Stable Boundary Layer Wind Profiles
A Comparison of Analytical Models and LiDAR Observations

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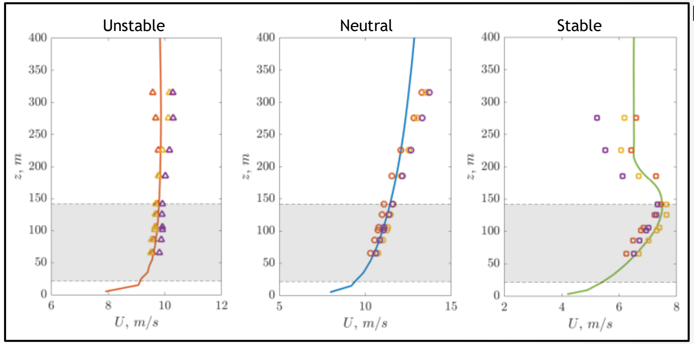
Atmospheric Stability and Wind Turbine Response

Thermal stratification influences the loading and power production of wind turbines through effects on:

1. Mean wind profiles:
   - Wind shear
   - Wind veer
2. Turbulence characteristics:
   - Turbulence intensity
   - Turbulence spectra
   - Coherence
3. Wake behaviour:
   - Wake recovery
   - Wake meandering
   - Wake skewing



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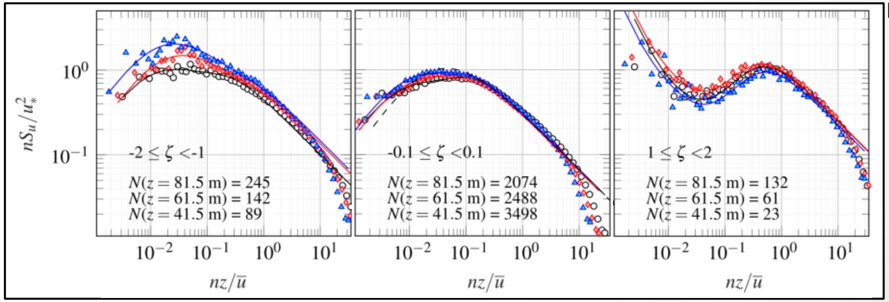

[2]

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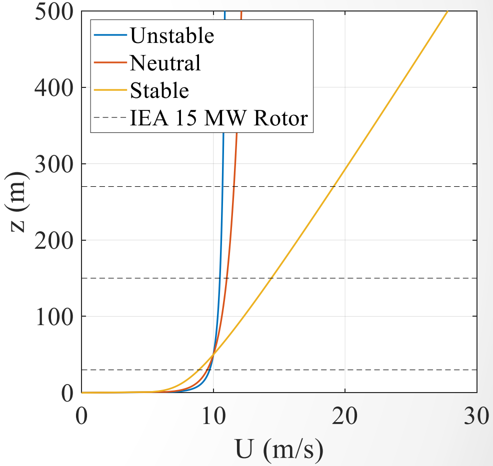
[1] Chanprasert, Warit, Sharma, Rajnish N., Cater, John E. and Norris, Stuart E. "Observation and Large Eddy Simulation of Coastal Winds at Anholt Offshore Wind Farm." Journal of Physics: Conference Series. Vol. 2362 No. 1 (2022): p. 012008. DOI 10.1088/1742-6596/2362/1/012008.
[2] Cheynet, Etienne, Jakobsen, Jasna B. and Reuder, Joachim. "Velocity spectra and coherence estimates in the marine atmospheric boundary layer." Boundary-layer meteorology. Vol. 169 No. 3 (2018): pp. 429-460. DOI 10.1007/s10546-018-0382-2.

Atmospheric Stability and the Mean Wind Profile

Within the surface layer, effects of thermal stratification are efficiently represented using the logarithmic wind profile:

- $U(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \psi\right]$
- Stability correction: $\psi = \mathrm{f}(z, L)$



However, in stable atmosphere, surface layer theory:

- tends to overestimate wind speeds above the surface layer.
- does not account for frequently occurring low-level jets.[3,4]
- does not account for frequently occurring wind veering.[1,5]

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[1] Chanprasert, Warit, Sharma, Rajnish N., Cater, John E. and Norris, Stuart E. "Observation and Large Eddy Simulation of Coastal Winds at Anholt Offshore Wind Farm." Journal of Physics: Conference Series. Vol. 2362 No. 1 (2022): p. 012008. DOI 10.1088/1742-6596/2362/1/012008.

