Characterization of Low-Level Jet Events at different Offshore Locations

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2. Measurement and detection of Low-Level Jets (LLJ)
3. Characterization of LLJs
4. Parameterization of LLJs by analytical profiles
5. Conclusion and outlook

1. Introduction

- LLJs are local maxima in a vertical wind profile at low altitudes
- Appear at height of swept rotor area of wind turbines
- Observed quite frequently in offshore regions

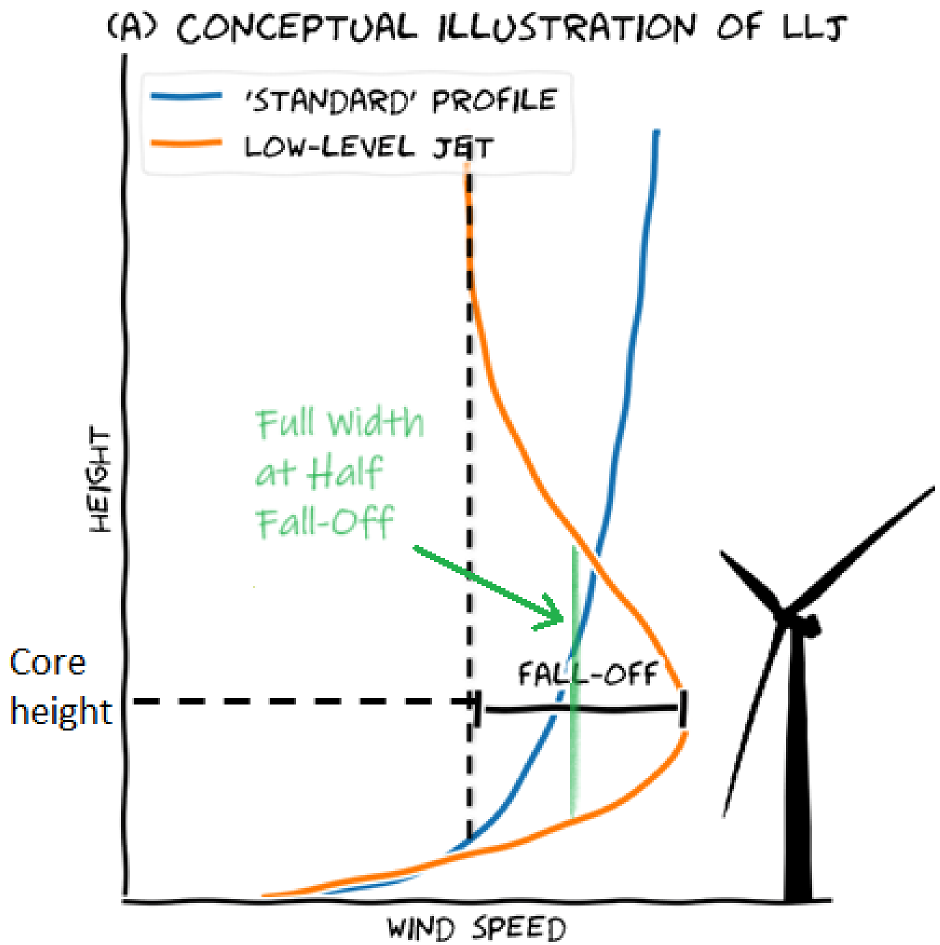
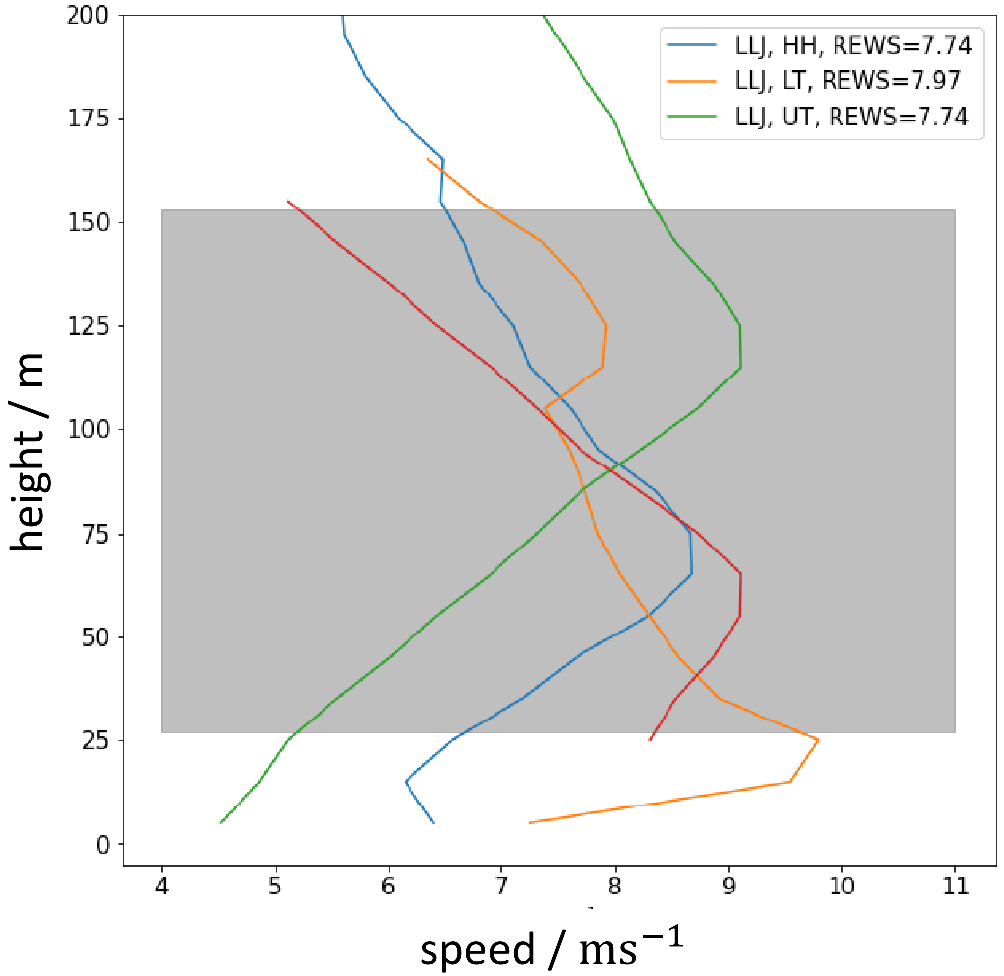


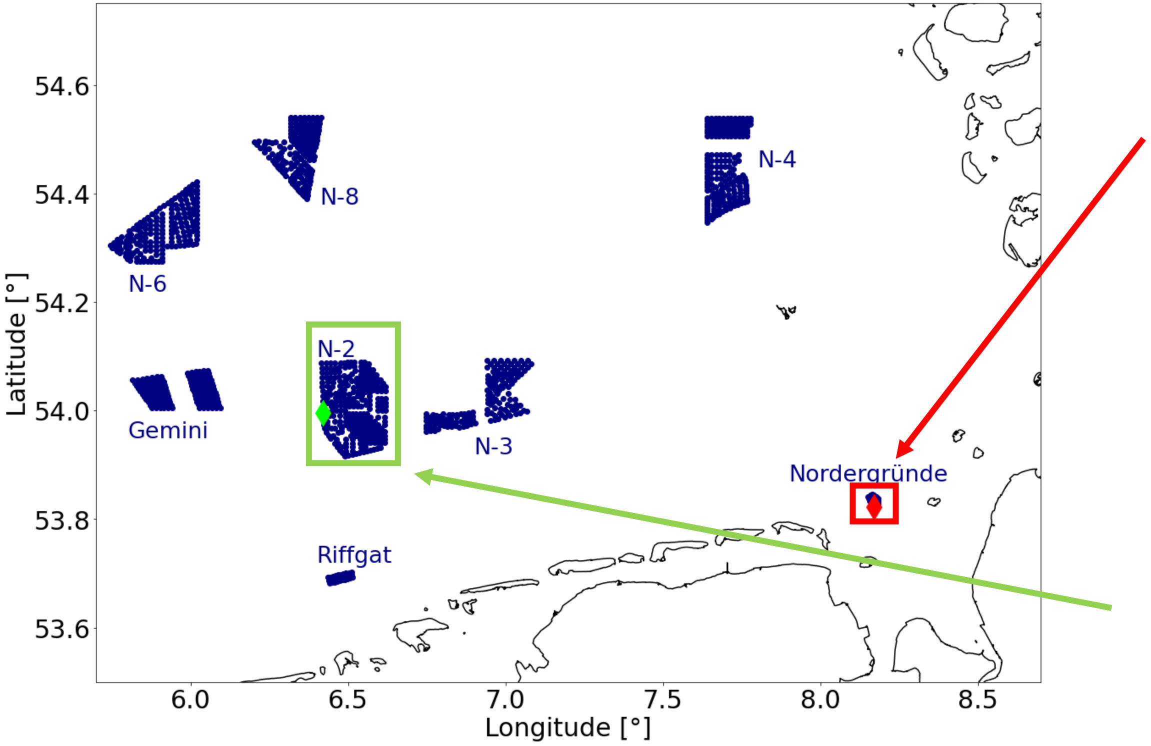
Figure adapted from: Kalverla et al., 2019

