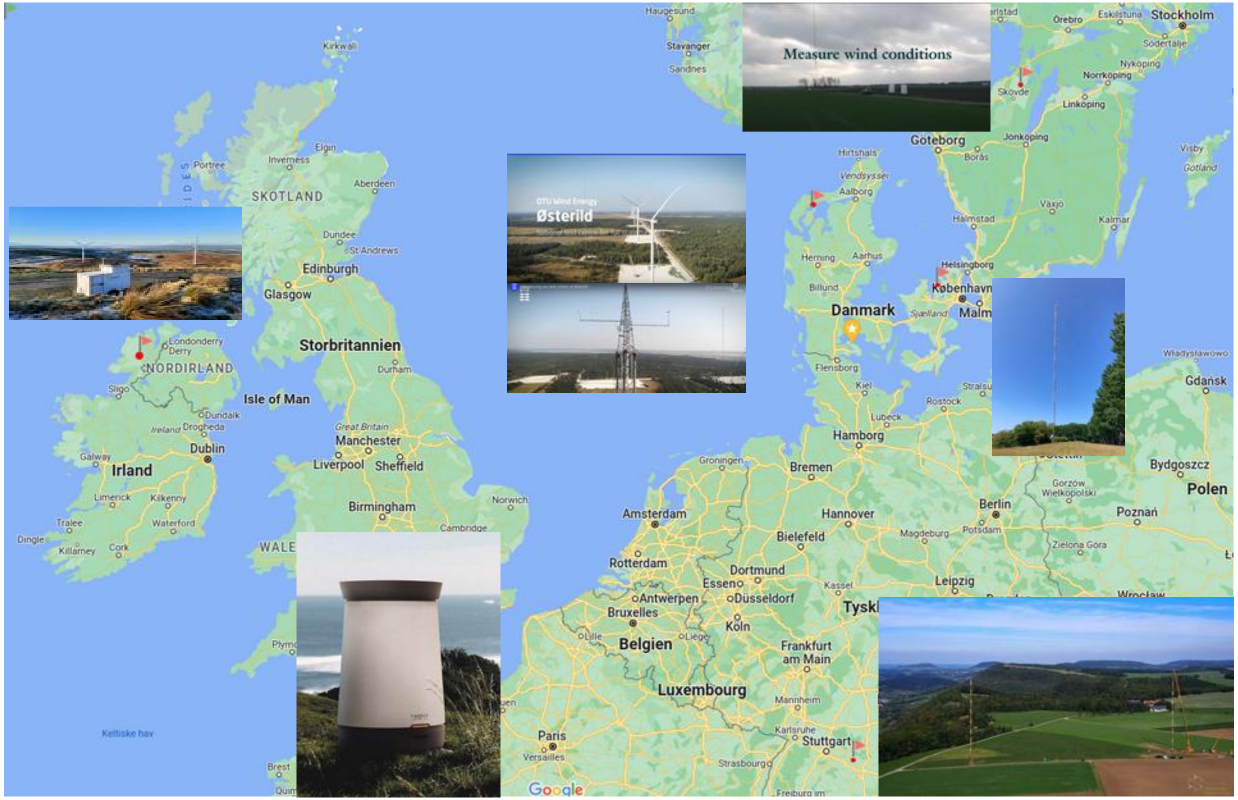
Site 3: Risø Campus, Roskilde, DK
windscanner, LIDARs

Complex terrain:

Site 4: Stötten (WINSENT Testsite),
Southwest Germany, 100m mast,
wind scanner (1200m)

Site 5: Windfarm in Co. Donegal,
Northwest Ireland, 100m mast

Site 6: Site Assessment in Co. Galway
West Ireland

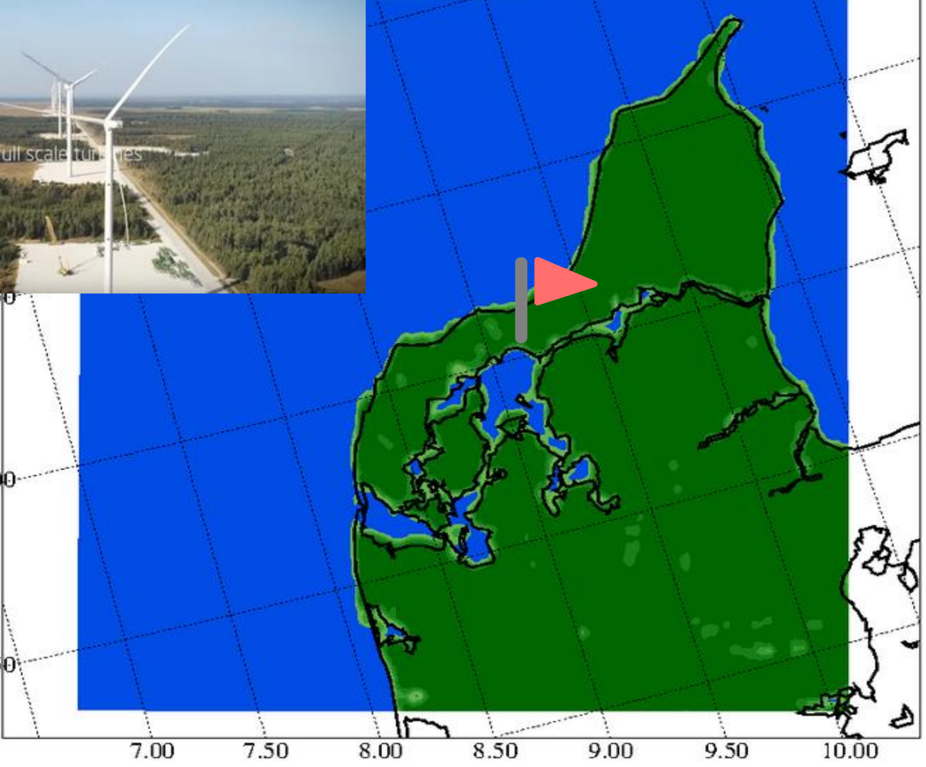


13 HighRes Experiments at DTU Testsite Østerild

Period: 3rd June 2022 - 28th June 2022

Mast Data (applied): Wind speed
Anemometer at 40m, 50m, 100m, 140m, 178m

SODAR: Wind Speed at 40m,70m, 100m, 178m



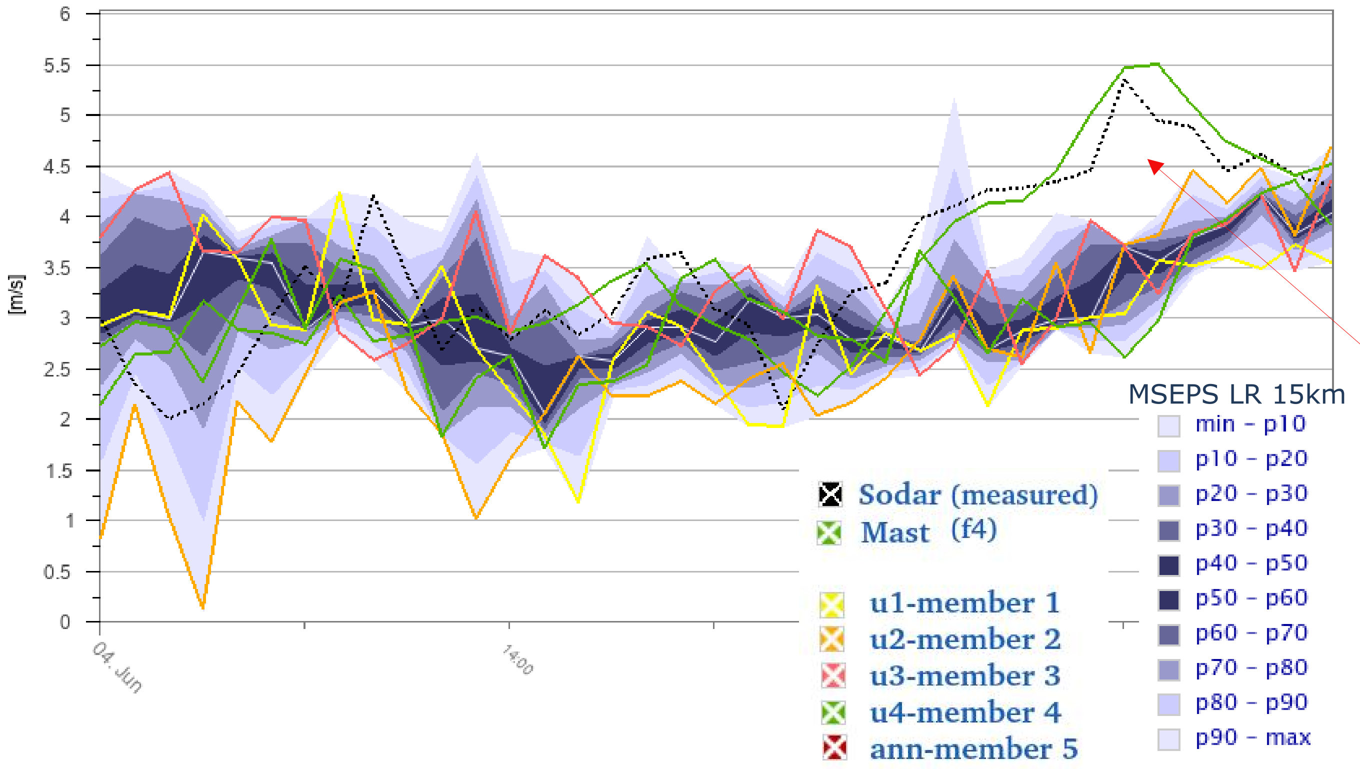
Purpose of Experiments with 5 MSEPS members:
What is the most effective resolution for the NWP models

Test:

1) At which time scales can measurements be resolved adequately
2) Apply different vertical diffusion schemes to verify how much
3) (wind) variability can be generated in the NWP model space
4) investigate the sensitivity of the optimal number of
   vertical levels for most realistic variability

Result from 13 High resolution NWP experiments* to explore fit measurements

Example Plots of 5 MSEPS V-diff-members + Measurements in 10min time resolution – 1.4km MSEPS level 72 (170m) –



High-resolution models have **same variability** as measurements, but **not the same phase…**

measurements are most, but not all the time **within the spread of low-resolution 75 member ensemble…**

Experiment description: see [presentation] Windintegration Workshop 2023 "EARS4WindEnergy – next level wind integration by listening to the wind"

Summary statistics of NWP experiments at Østerild Test site

RESULTS	Resolution	MAE Ranking	RMSE Ranking	Description of results
Exp01	1.4km	13	13	similar variability as in measurements, but out of phase
Exp02	1.4km	7	7	Normal variability and the result improved
Exp03	1.4km	4	5	Resolution creates too high phase errors
Exp04	1.4km	3	6	very small improvement but not on all members
Exp05	1.4km	10	11	One diffusion scheme is superior in 1.4km
Exp06	5km	11	12	1.4km score marginally better than 5km
Exp07	5km	8	8	4d-analysis incremenation improves
Exp08	5km	9	9	72 level is better than 60 level
Exp09	5km	12	10	significantly simplified, the result is comparable to Exp01-02
Exp10	5km	5	3	different condensation schemes are important
Exp11	5km	6	4	best single member performance so far for the KF
Exp12	2.5km	1	1	best score with KainFritsch condensation and good mean
Exp13	2.5km	2	2	no sensitivity to finer climate data