[3] De Jong, Emily, Quon, Eliot and Yellapantula, Shashank. "Mechanisms of Low-Level Jet Formation in the US Mid-Atlantic Offshore." Journal of the Atmospheric Sciences. Vol. 81 No. 1 (2024): pp. 31-52. DOI 10.1175/JAS-D-23-0079.1.

[4] Borvarán, Dager, Peña, Alfredo and Gandoin, Rémi. "Characterization of offshore vertical wind shear conditions in Southern New England." Wind Energy. Vol. 24 No. 5 (2021): pp. 465-480. DOI 10.1002/we.2583.

[5] Berg, Jacob, Mann, Jakob and Patton, Edward G. "Lidar-observed stress vectors and veer in the atmospheric boundary layer." Journal of Atmospheric and Oceanic Technology. Vol. 30 No. 9 (2013): pp. 1961-1969. DOI 10.1175/JTECH-D-12-00266.1.

Overview

Stable Boundary Layer Wind Profiles –
A Comparison of Analytical Models and LiDAR Observations

- Datasets
- Analytical Wind Profile Models
  - Theory
  - Parametrization
- Wind Profile Comparisons
- Conclusion

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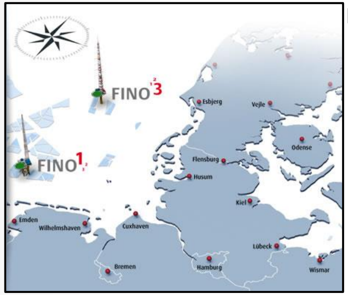
Datasets



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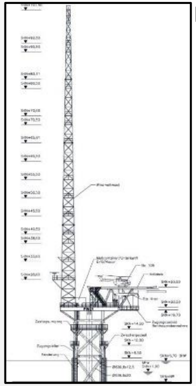
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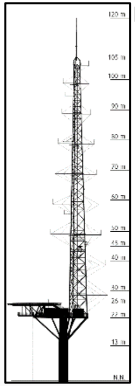
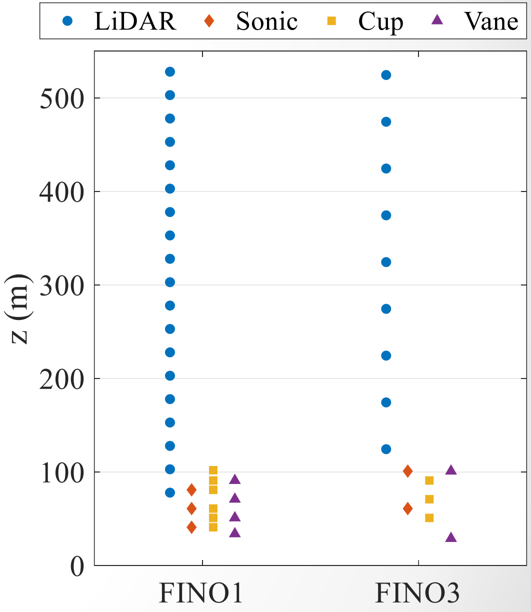

[8]

FINO1	FINO3
June 2015 – Oct. 2016	Aug. 2013 – Oct. 2014
WindCube 100S $z = 78 \ldots 3528$ m with $\mathrm{d}z = 25$ m	WindCube WLS70 $z = 125 \ldots 2025$ m with $\mathrm{d}z = 50$ m
Mast data at $z = 34 \ldots 102$ m	Mast data at $z = 29 \ldots 101$ m



[6] https://www.fino-offshore.de. Accessed 09.01.2025.
[7] https://www.fino1.de/en/about/design.html. Accessed 09.01.2025.
[8] https://www.fino3.de/en/location/design.html. Accessed 09.01.2025.