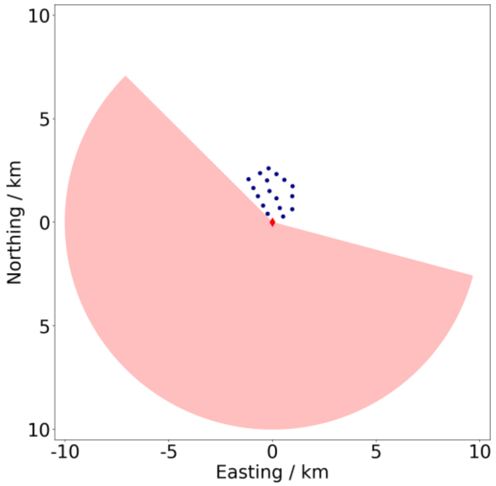
Motivation

- May influence power production and dynamic loads
- Will become more important with larger turbines
- Many definitions available
- Analytical functions to improve description of LLJ properties

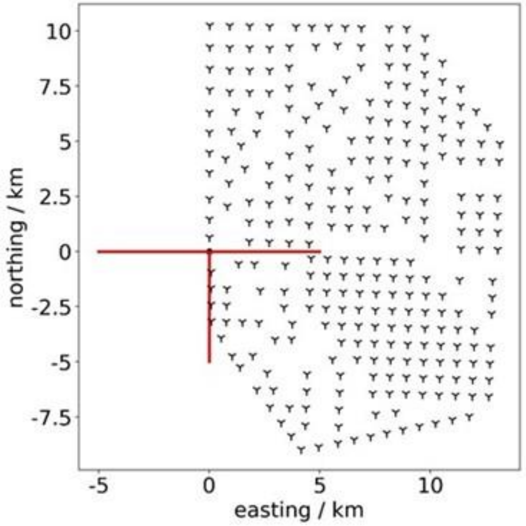


2. Measurement and detection of LLJ





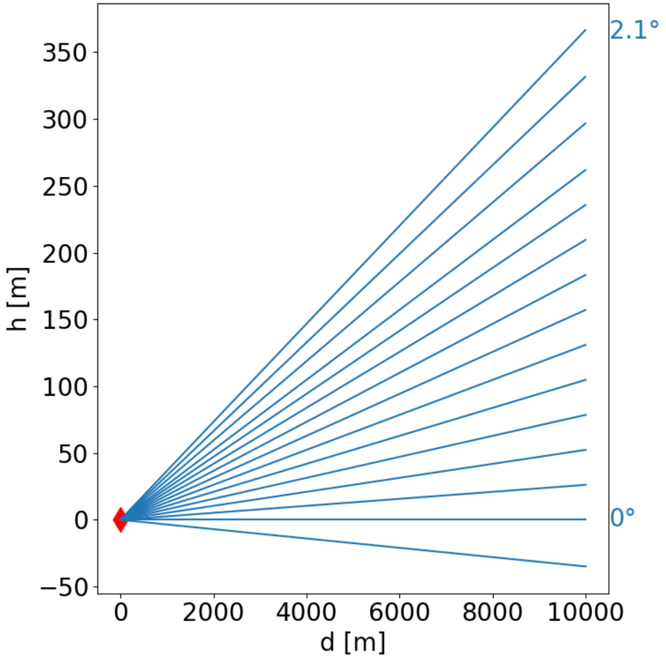
Nordergründe (NG):
- Plan-position indicator (PPI)



DolWin Gamma (DWG):
- Range-height indicator (RHI)
- Doppler Beam Swing (DBS)

Profile measurements by scanning Lidars

Location	Measurement technique	Max. height	Vertical resolution	Temporal resolution	Duration
NG	Multi-Elevation horizontal PPI	350 m	10 m	30 min	15 month
DWG	RHI	2290 m	5 m	30 min	13 month
DWG	DBS	1220 m	6 m	30 min	10 month



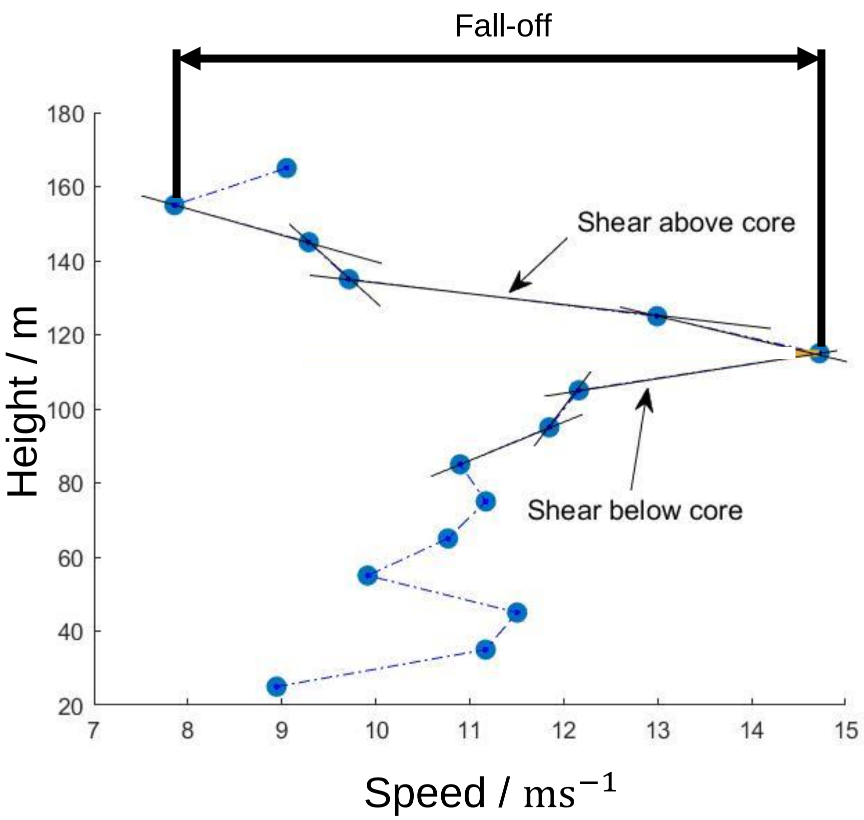
15 consecutive PPI scans with increasing elevation