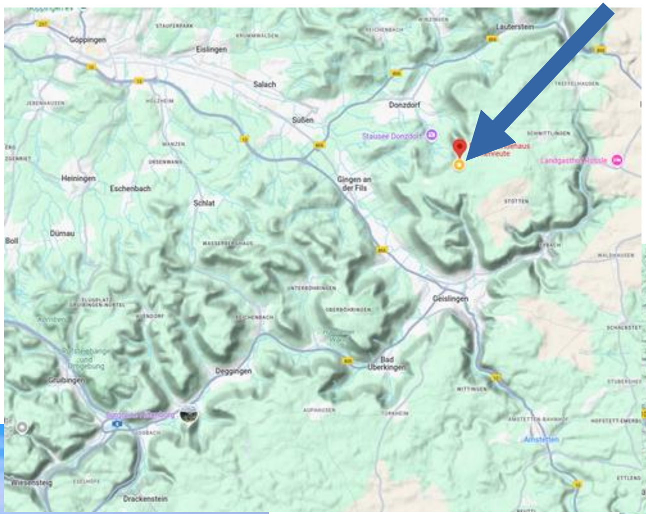
Rank	MAE [m/s]		RMSE [m/s]	
	Exp	Best	Exp	Best
1	12	1.02	12	1.30
2	13	1.02	13	1.31
3	4	1.03	10	1.33
4	3	1.04	11	1.33
5	10	1.04	3	1.34
6	11	1.04	4	1.34
7	2	1.05	2	1.36
8	7	1.05	7	1.36
9	8	1.05	8	1.36
10	5	1.07	9	1.37
11	6	1.07	5	1.38
12	9	1.07	6	1.38
13	1	1.08	1	1.39

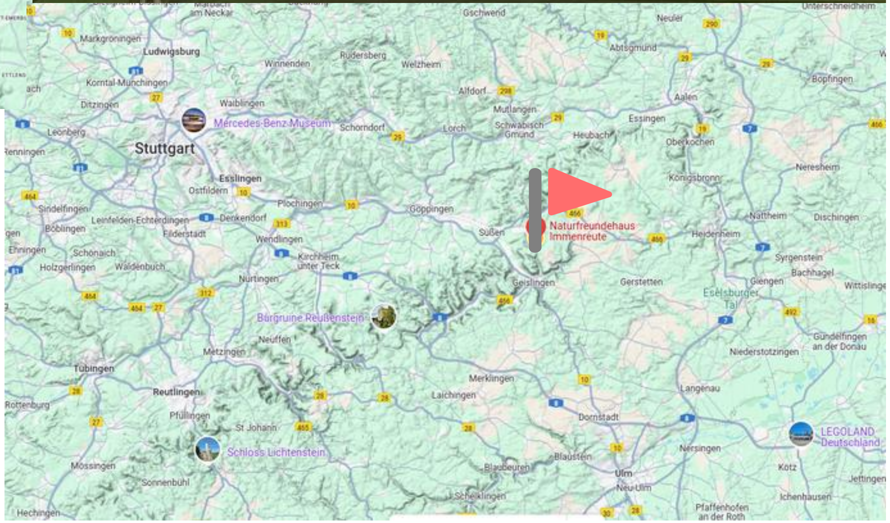
- Higher resolution does not perform better statistically
- Error difference from best to worst is not significant…
- High-resolution forecast shows similar variability as SODAR data, but is not in phase with measurements
- Knowing the effective best resolution + use of physical uncertainty is a useful combination for improved forecasting & gap filling

In-situ measurement campaign WINSENT Test site

Site: Stötten (WINSENT Testsite), SW Germany

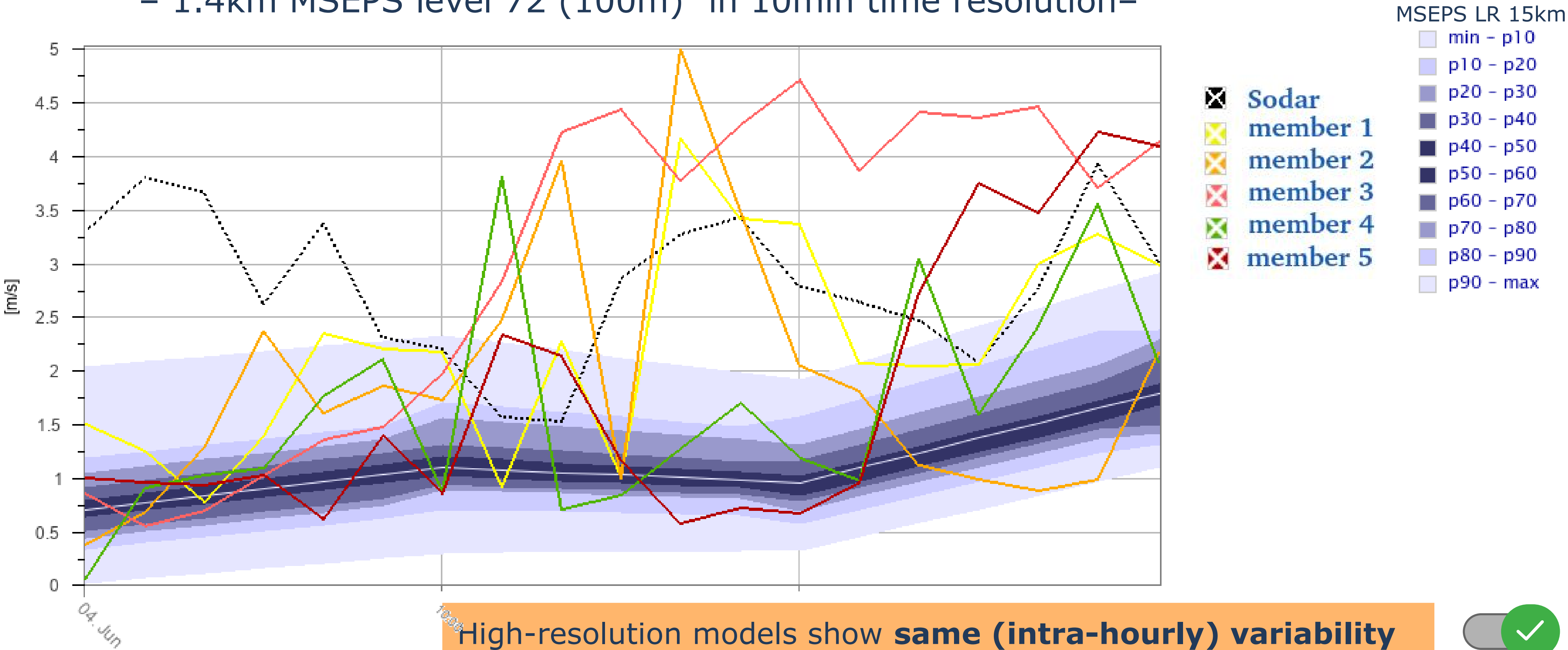
… in the swabian alps …





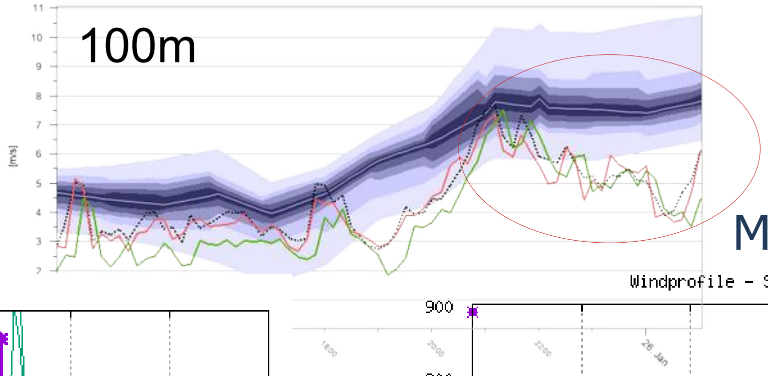
NWP experiments to fit measurements

Example Plot of 5 MSEPS V-diff-members + Measurements
– 1.4km MSEPS level 72 (100m) in 10min time resolution–

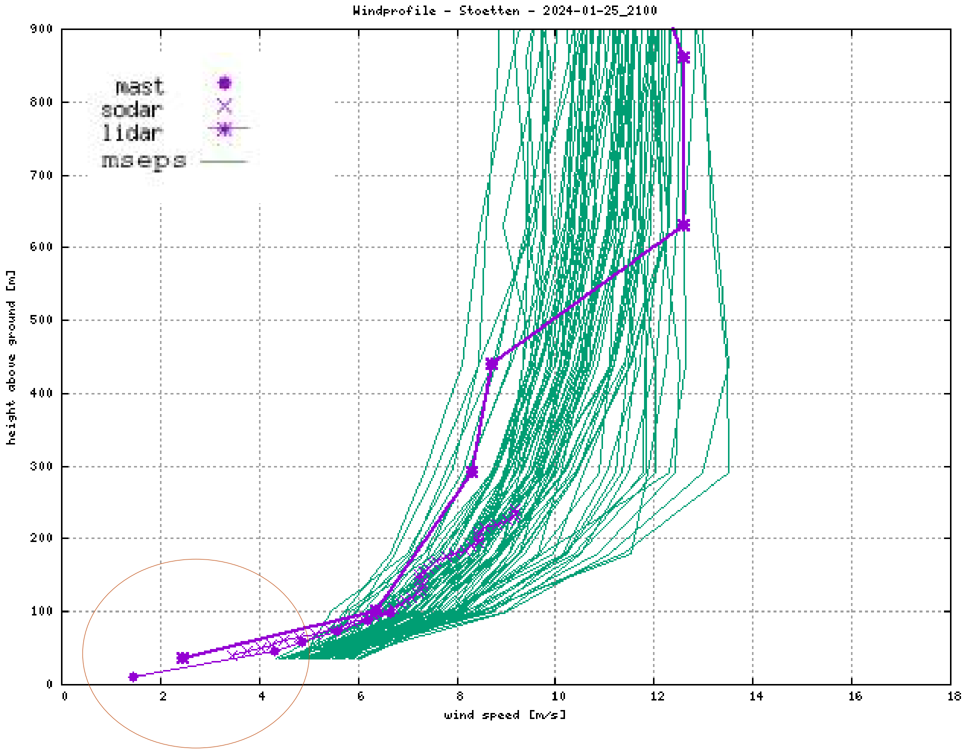


High-resolution models show **same (intra-hourly) variability** as measurements, but **not the same phase...**