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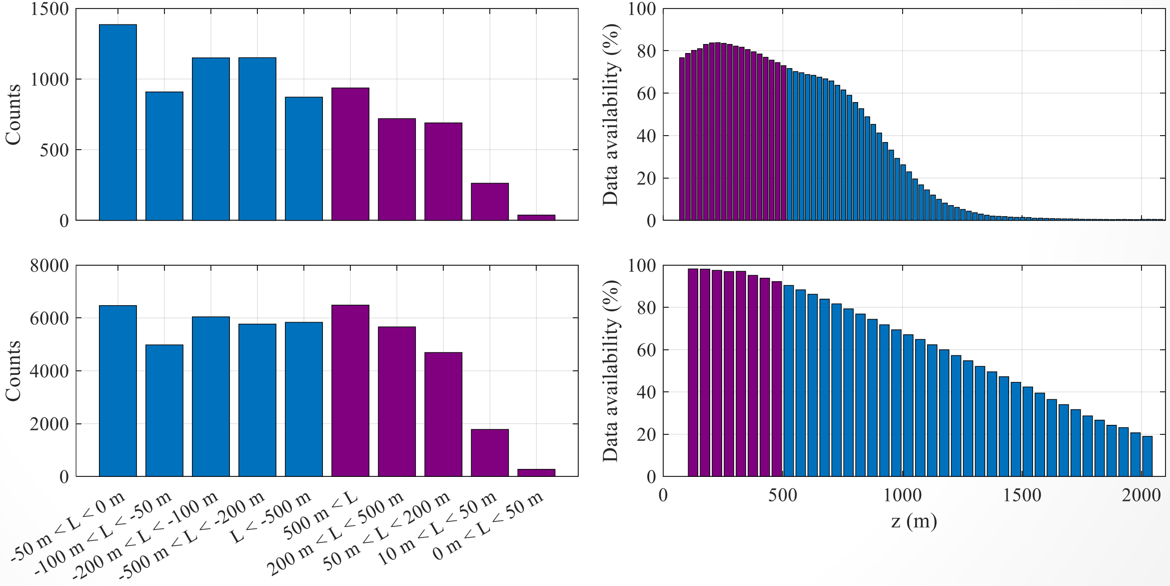
Data Filtering

- 10-min. averaged LiDAR profiles classified using ERA5 Obukhov length estimate.
- Observations filtered for $L \geq 0\ \mathrm{m}$ and $z \leq 500\ \mathrm{m}$.

- FINO1
- FINO3



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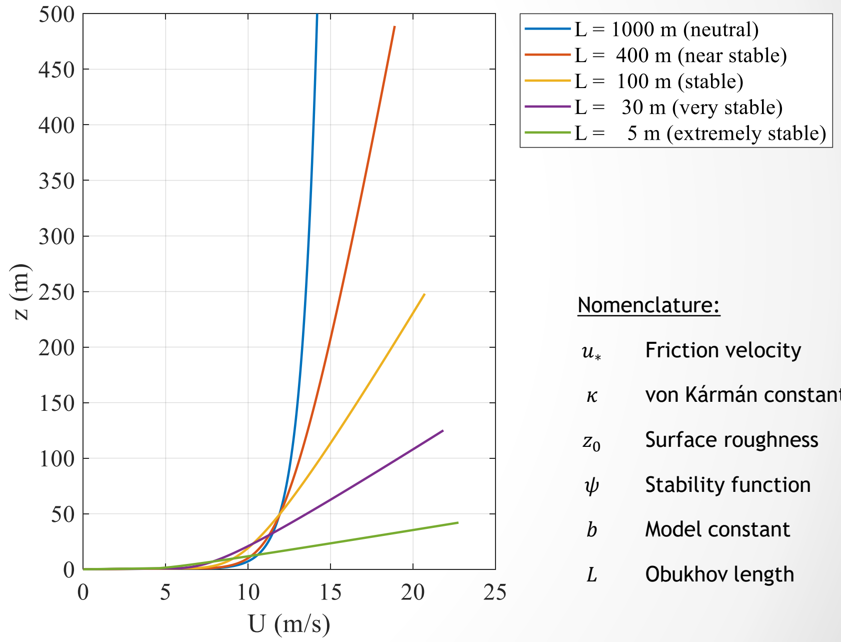
Logarithmic Wind Profile

Surface layer theory with stability correction:

- $U(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) + \psi\right]$
- $\psi = 4.7\frac{z}{L}$

[9]



Nomenclature:

u_*	Friction velocity
κ	von Kármán constant
z_0	Surface roughness
ψ	Stability function
b	Model constant
L	Obukhov length