Data preprocessing

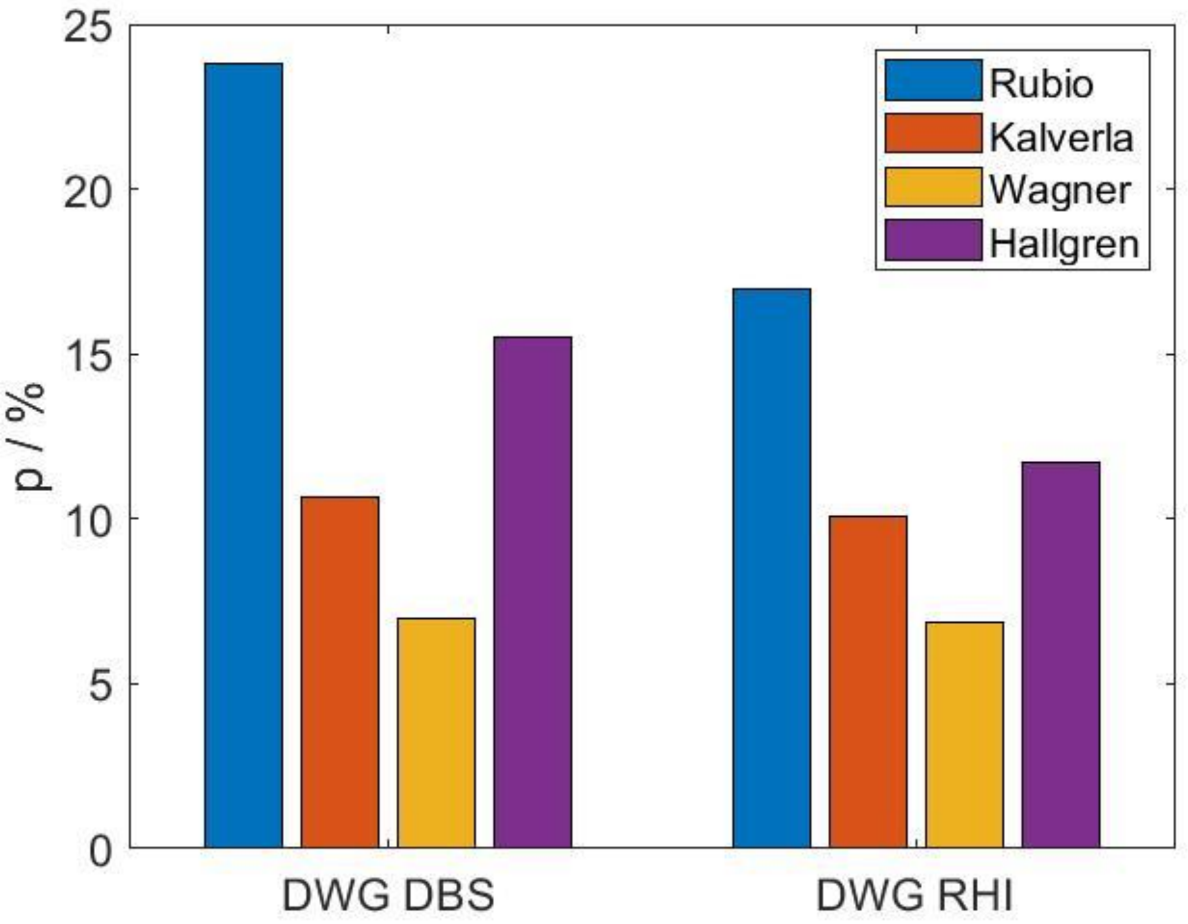
- Horizontal wind speed via VAD algorithm
- For PPI and RHI: Averaging over heights and 30 min temporal averaging
- Filtering for wind direction
- Rolling average to smooth profile
- Filtering of outliers
- 5 erroneous values in a row → profile not considered

LLJ detection criteria

Defined by	Criteria (Conjunctive)
Hallgren et al. (2023)	- Shear above the core $\leq -0.01\,\mathrm{s}^{-1}$ - Shear below the core $\geq 0.01\,\mathrm{s}^{-1}$
Kalverla et al. (2019)	- Absolute fall-off $\geq 2\,\mathrm{ms}^{-1}$
Rubio et al. (2022)	- Absolute fall-off $\geq 1\,\mathrm{ms}^{-1}$
Wagner et al. (2019)	- Absolute fall-off $\geq 2\,\mathrm{ms}^{-1}$ - Relative fall-off $\geq 25\,\%$



LLJ detection: criteria and scanning techniques

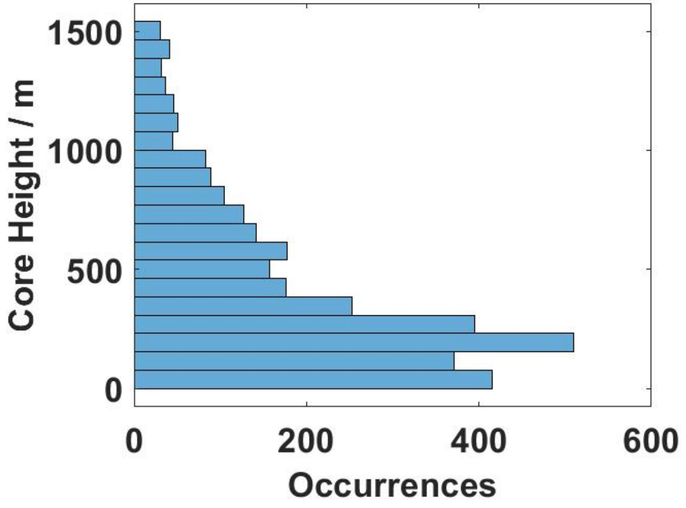


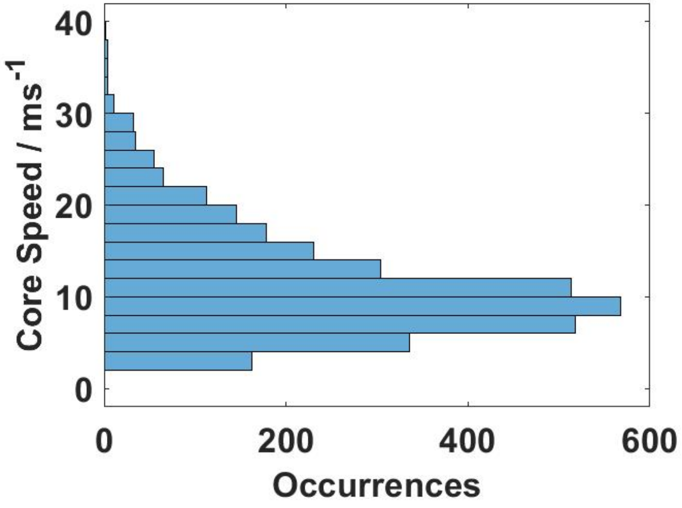
Measurement campaign	Number of LLJ instances	Percentage / %
DWG DBS	2953	23.8
DWG RHI	2417	17.0

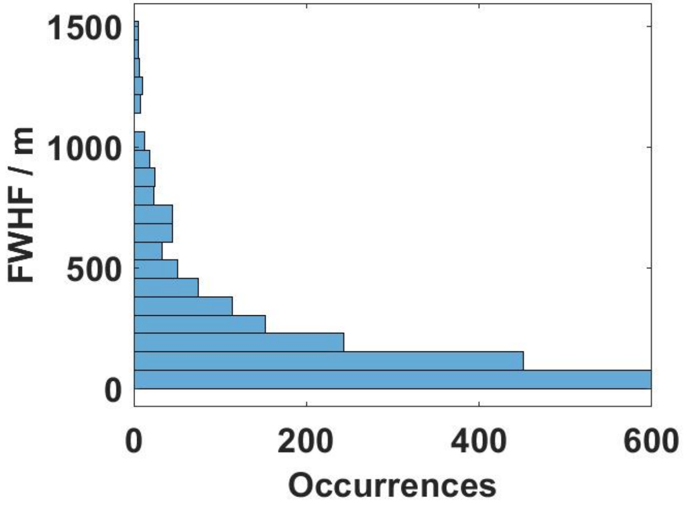
3. Characterization of LLJ

DWG DBS

- Core height usually < 500 m
- „Full width at half fall-off“ (FWHF) mostly < 300 m
- Core speed around 10ms^{-1}
- Measurements shifted up by 50 m because of measurement platform