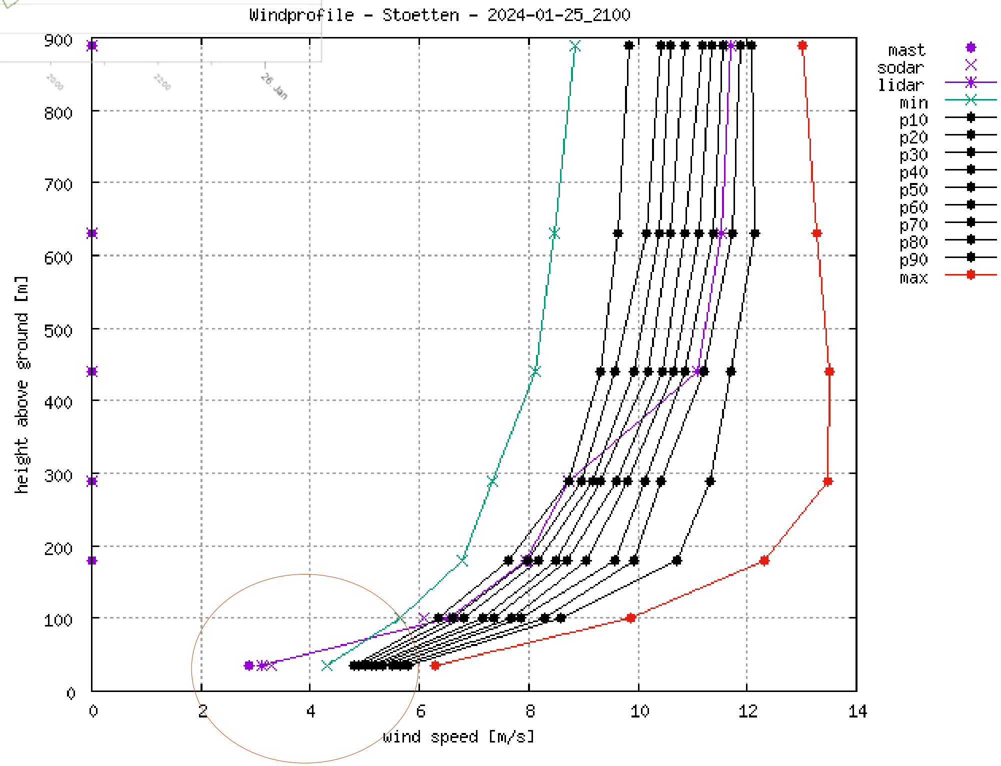
Understanding forecast errors: wind profiles at Stötten



75 MSEPS members



MSEPS percentiles



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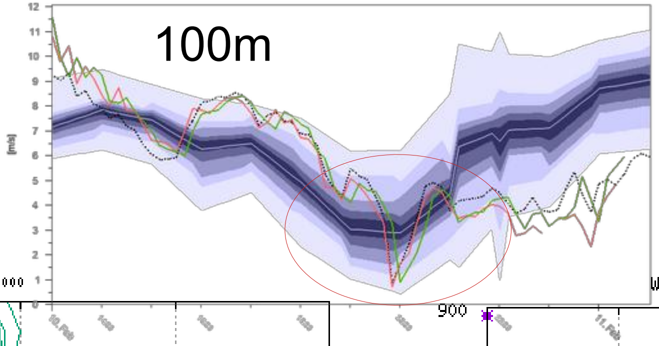
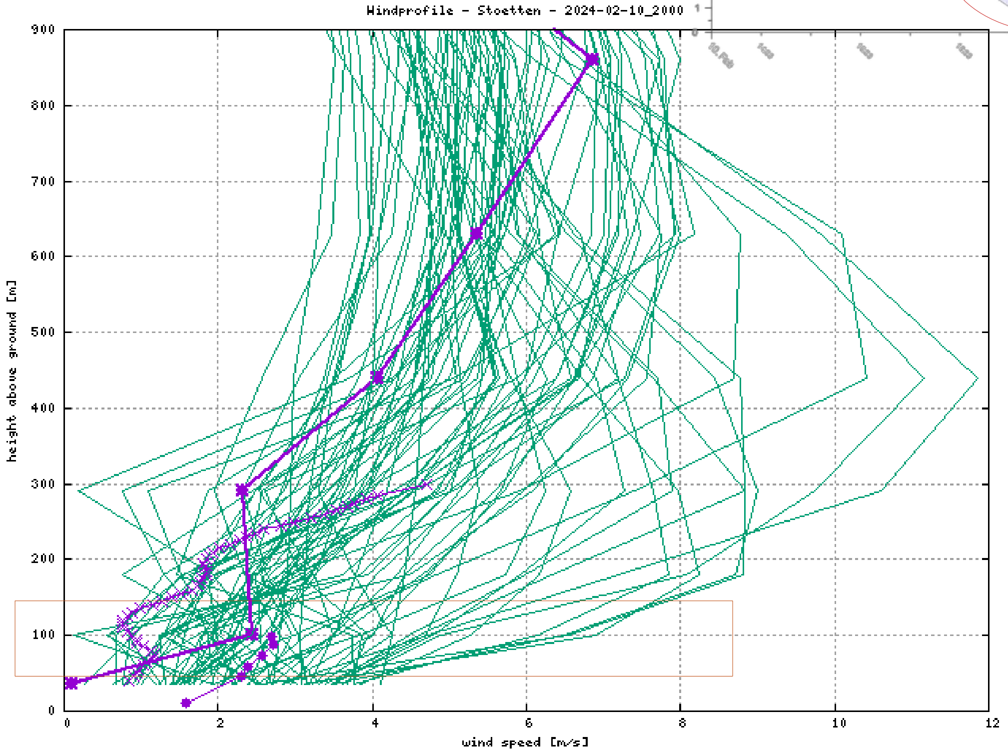
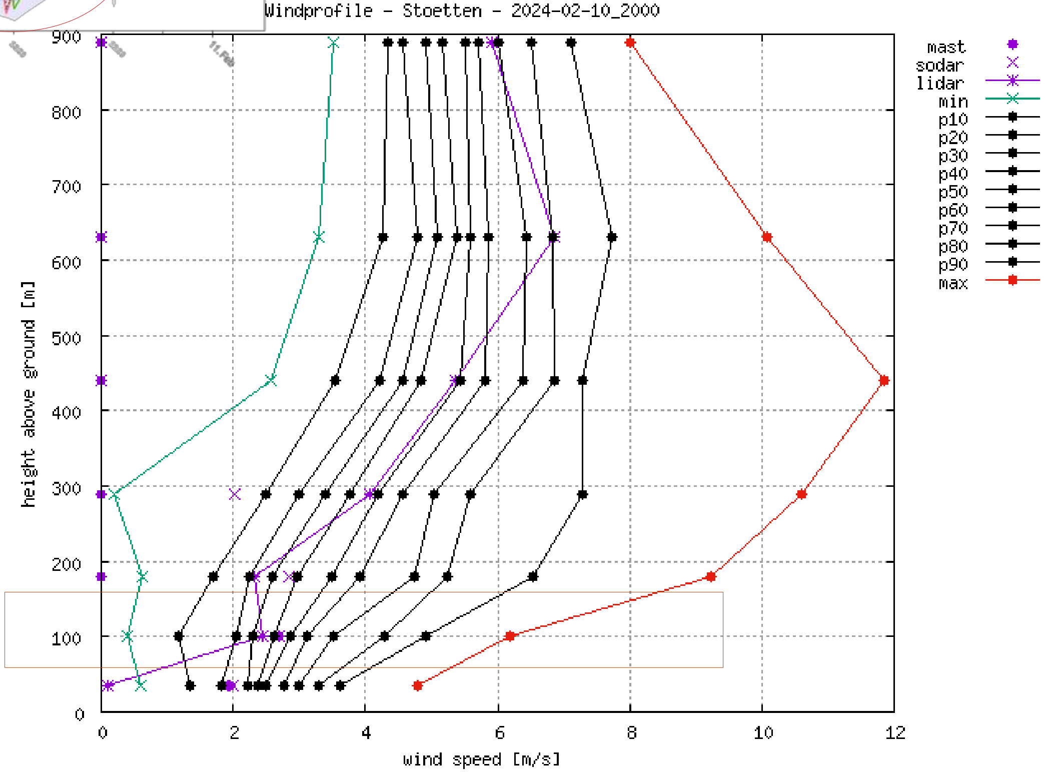