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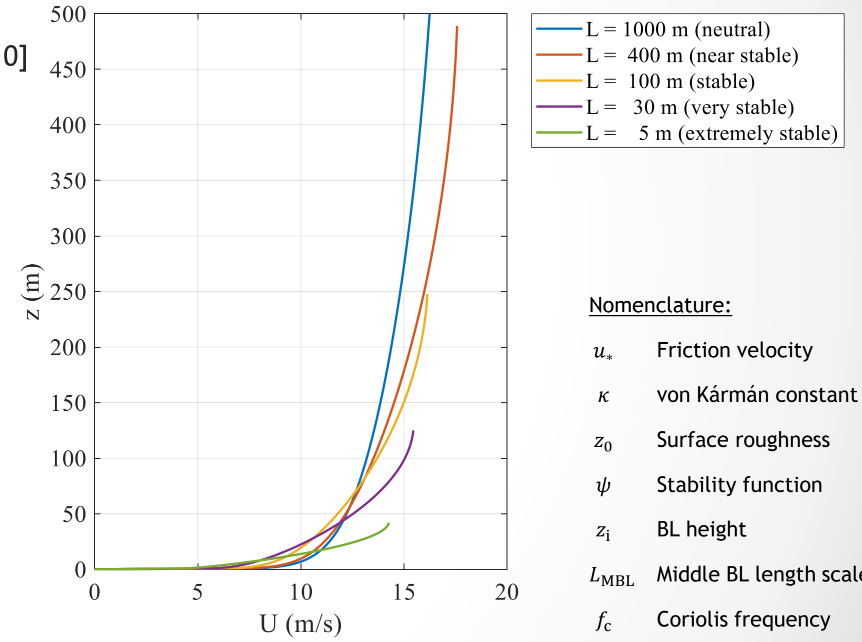
[9] Businger, Joost A., Wyngaard, John C., Izumi, Yutaka and Bradley, Edward F. "Flux-profile relationships in the atmospheric surface layer." Journal of the Atmospheric Sciences. Vol. 28 No. 2 (1971): pp. 181-189. DOI 10.1175/1520-0469(1971)028<0181:FPRITA>2.0.CO;2.

Gryning Wind Profile

Extension of the logarithmic profile: [10]

- $$U(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \psi\left(1 - \frac{z}{2\,z_\mathrm{i}}\right) + \frac{z}{L_\mathrm{MBL}} - \frac{z}{z_\mathrm{i}}\left(\frac{z}{2\,L_\mathrm{MBL}}\right)\right]$$
- $$\frac{u_*}{f_\mathrm{c}\,L_\mathrm{MBL}} = \left[-2\ln\left(\frac{u_*}{f_\mathrm{c}\,z_0}\right) + 55\right] e^{\left[-\frac{u_*^2/(f_\mathrm{c}\,L)^2}{400}\right]}$$



Nomenclature:

u_*	Friction velocity
κ	von Kármán constant
z_0	Surface roughness
ψ	Stability function
z_i	BL height
L_MBL	Middle BL length scale
f_c	Coriolis frequency
L	Obukhov length

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[10] Gryning, Sven-Erik, Batchvarova, Ekaterina, Brümmer, Burghard, Jørgensen, Hans and Larsen, Søren. "On the extension of the wind profile over homogeneous terrain beyond the surface boundary layer." Boundary-layer meteorology. Vol. 124 (2007): pp. 251-268. DOI 10.1007/s10546-007-9166-9.

Narasimhan Stable ABL Model

Coupling of surface and Ekman layer flow: [11]

Model inputs: L, z_0, f_c, N_∞, G

Streamwise wind velocity:

- $U(\hat{\xi} \le \hat{\xi}_m) = u_* \left[\frac{1}{\kappa} \ln\left(\frac{\hat{\xi}}{\hat{\xi}_0}\right) + (5\mu + 0.3\mu_N)(\hat{\xi} - \hat{\xi}_0)\right]$
- $U(\hat{\xi} \ge \hat{\xi}_m) = u_* \left[-g'(\hat{\xi})\left(1 - \frac{\hat{\xi}}{\hat{\xi}_i}\right)^{3/2} + g(\hat{\xi})\frac{3}{2\hat{\xi}_i}\sqrt{1 - \frac{\hat{\xi}}{\hat{\xi}_i}}\right] + U_g$

Lateral wind velocity:

- $V(\hat{\xi}) = u_* \left[\frac{g(\hat{\xi})g'(\hat{\xi})}{\sqrt{1-g(\hat{\xi})^2}}\left(1 - \frac{\hat{\xi}}{\hat{\xi}_i}\right)^{3/2} + \frac{3}{2\hat{\xi}_i}\sqrt{1 - g(\hat{\xi})^2}\left(1 - \frac{\hat{\xi}}{\hat{\xi}_i}\right)^{1/2}\right] + V_g$

- $\hat{\xi} = z\, f_c/u_*$
- $\hat{\xi}_0 = z_0\, f_c/u_*$
- $\hat{\xi}_i = z_i f_c/u_*$
- $\hat{\xi}_m = z_m\, f_c/u_* = 0.2\hat{\xi}_i$