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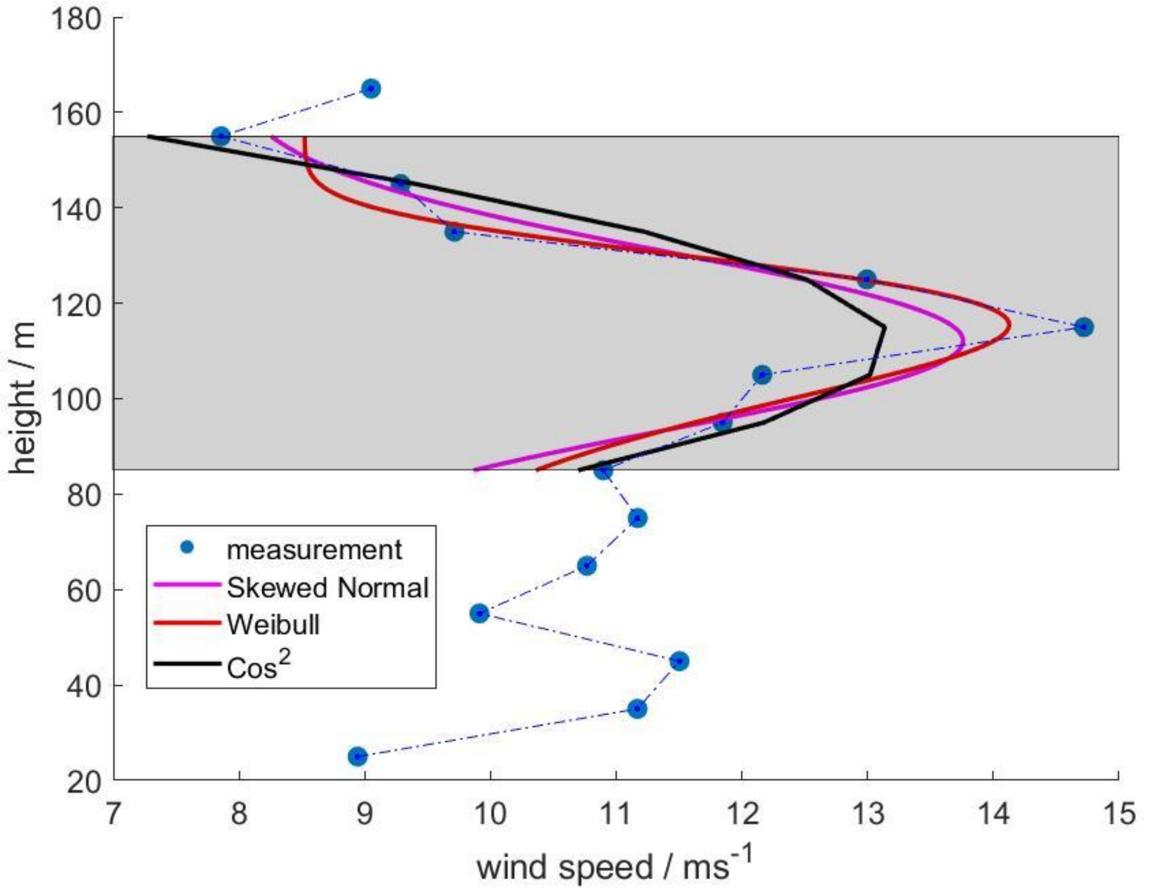
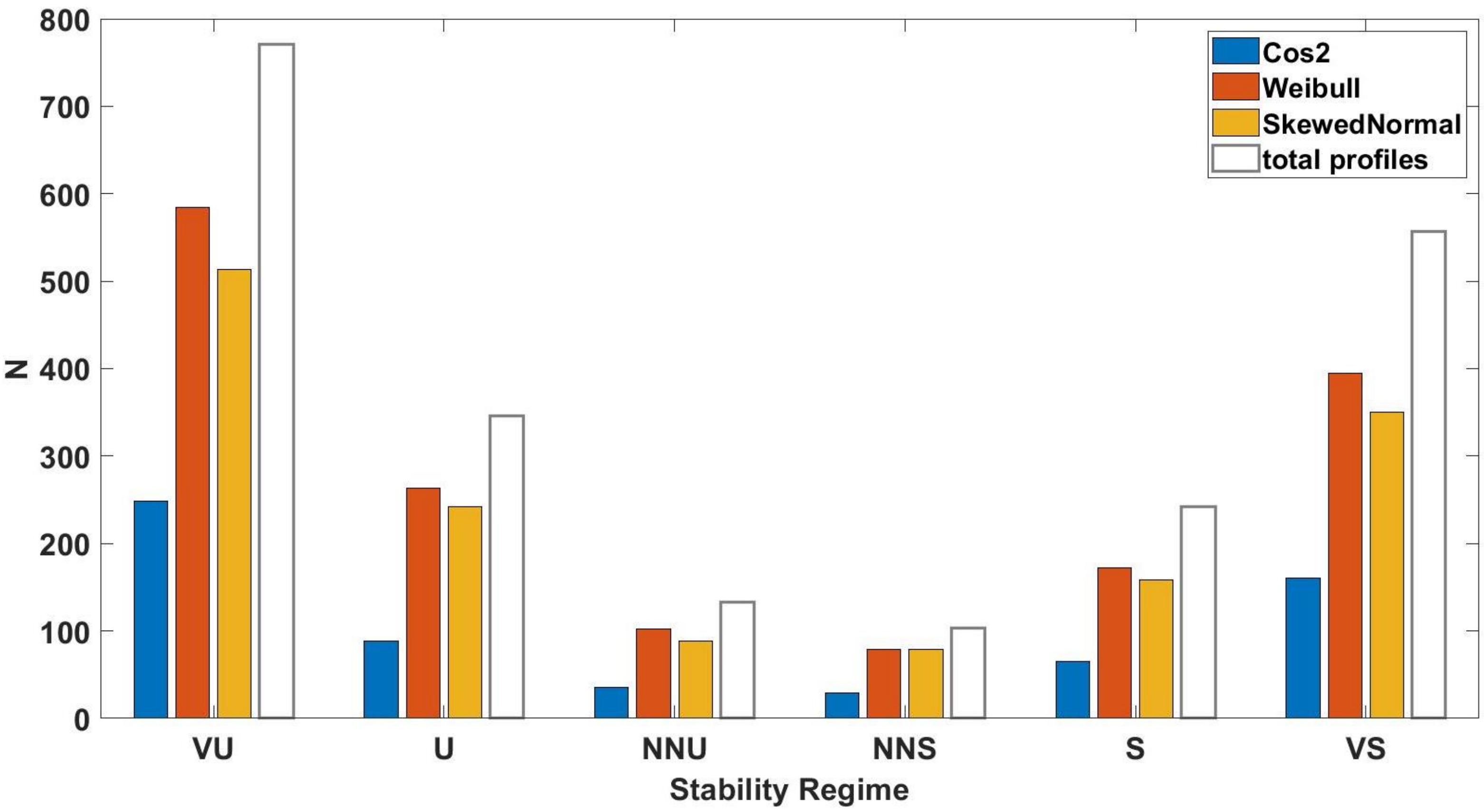
4. Parameterization of LLJ by analytical profiles



- Generalization by analytical profile
- Least-squares fitting
- Fit applied between local minima above and below core

Quality of core region fit



- Number of fits per stability regime with coefficient of determination $R^2 \geq 0.8$
- Weibull reaches threshold for ~70-80% of profiles

5. Conclusion

Characterization

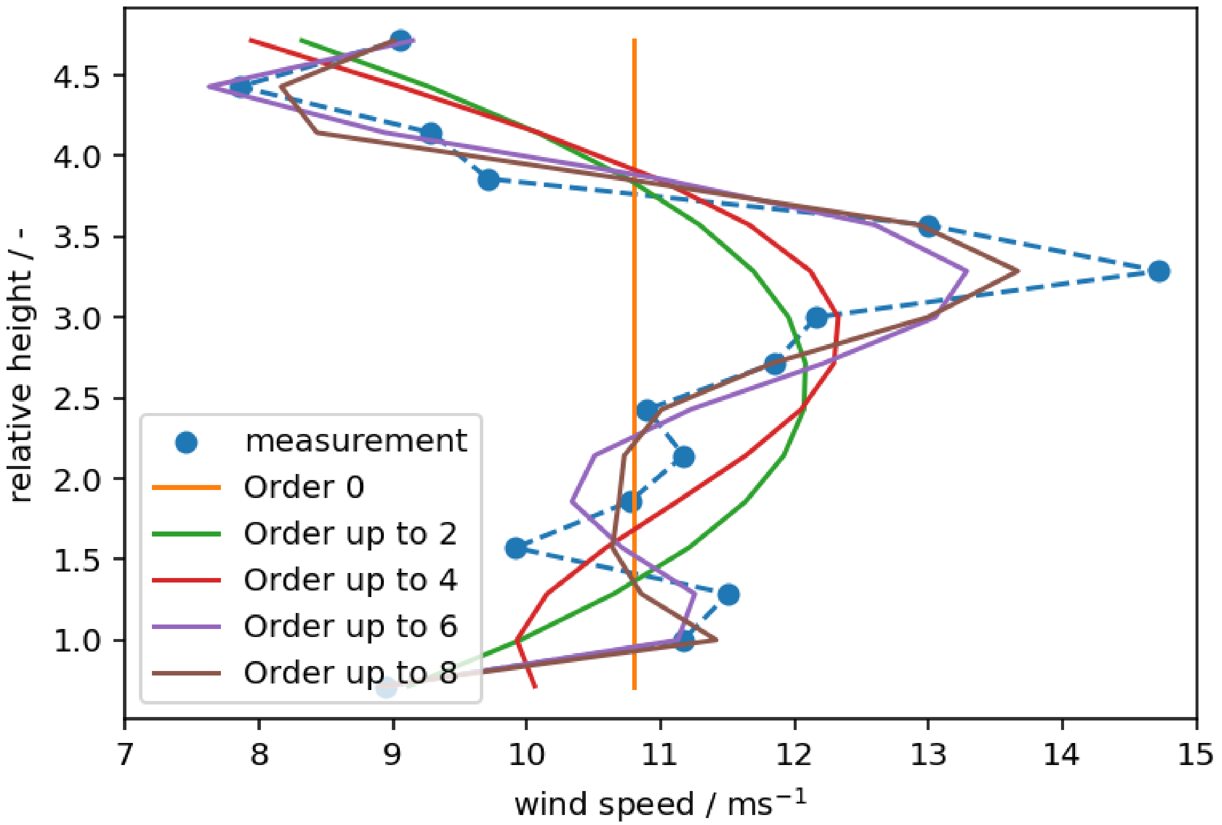
- Comparison difficult due to different locations, measurement techniques and Lidar systems
- LLJ core often at height of rotor swept area (~23% in DWG DBS)