75 MSEPS members

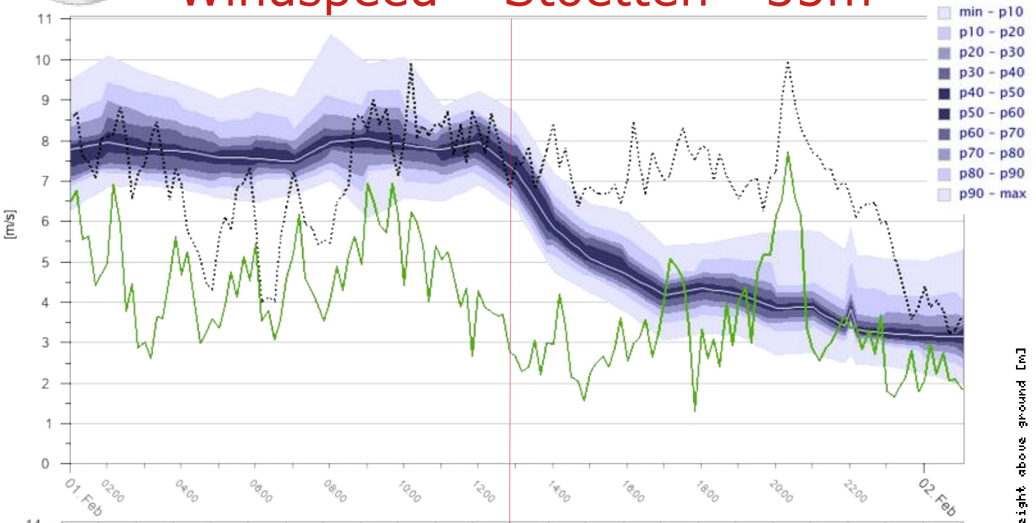


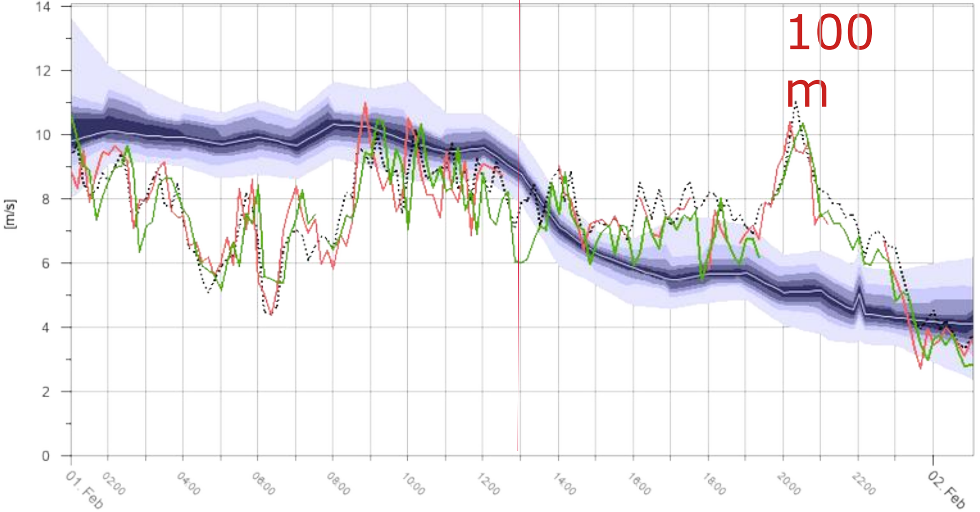
MSEPS percentiles



Understanding forecast errors: wind profiles at Stötten

Windspeed – Stoetten - 35m





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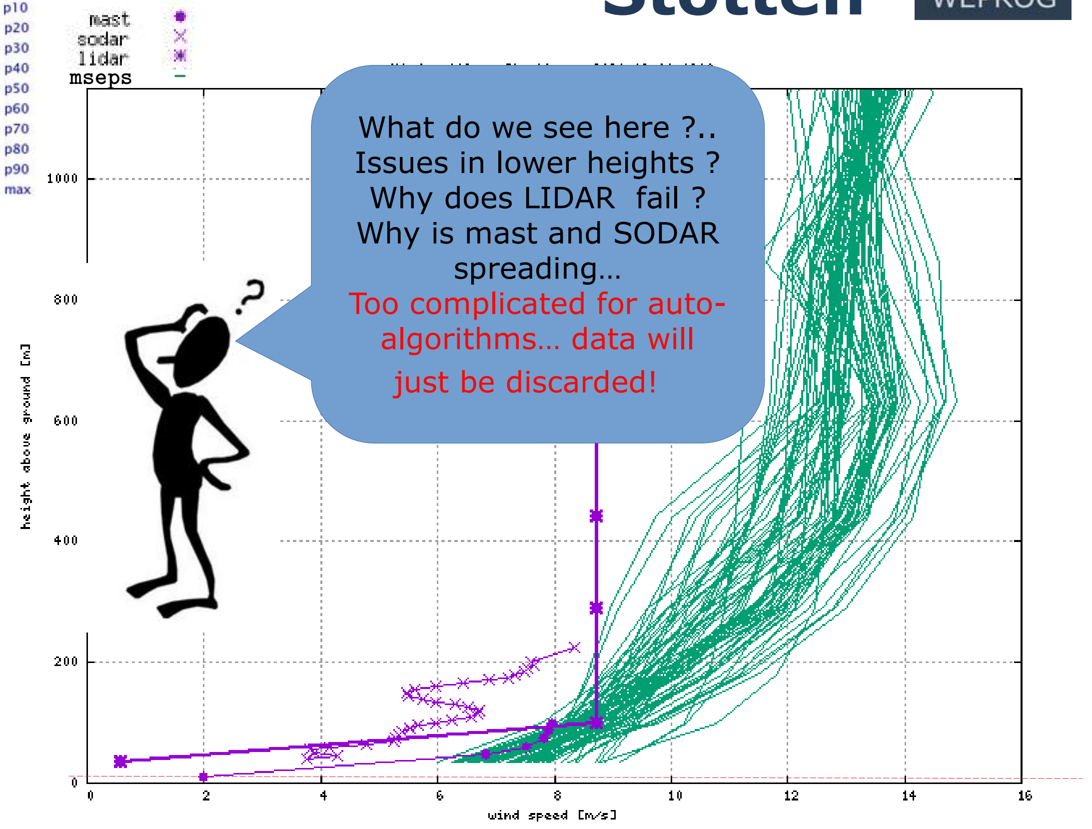
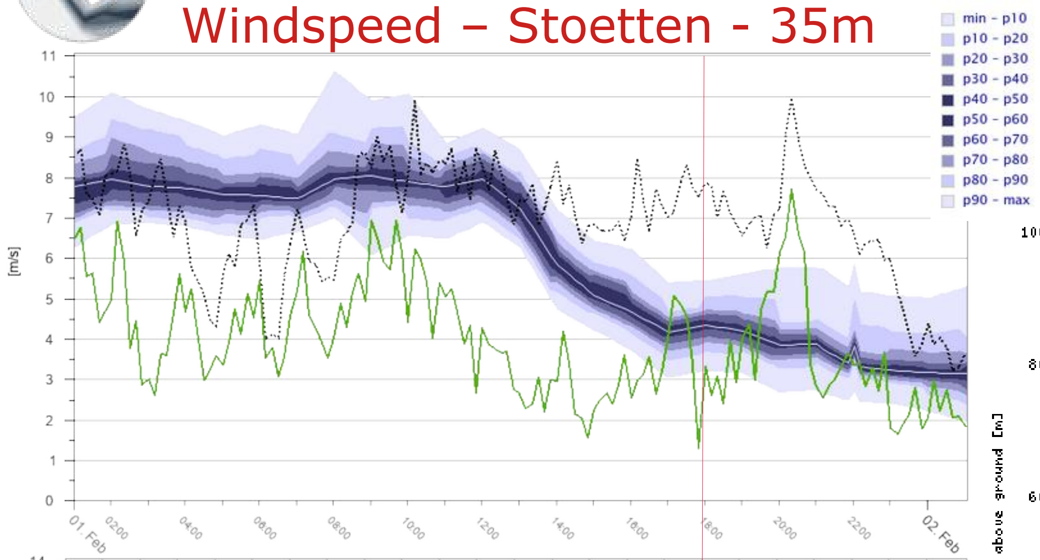
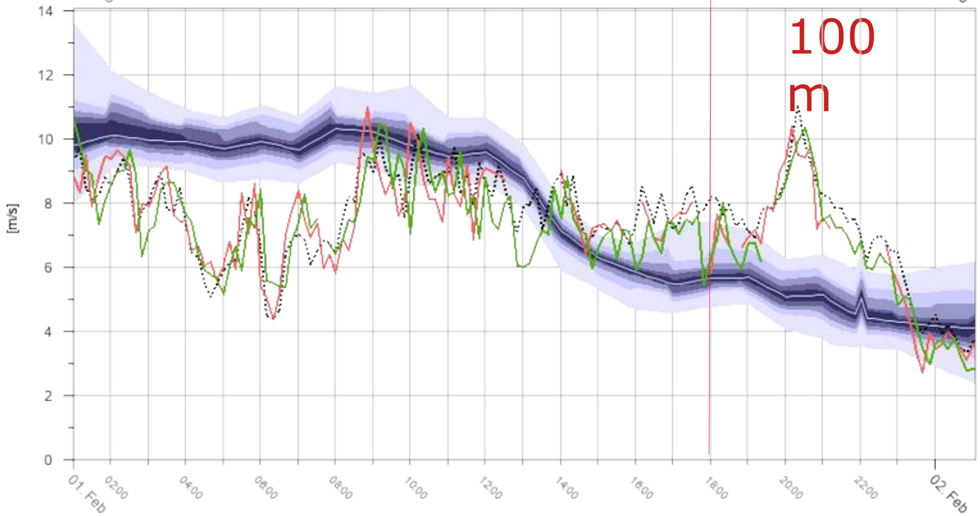
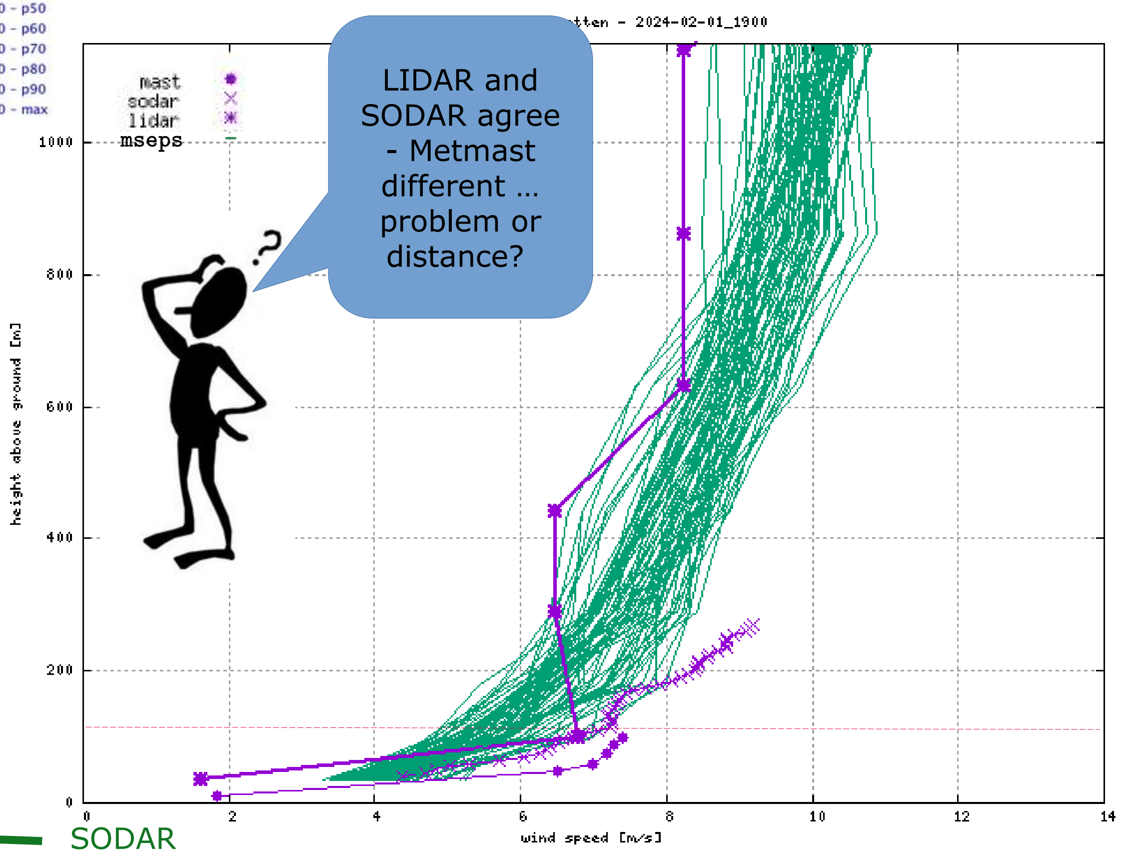