- $\mu = u_*/(\kappa\, f_c\, L)$
- $\mu_N = N_\infty/f_c$

- $g(\hat{\xi}) = c_g\left[1 - e^{-\hat{\xi}/(\Gamma\,\hat{\xi}_i)}\right]$
- $g'(\hat{\xi}) = \frac{c_g}{\Gamma\,\hat{\xi}_i}\, e^{-\hat{\xi}/(\Gamma\,\hat{\xi}_i)}$
- $c_g = 1.43$
- $\Gamma = 0.83$

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[11] Narasimhan, Ghanesh, Gayme, Dennice F. and Meneveau, Charles. "Analytical model coupling Ekman and surface layer structure in atmospheric boundary layer flows." Boundary-Layer Meteorology. Vol. 190 No. 4 (2024): p. 16. DOI 10.1007/s10546-024-00859-9.

Narasimhan Stable ABL Model

Geostrophic drag law:

- $\frac{\kappa\, U_g}{u_*} = \ln\left(\frac{u_*}{f_c\, z_0}\right) - A$
- $\frac{\kappa\, V_g}{u_*} = -B$
- $G = \sqrt{U_g^2 + V_g^2}$

Derived constants:

- $A = -\ln \hat{\xi}_m - \kappa\left[(5\mu + 0.3\mu_N)(\hat{\xi}_m - \hat{\xi}_0) + g'(\hat{\xi}_m)(1 - c_m)^{\frac{3}{2}} - g(\hat{\xi}_m)\left(\frac{3}{2}\hat{\xi}_i\right)\sqrt{1 - c_m}\right]$
- $B = \frac{3\,\kappa}{2\,\hat{\xi}_i}$

Boundary layer height model:

- $\hat{\xi}_i = (C_{TN}^{-2} + C_{CN}^{-2}\,\mu_N + C_{NS}^{-2}\,\mu)^{-1/2}$

- $c_m = z_m / z_i = 0.2$

- $C_{TN} = 0.5$
- $C_{CN} = 1.6$
- $C_{NS} = 0.78$

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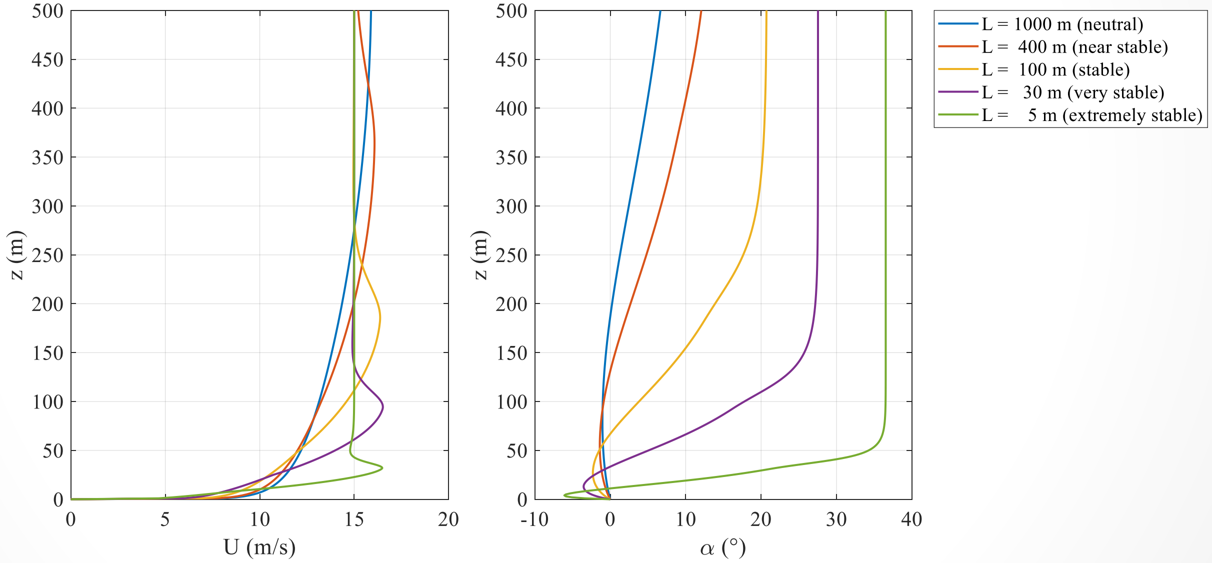
Narasimhan Stable ABL Model