Parametrization

- Weibull and Skewed Normal functions fit the region around core quite well
- $\cos^2$- function only works for very symmetrical LLJ

5. Outlook

- Test parameterization with Laguerre polynomials
- Analyze turbine response on LLJ
  - Aeroelastic simulations of power and loads with parameterized LLJ profiles
  - Power data (SCADA) at measured LLJ situations



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Any questions?

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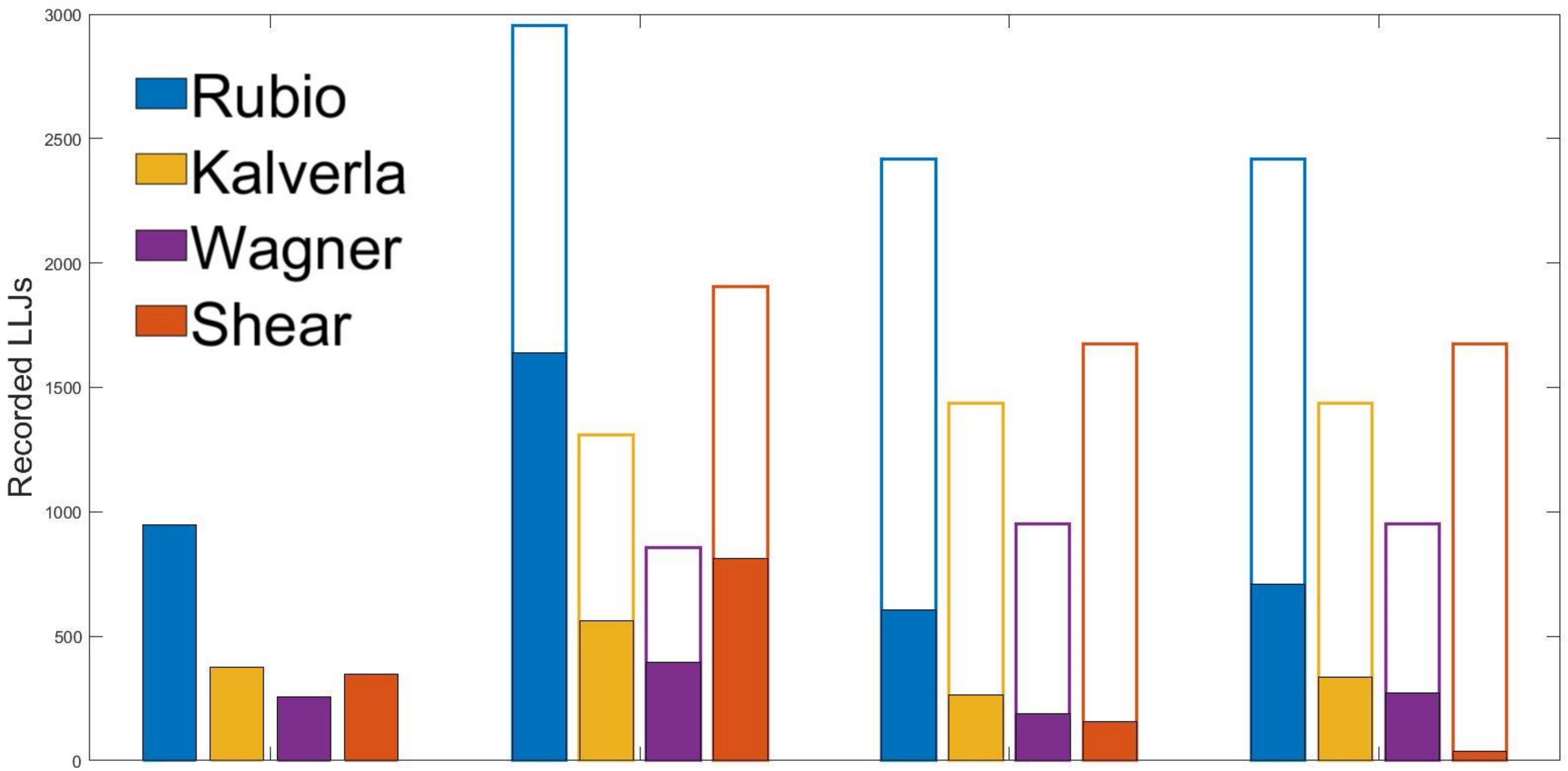
Fitting functions

- cos^2-function: $u = u_{min} + a * \cos(b * h + c)^2$
- Weibull distribution: $u = u_{min} + a * \left(\frac{k}{\lambda}\right)\left(\frac{h}{\lambda}\right)^{k-1} * \exp\left(-\left(\frac{x^k}{\lambda}\right)\right)$
- Skewed normal distribution:

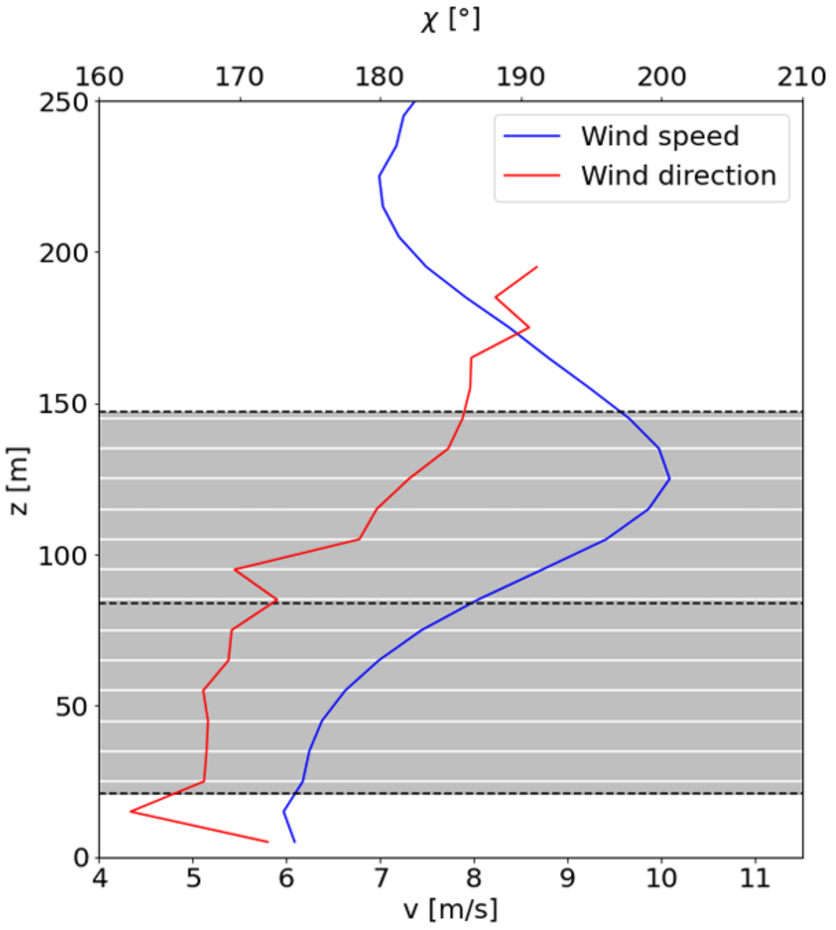
$$u = u_{min} + a * \frac{2}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \int_{-\infty}^{\lambda\frac{(h-\mu)}{\sigma}} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{t^2}{2}\right) dh$$