Understanding forecast errors: wind profiles at Stötten



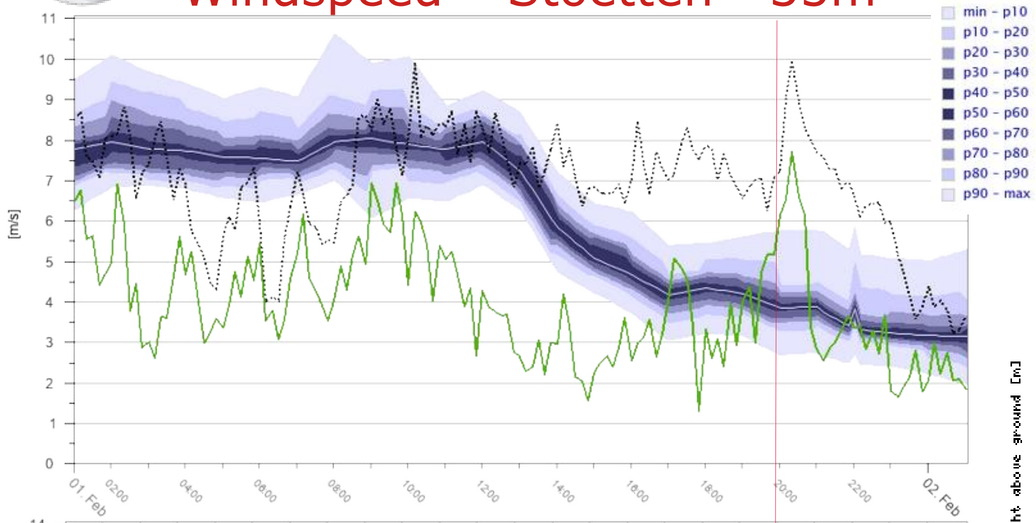




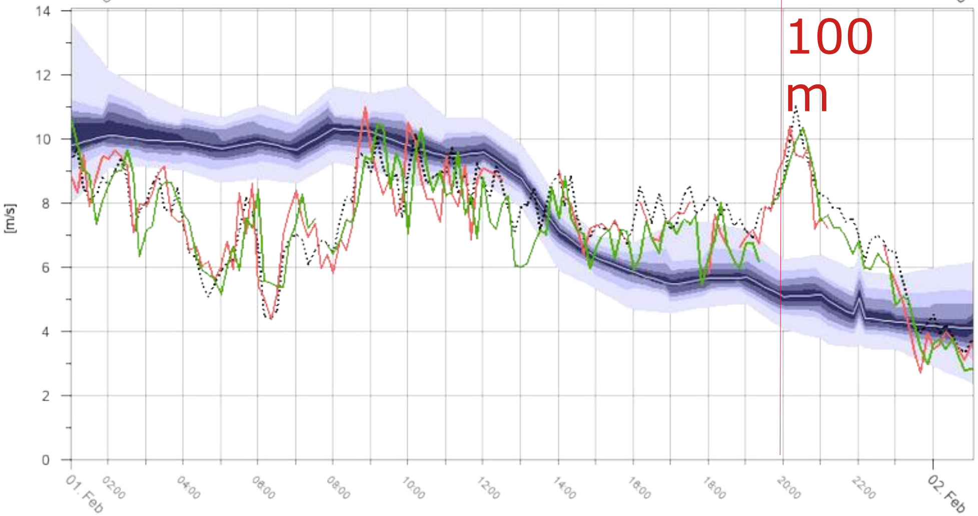
SODAR
Metmast
LIDAR

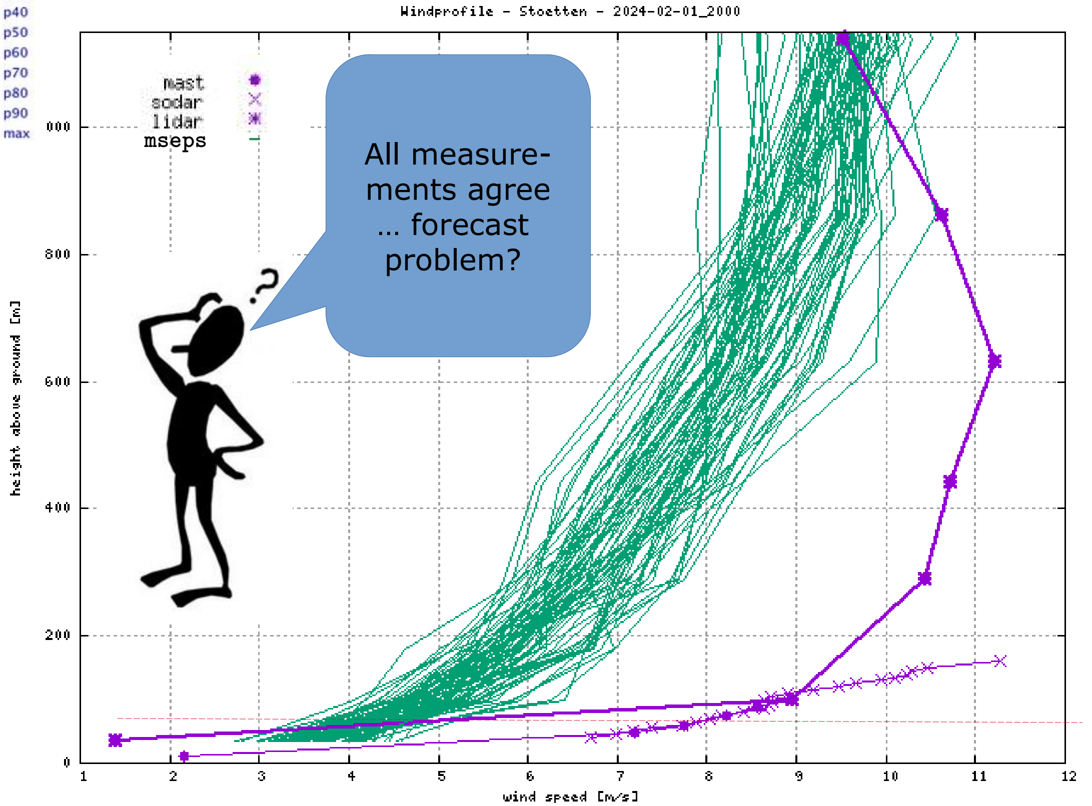
Understanding forecast errors: wind profiles at Stötten

Windspeed – Stoetten - 35m



100 m





SODAR
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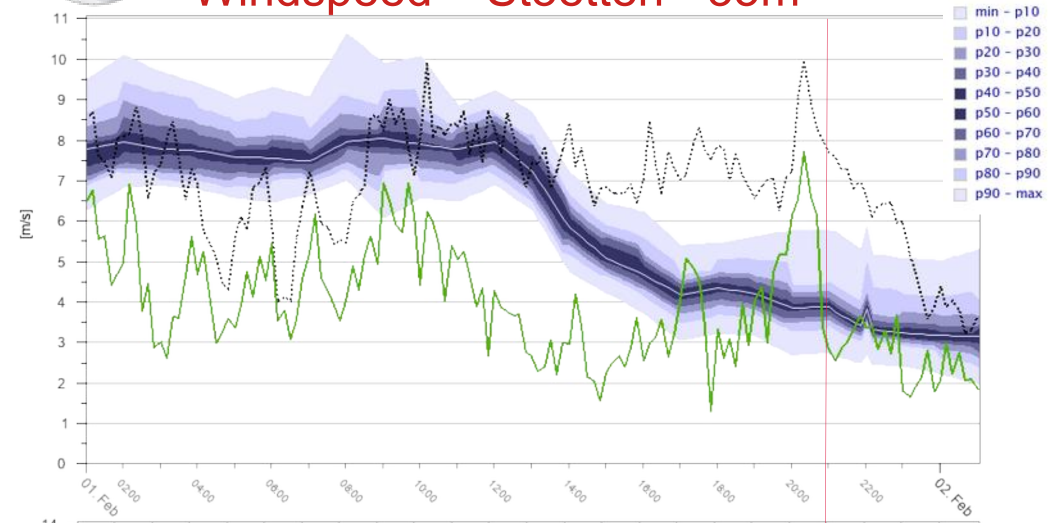
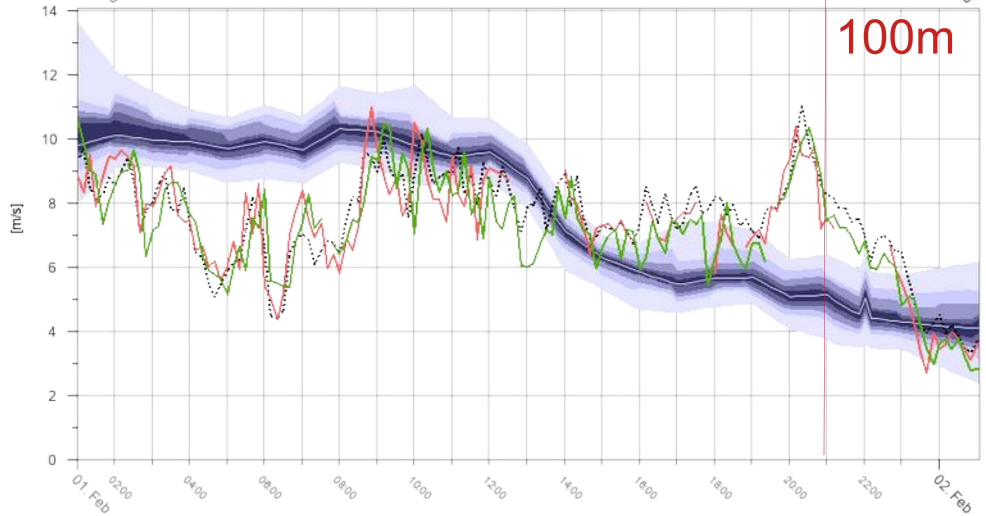
Understanding forecast errors: wind profiles at Stötten