Resulting wind velocity and direction profiles:



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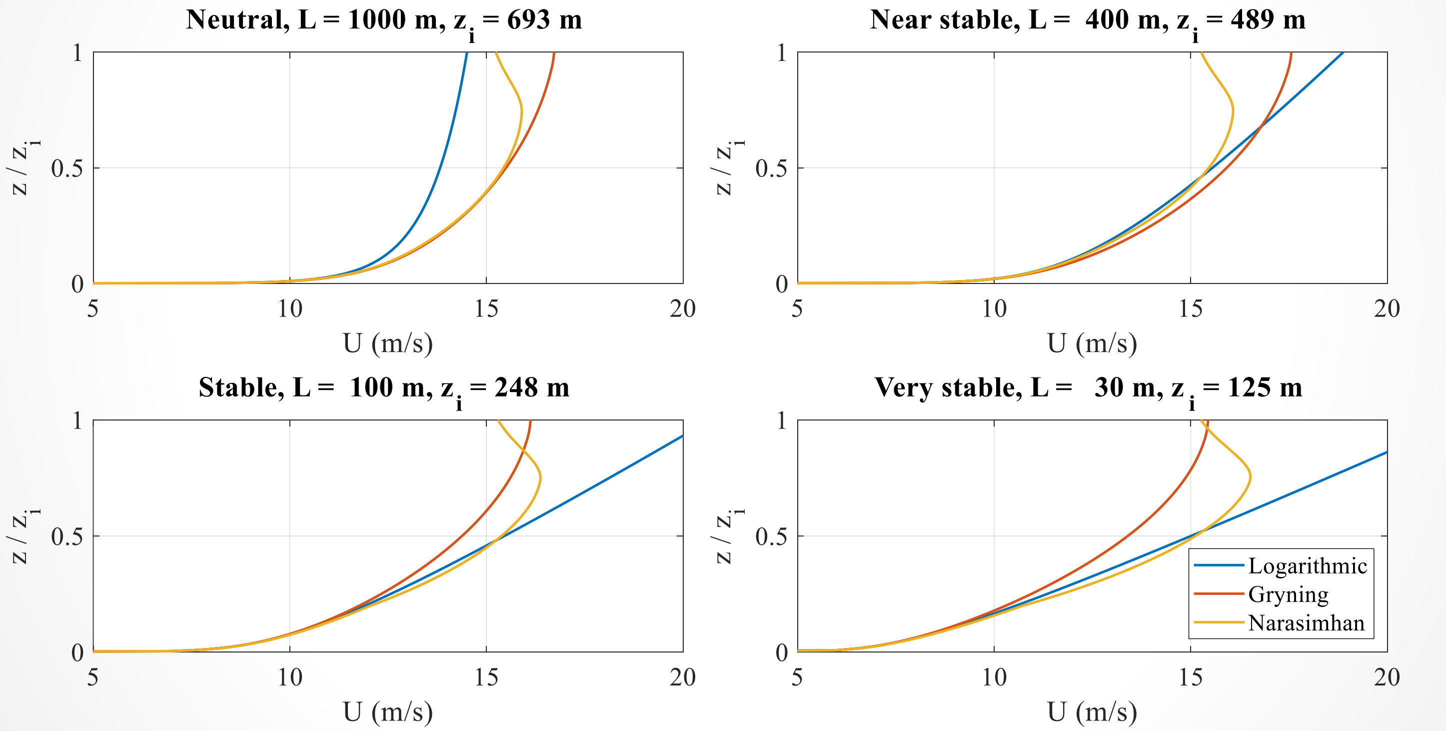
Model Comparison for Different Stability Conditions



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Model Parametrization

Parameter		Logarithmic	Gryning	Narasimhan	Source
Geostrophic wind velocity	G				Fitted to sonic anemometer wind speed at $z = 81\ \mathrm{m}\ \vert\ 101\ \mathrm{m}$
Friction velocity	u_*				Fitted to sonic anemometer wind speed at $z = 81\ \mathrm{m}\ \vert\ 101\ \mathrm{m}$
Obukhov length	L				From ERA5 hindcast data
Surface roughness	z_0				From Charnock's relation using $C = 0.018$
Coriolis frequency	f_c				From FINO1 | FINO3 latitude
Boundary layer height	z_i				From ERA5 hindcast data