Accounting for diffence between measurement campaigns



NG DWG DBS DWG RHI DWG RHI 10 m

Wind veer


χ [°]
160
170
180
190
200
210
250
200
150
100
50
0
z [m]
Wind speed
Wind direction
4
5
6
7
8
9
10
11
v [m/s]

Stability regimes

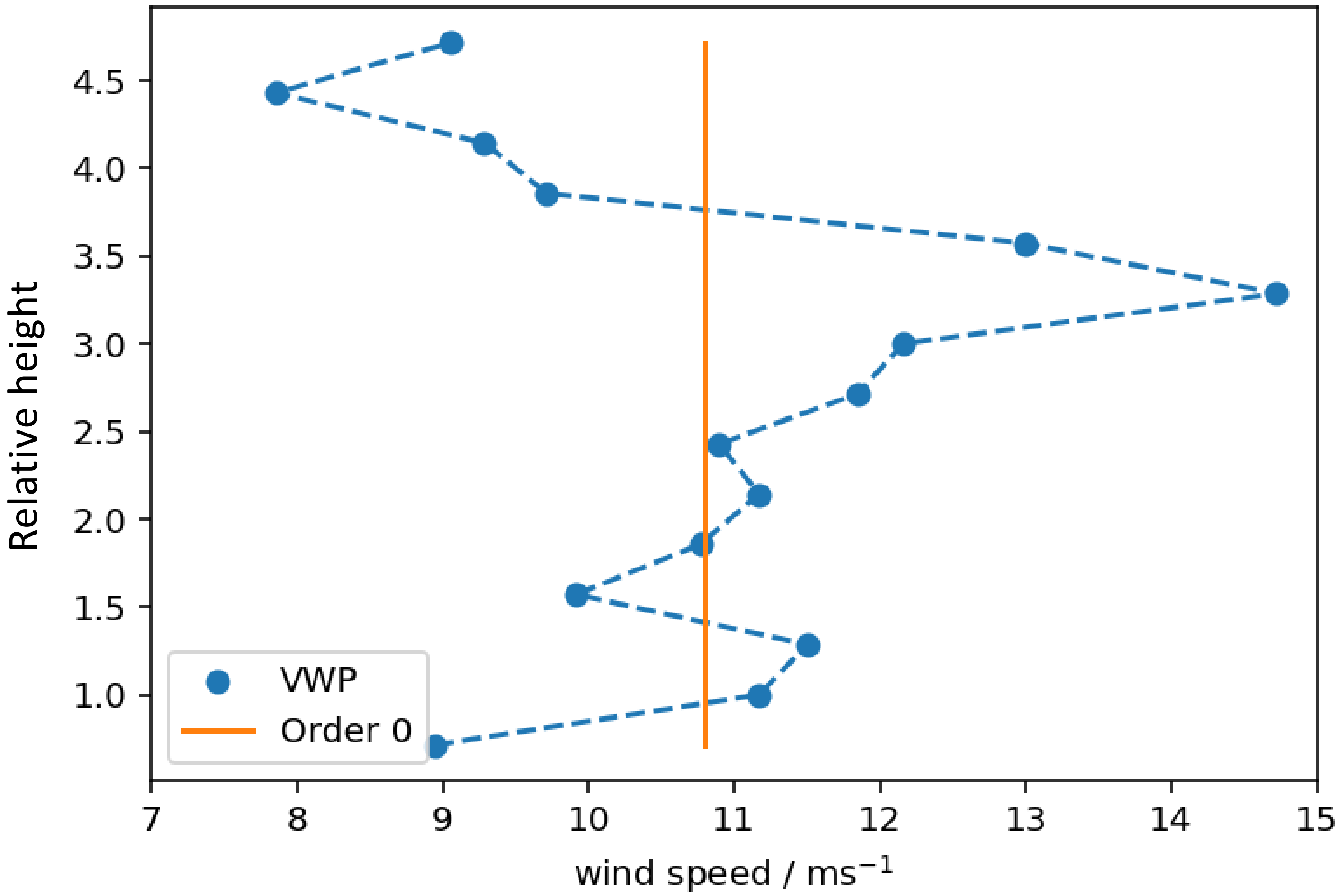
Table 2: Obhukov Length L_* and the corresponding stability regime

Stability Class	Range of L_*
Very Stable (VS)	$0 \leq L_* < 200$
Stable (S)	$200 \leq L_* < 1000$
Near neutral (NN)	$1000 \leq \lvert L_* \rvert$
Unstable (U)	$-1000 < L_* \leq -200$
Very unstable (VU)	$-200 < L_* \leq 0$

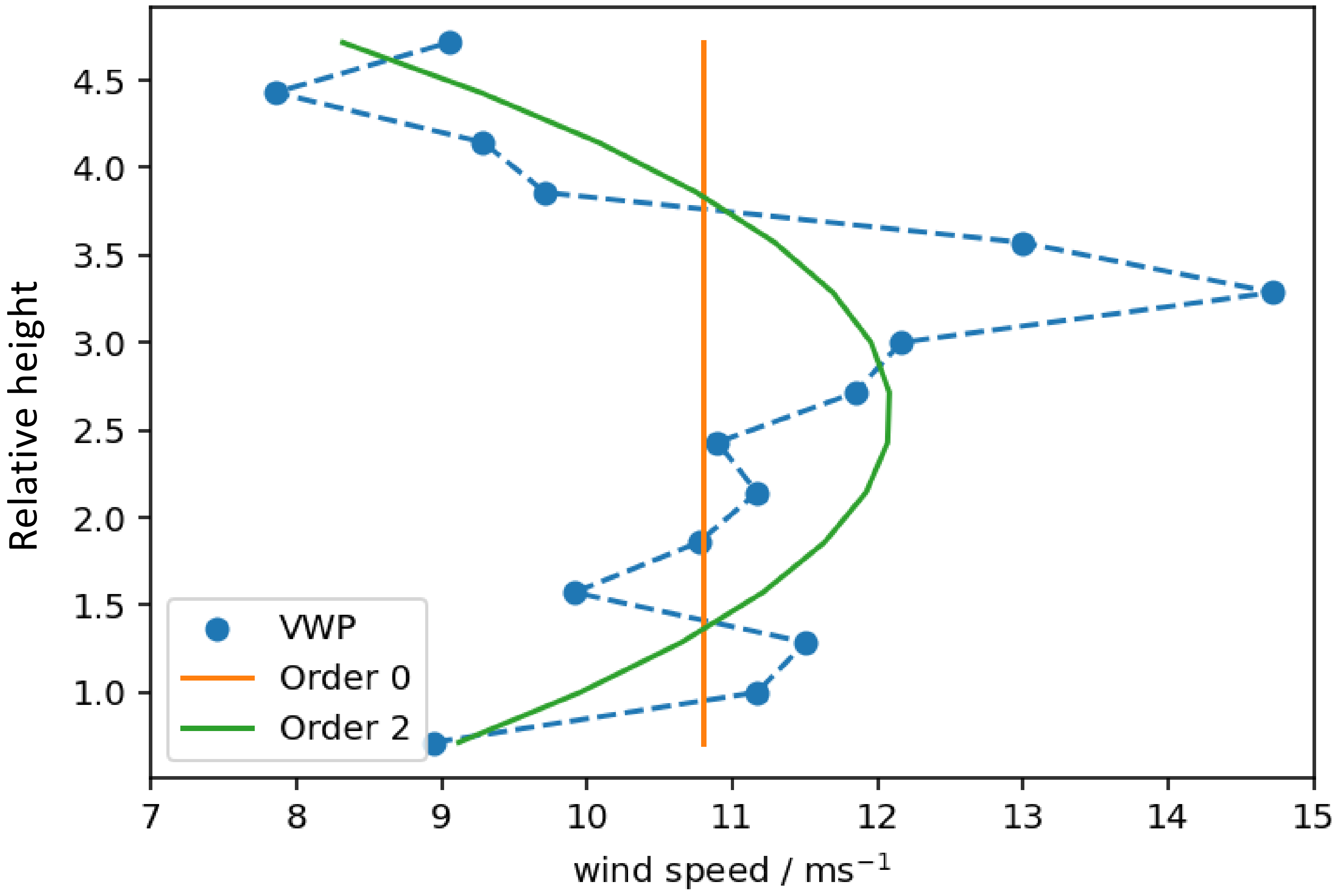
Table 5: Probability at which the stability regimes can be observed for DWG and NG