Windspeed – Stoetten - 35m





SODAR
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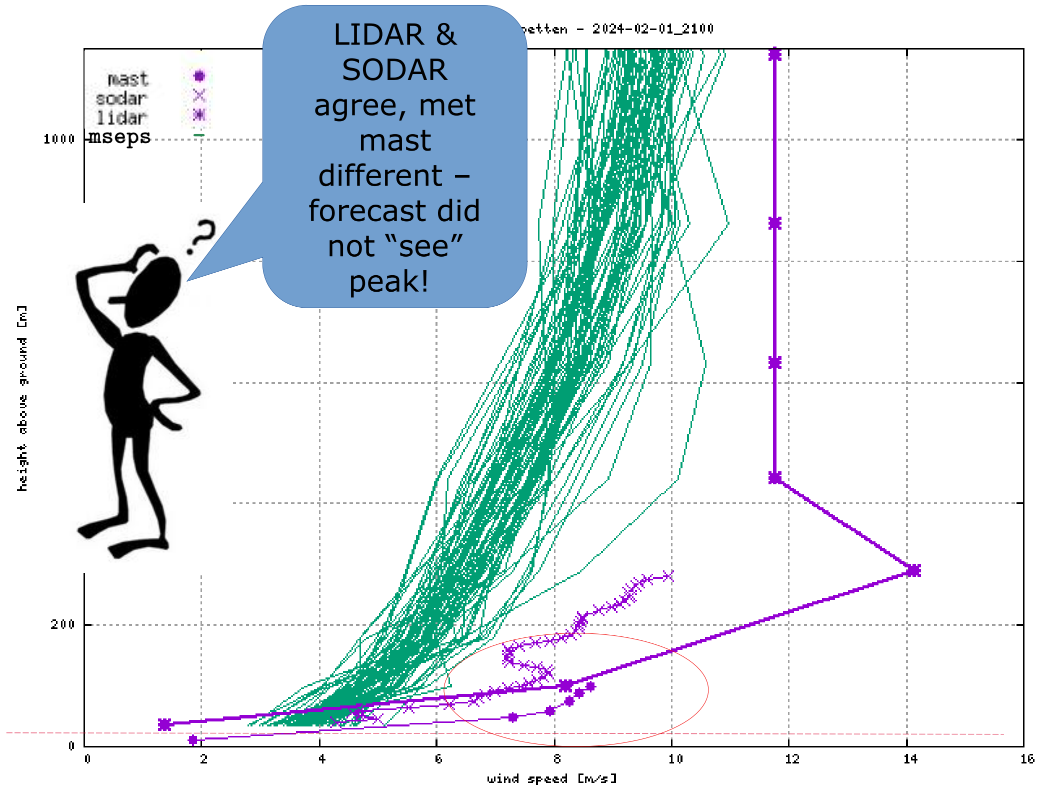
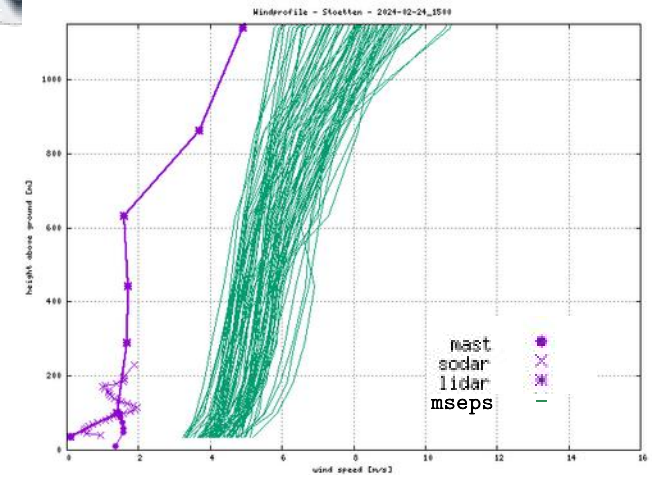
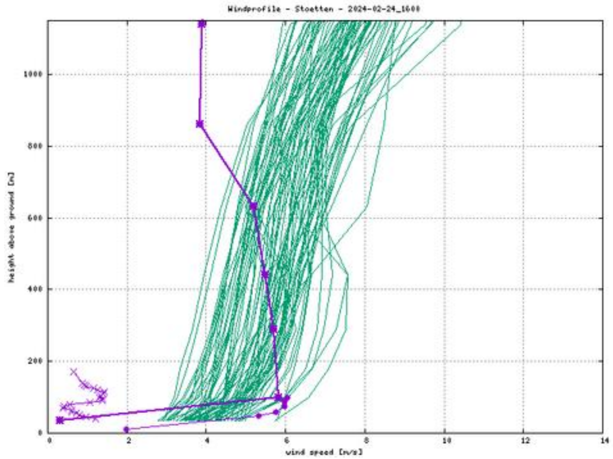
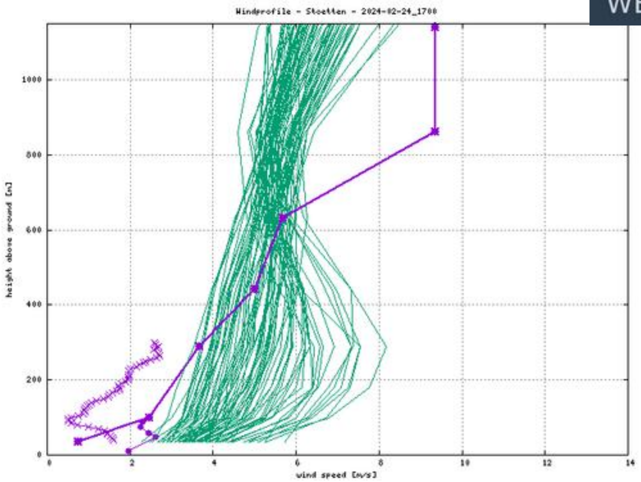
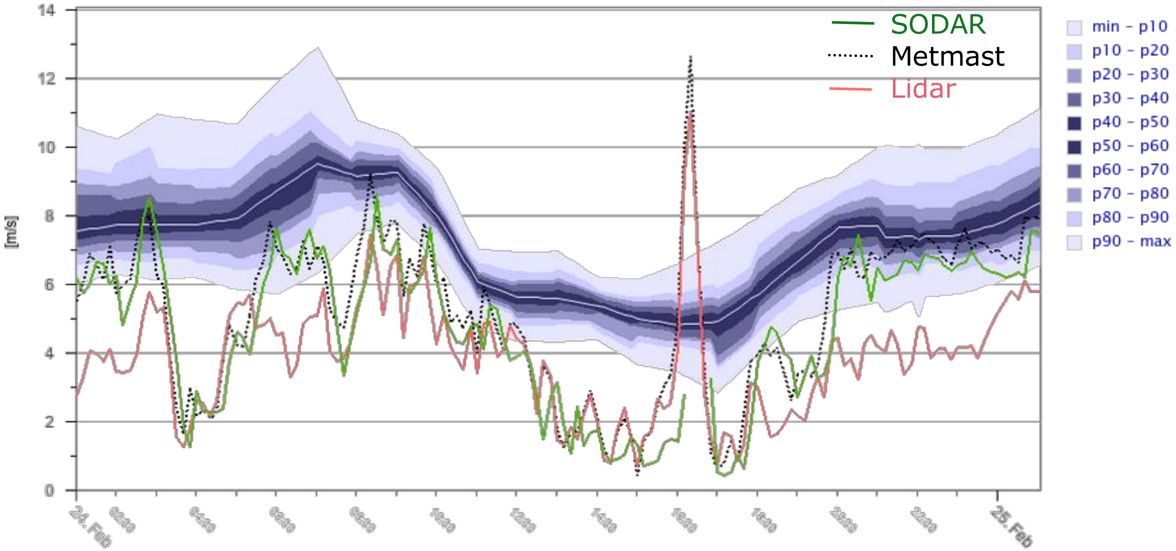


Understanding forecast errors with help from wind profiles at Stötten



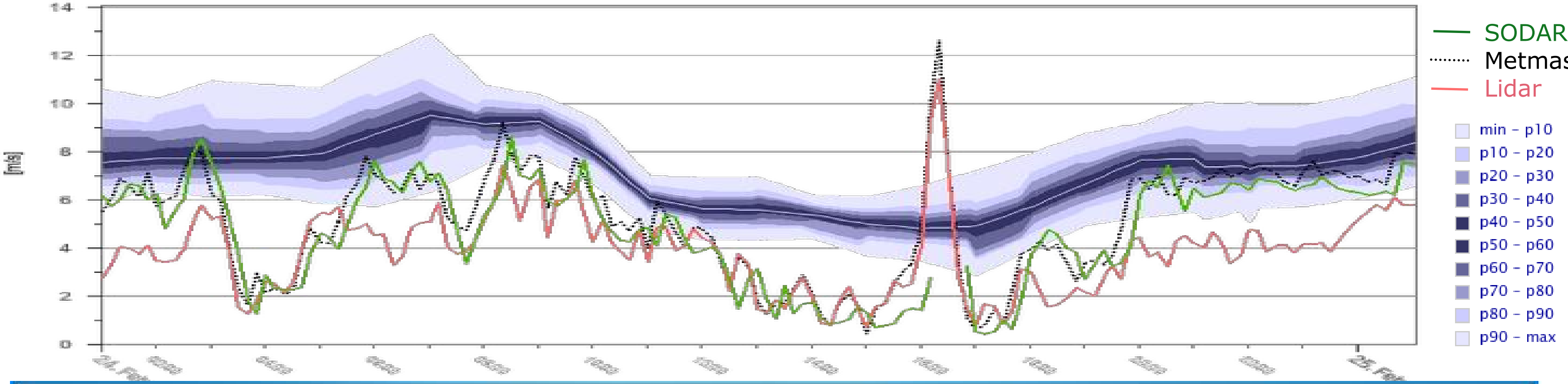


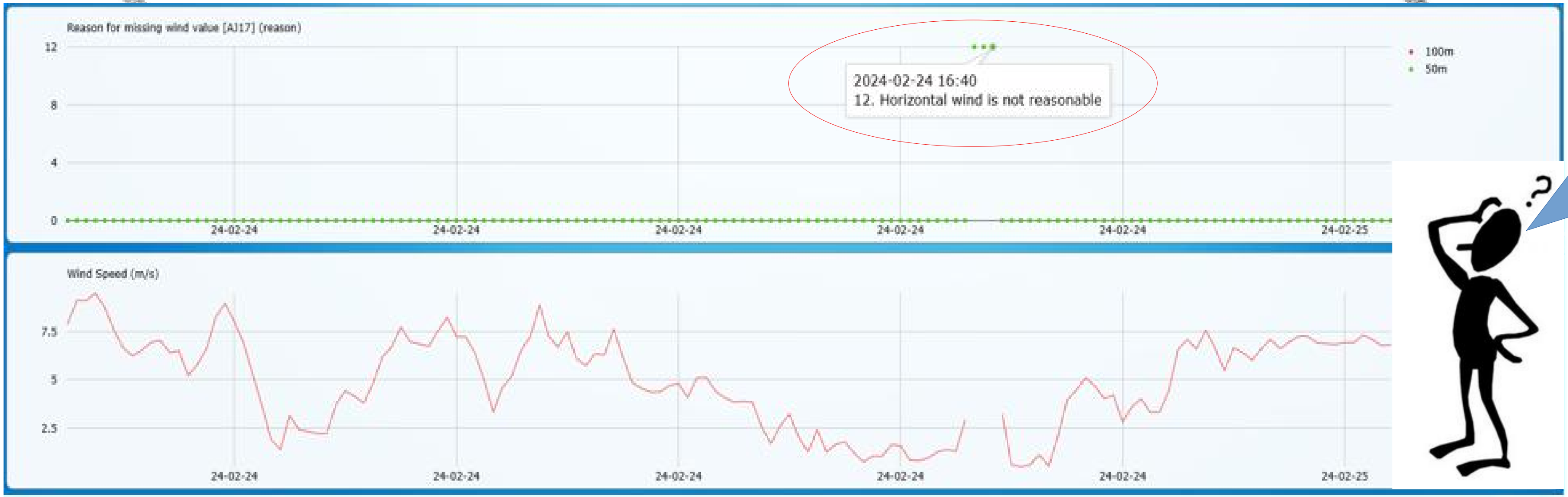




Another peak the forecast did not see …
– this time, the SODAR also stopped

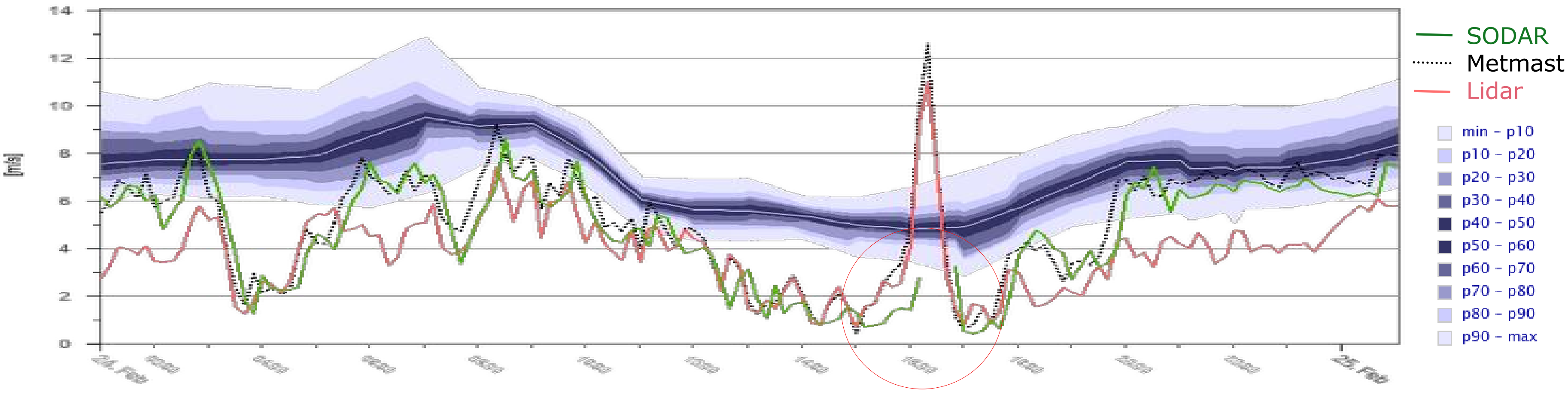
Understanding forecast errors with help from wind profiles at Stötten





SODAR signal processing discards strong ramps!!!!
~2 → 11m/s in 10min...