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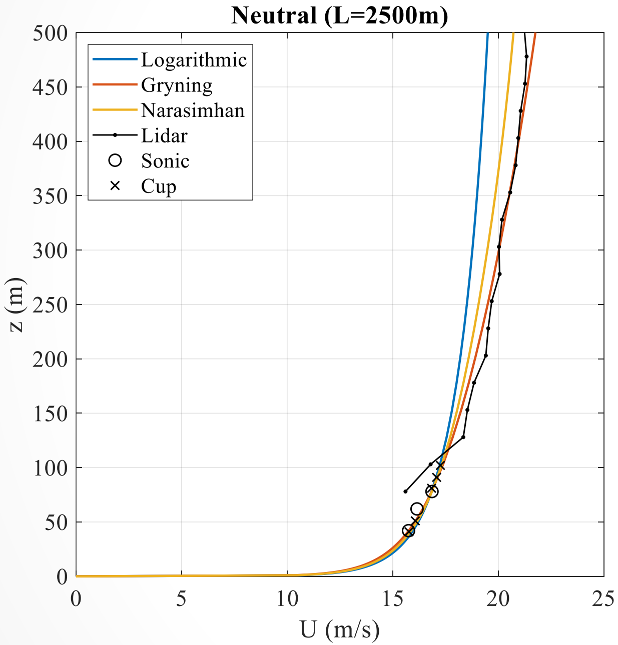
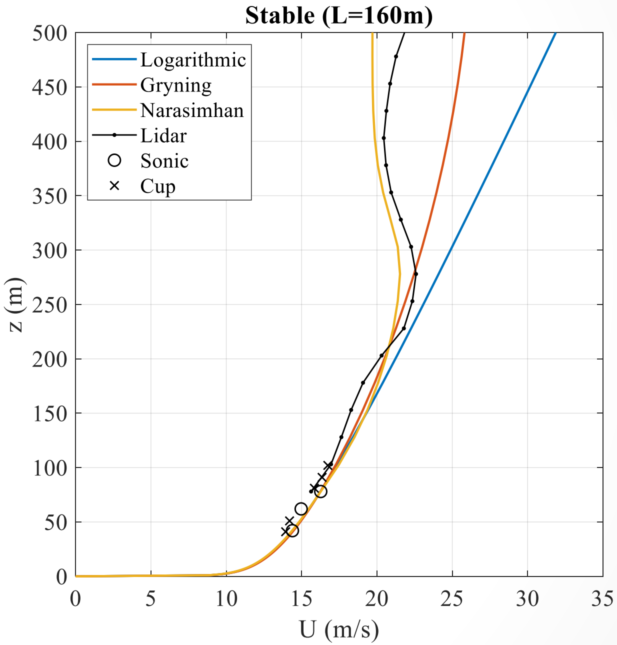
Wind Profile Comparison