	VU	U	NNU	NNS	S	VS
DWG	13 %	37 %	5 %	4 %	14 %	25 %
NG	12 %	53 %	2 %	2 %	9 %	20 %

Fitting process (the entire profile)



Fitting process (the entire profile)



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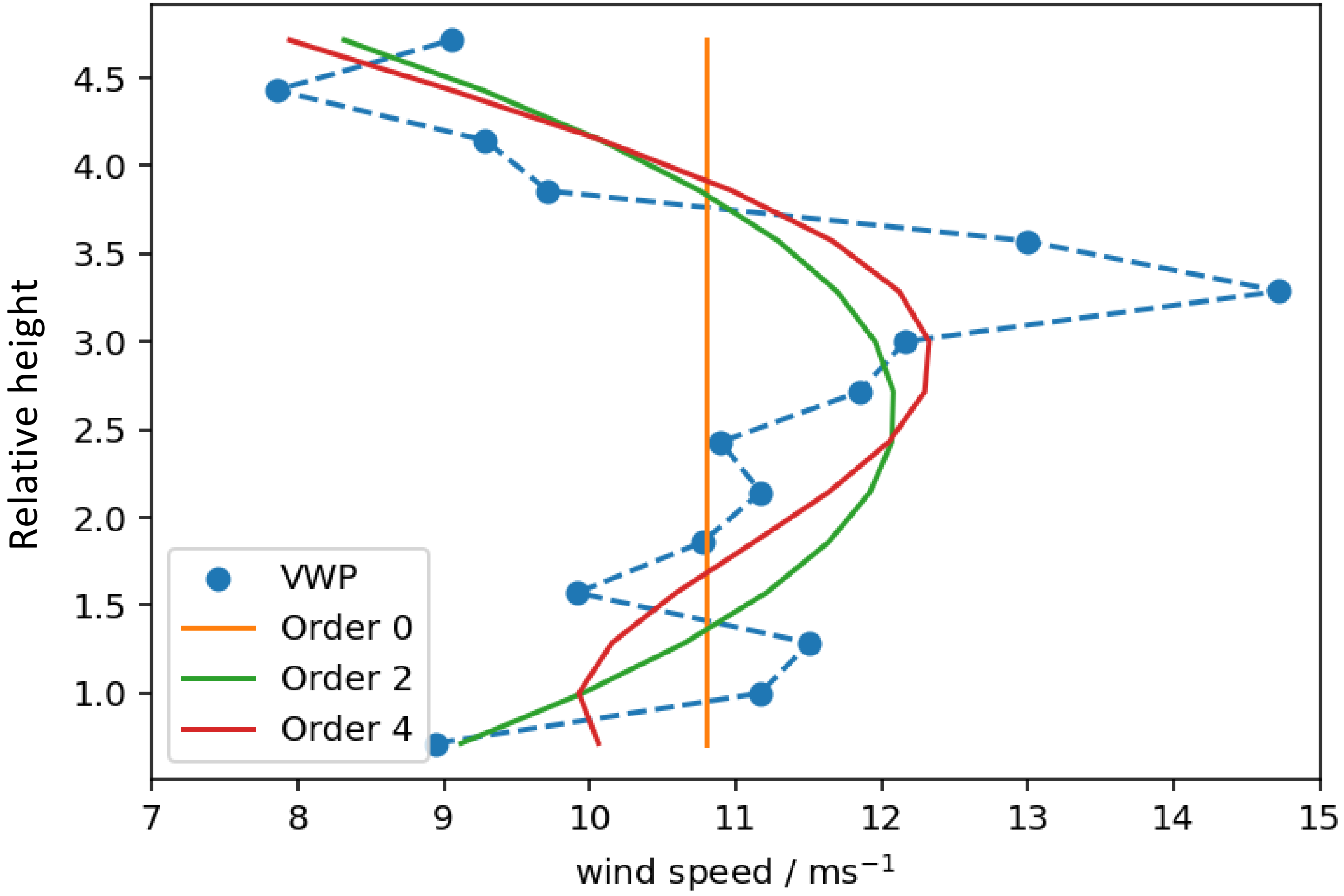

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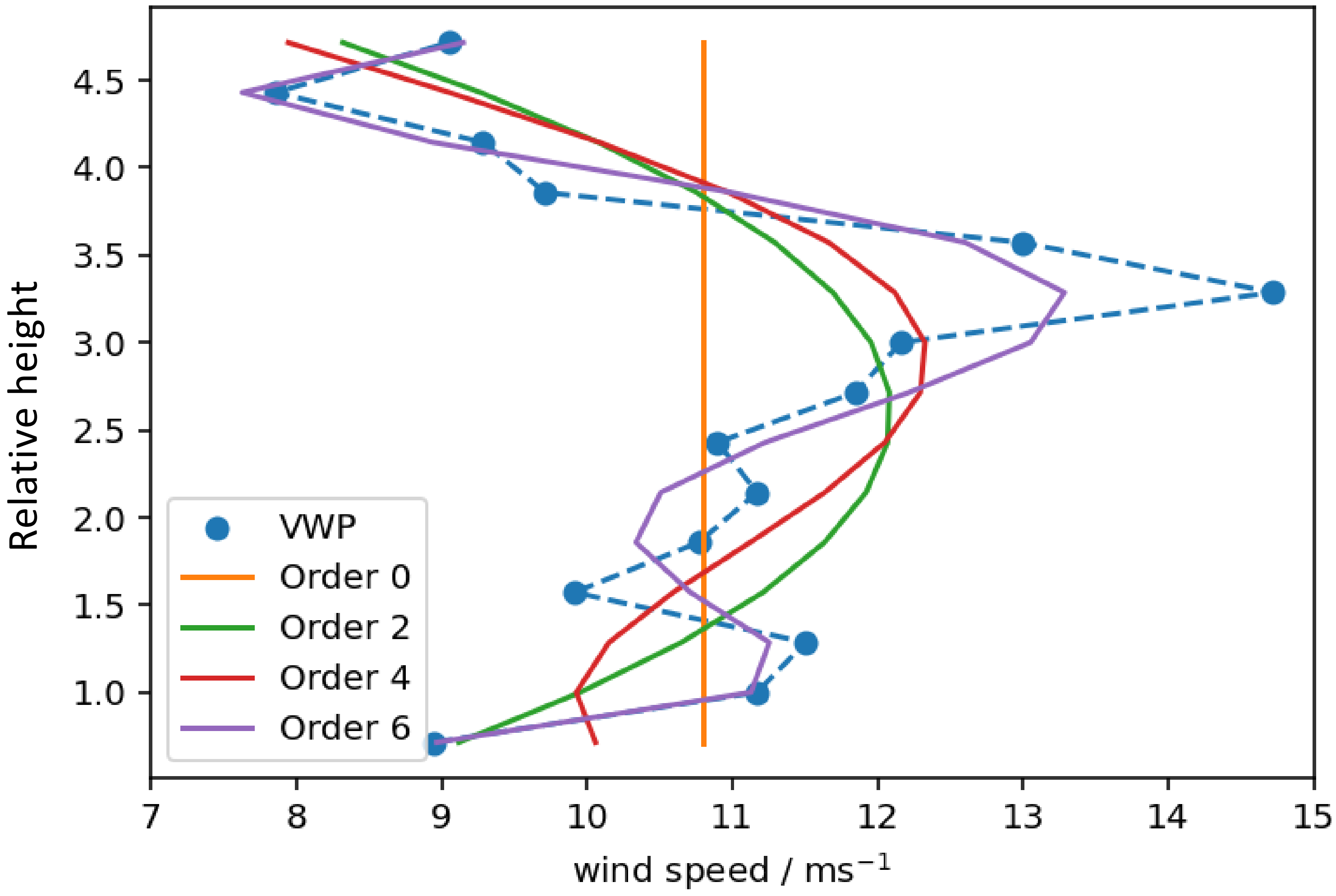