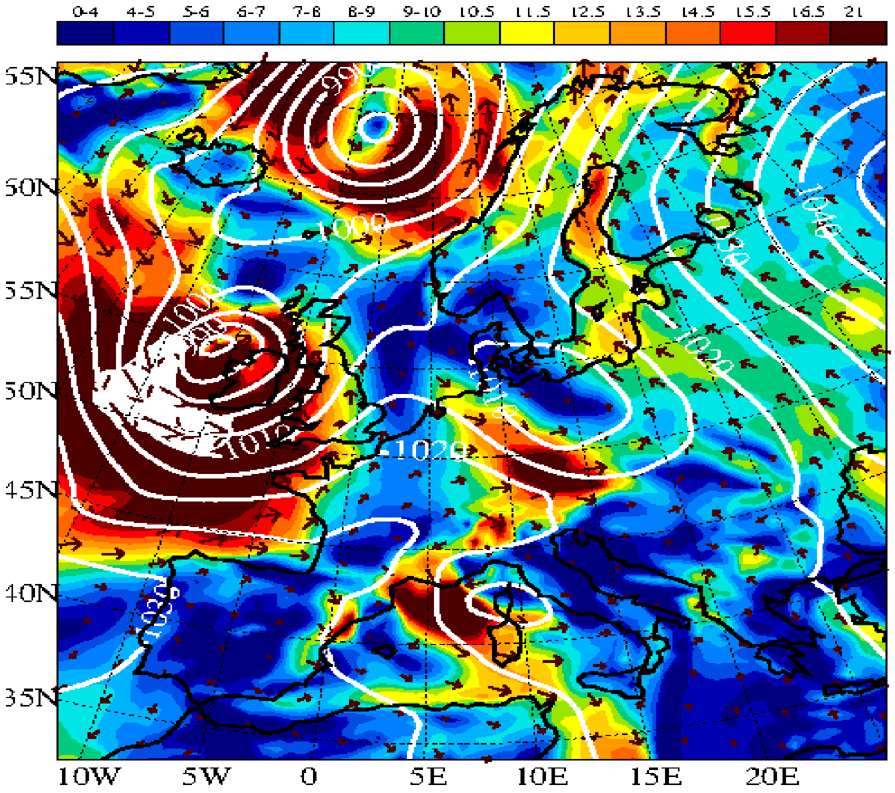
Understanding forecast & measurement errors: wind extreme in Stötten

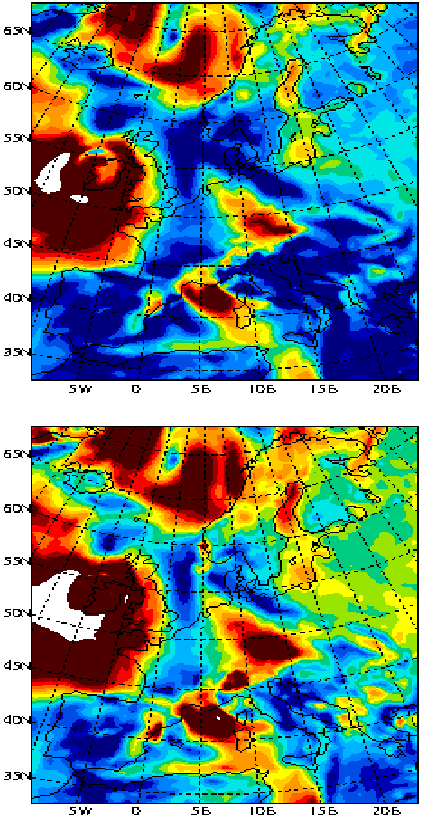


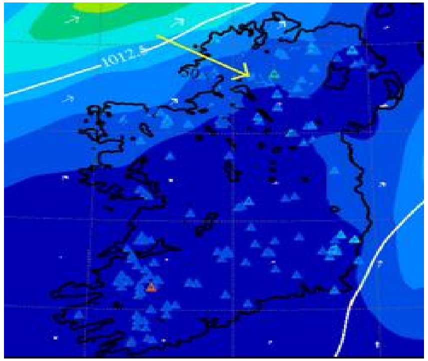
With the help of the frequency index and the raw data, the SODAR agrees with met mast ...

Extreme event at an Irish wind farm

Another example of the challenges for the profiler adaptation to real-time application at a location, where high-speed shutdown is regularly in autumn and winter...

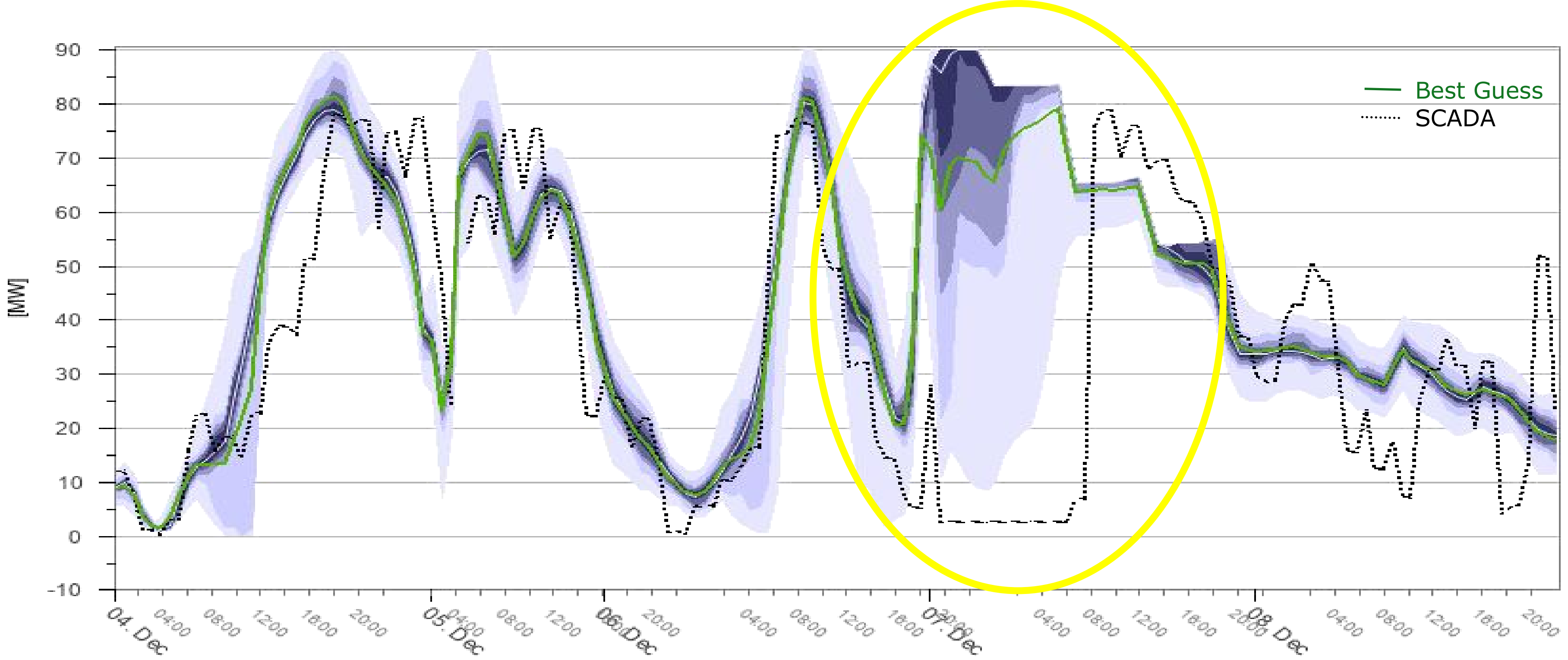




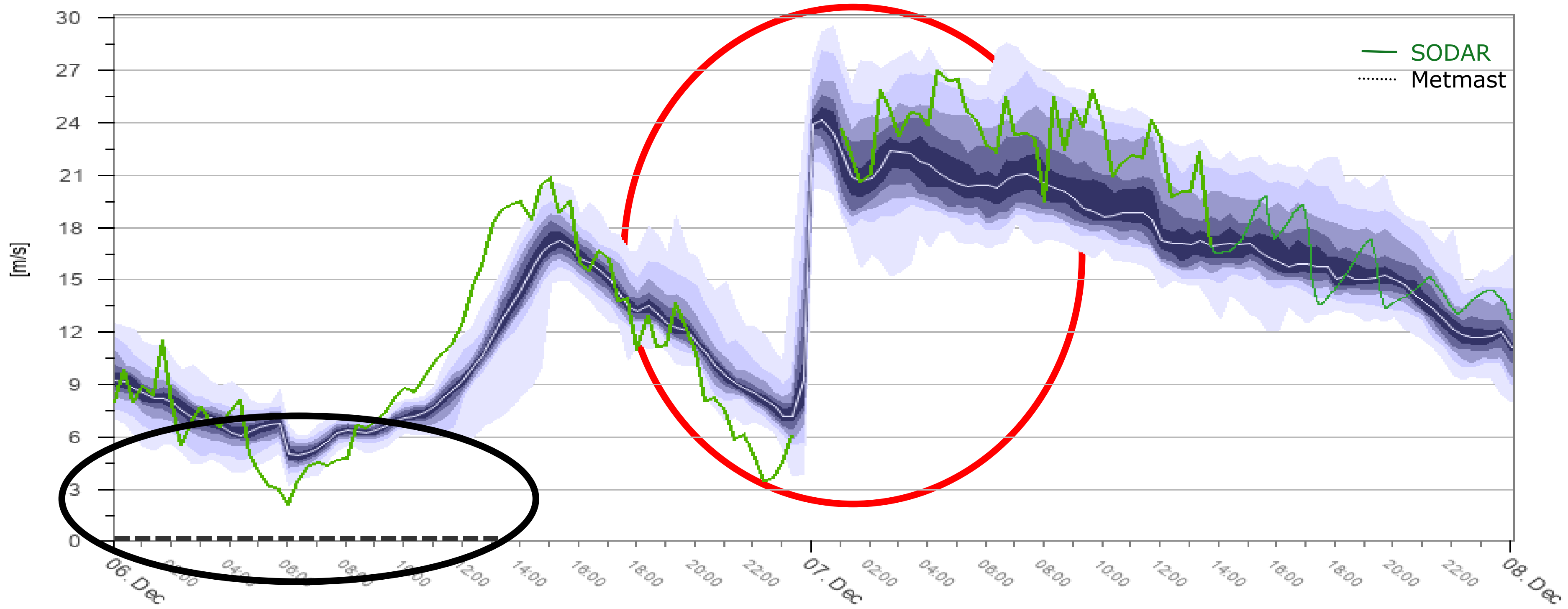


Extreme event at an Irish wind farm
Example of profiler adaptation to real time application