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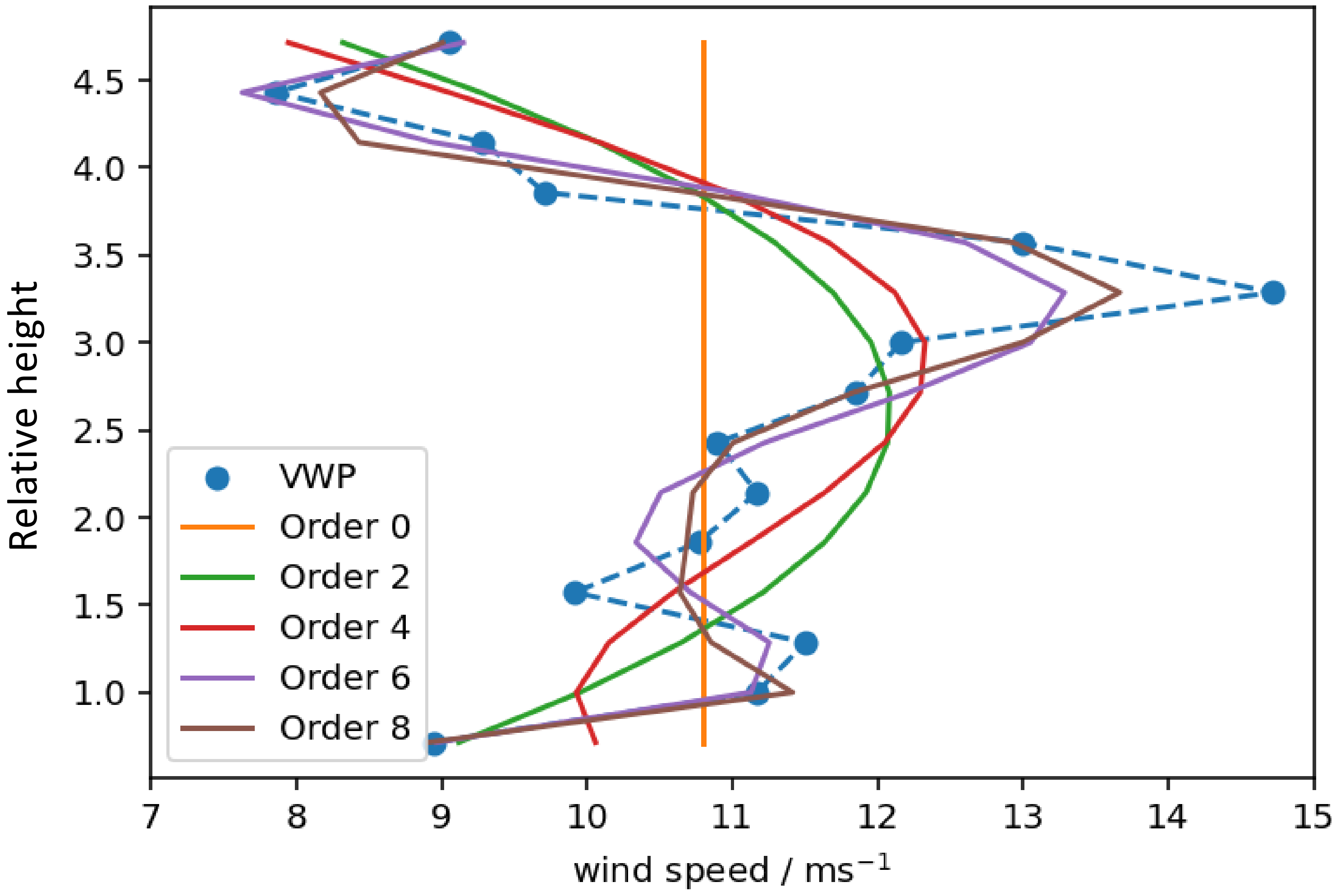
Fitting process (the entire profile)



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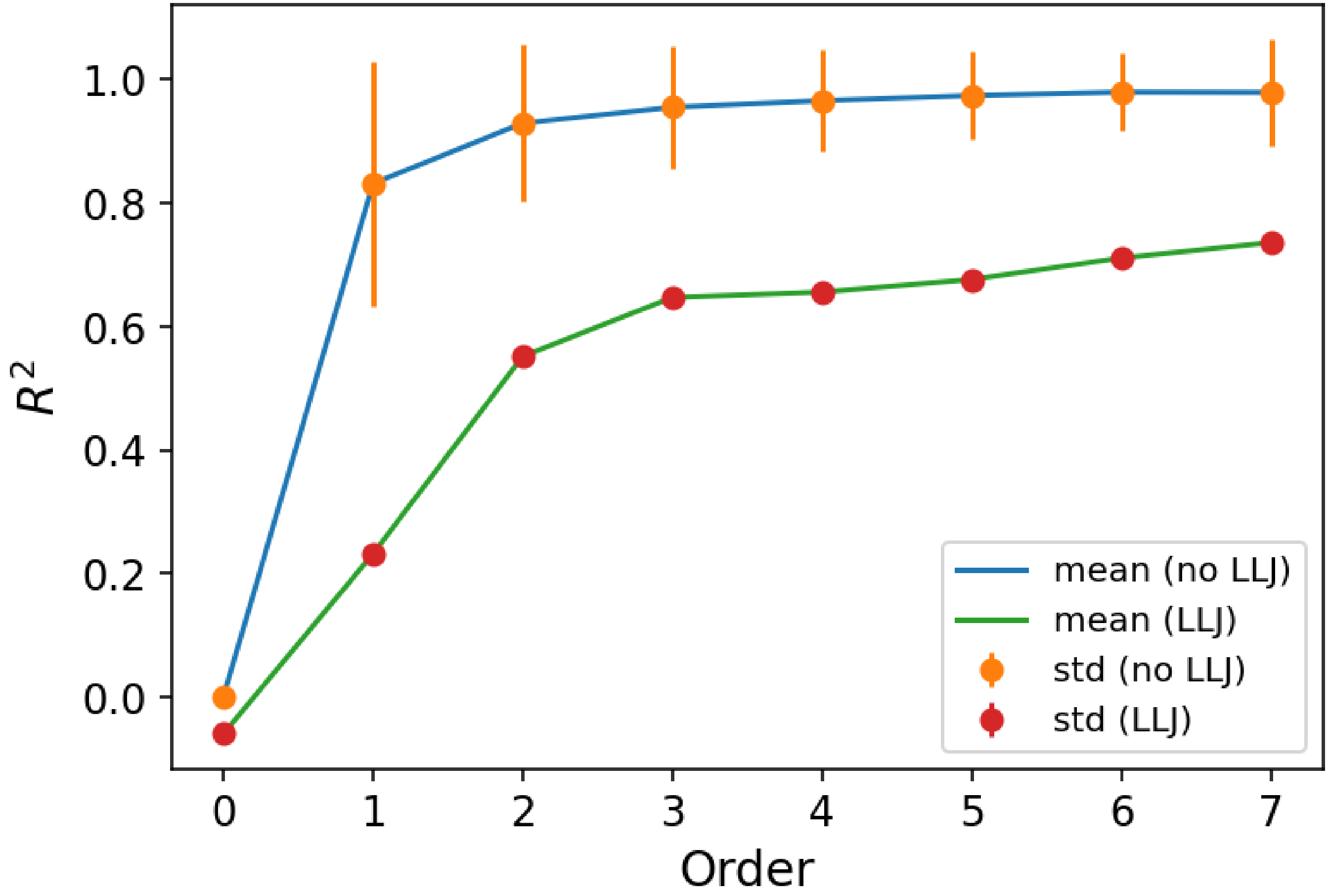
Quality of Laguerre Fits

-Mean R^2 for LS over the highest Order



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