MSEPS power forecast indicated a chance of cut-out that indeed happened as curtailment



Extreme event at an Irish wind farm



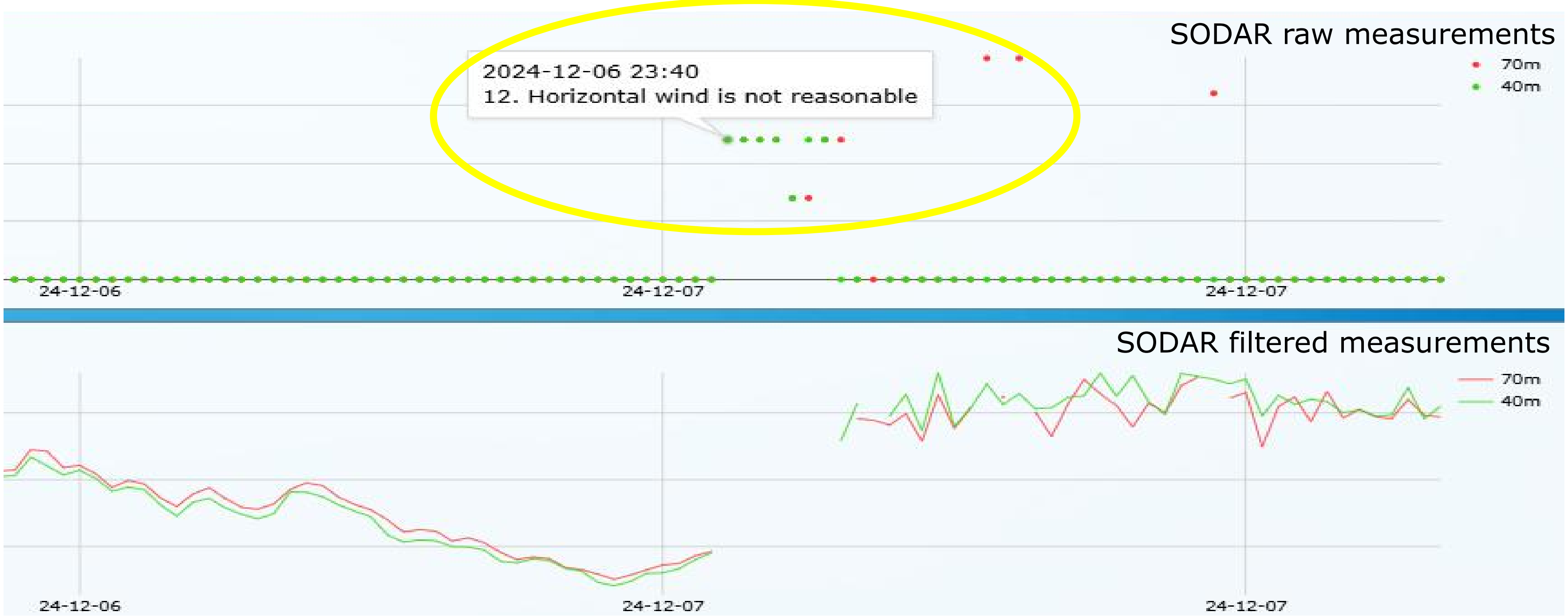
Official tower measurements were unavailable

Extreme event at an Irish wind farm
Example of profiler adaptation to real time application

WEPROG

AQSystem
Remote sensing technique

An investigation showed that the sodar wind speed was filtered out due to some activated flags that disallow strong ramps!

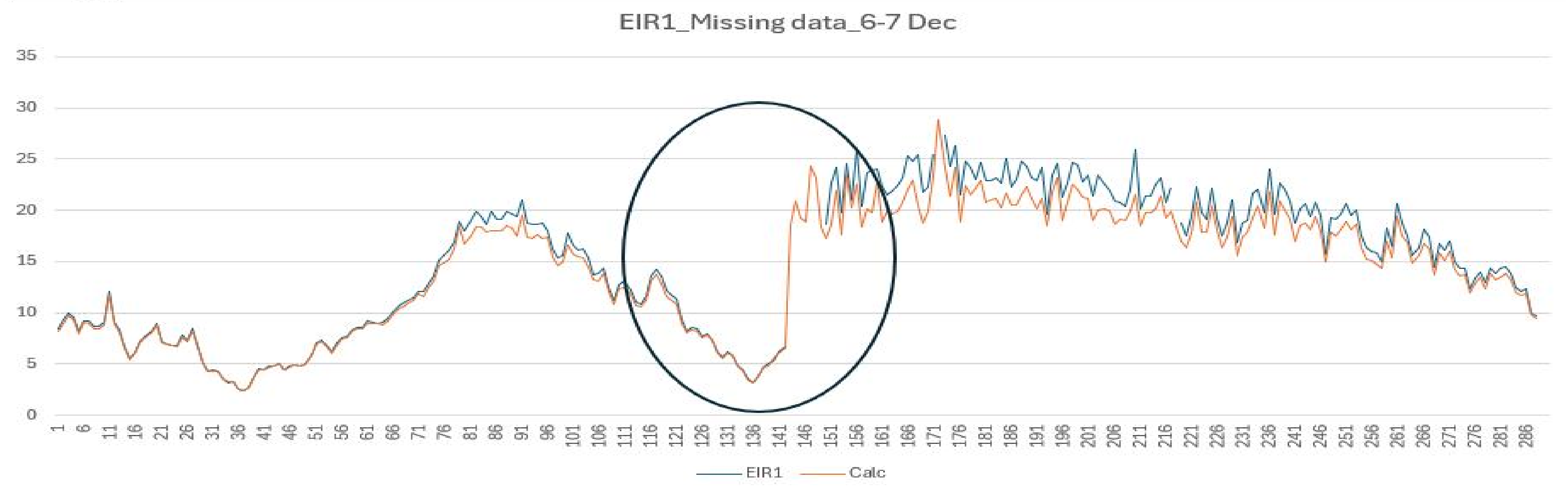


Extreme event at an Irish wind farm
Example of profiler adaptation to real time application

WEPROG

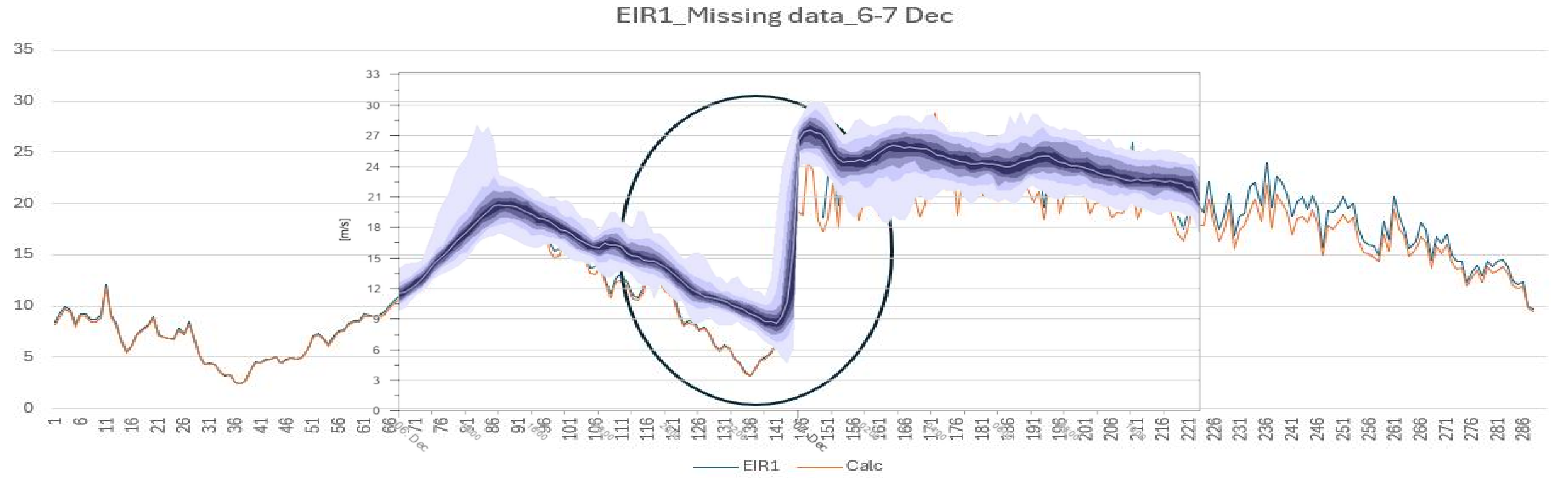
AQSystem
Remote sensing technique

Relaxing a filter in the sodar signal processing routine completely recovered the wind speed during the entire event



Extreme event at an Irish wind farm
Example of profiler adaptation to real time application

Relaxing a filter in the sodar signal processing routine completely recovered the wind speed during the entire event … and confirmed also the goodness of forecasts !



Summary from adaptation of a SODAR to real-time applications

WEPROG

Signal processing needs to be adapted to target interest:

Resource assessment ↔ Real-timer operation

Area and **distance BIAS** needs attention to not overestimate wind speed

Profilers can inform, give indication & "fix" **time resolution problems in forecasts**
(reduce missing impact-full "peaks" & reduce phase errors)

If data shall be used for extreme events, **ramping filters** need adaptation

Forecast Skill

Ensemble forecast can provide a consistent and complete picture of weather to profiler & use it's data to reduce forecast errors

Instrument Tuning

Adaptation of signal processing required in order to make profilers useful for different tasks: resource assessment, real-time forecasting or Operation & Maintenance

Lessons Learned and Take-aways

- NWP Ensemble models can provide skillful information in case of no/corrupt observations, when they are tuned to the instrument
- Vertical profiles help understand the complexity of weather related environmental conditions the instruments work in
- Ensemble forecasts with the MSEPS provides a possibility to use the intelligence of the physical representation in an AI framework

Thank you for you attention

Questions …

Funded by:

EUREKA Eurostar III Call 3 project
Project no. E2442

WIKKI project funded by
Deutsche Bundesstiftung Umwelt (DBU) Germany
Project no. 37549/01

Supported by:

WinForS Consortium and WINSENT Testfield Coordinator:
ZSW Baden-Wurttemberg, Germany
https://www.windfors.de/en/projects/test-site/winsent/

EARS4WindEnergy
Ensemble-based Approach utilizing a Refined SODAR for Wind Energy Applications

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