Exemplary 10-minute Profiles Recorded at FINO1





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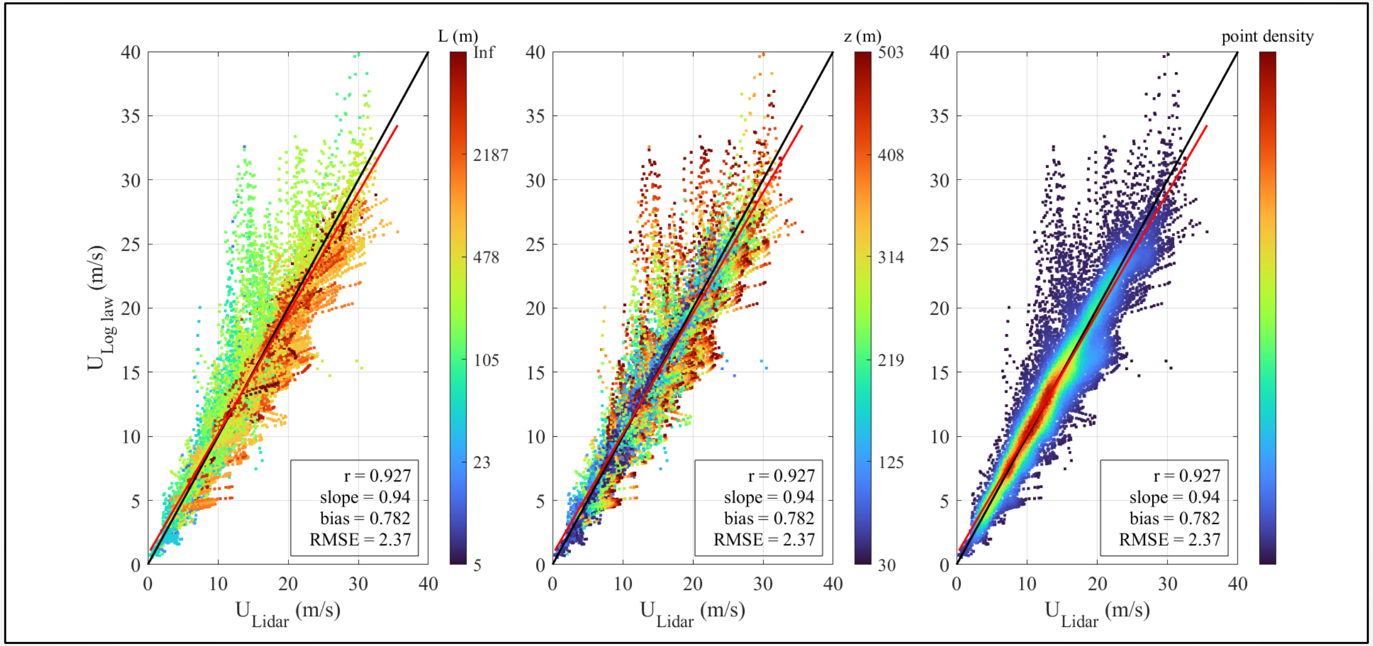
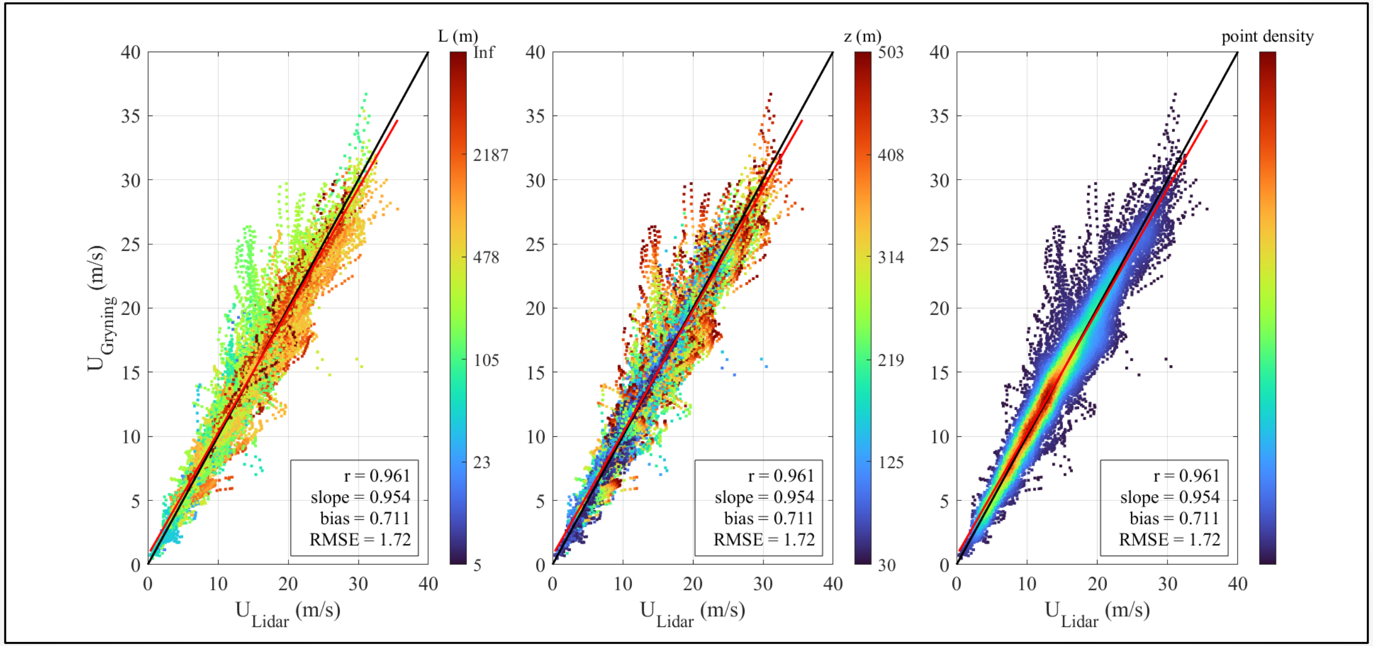
Logarithmic Velocity Profile vs. Observations

Data from FINO1 for $L \geq 0$ and $z \leq \min(z_i, 500\ \mathrm{m})$.



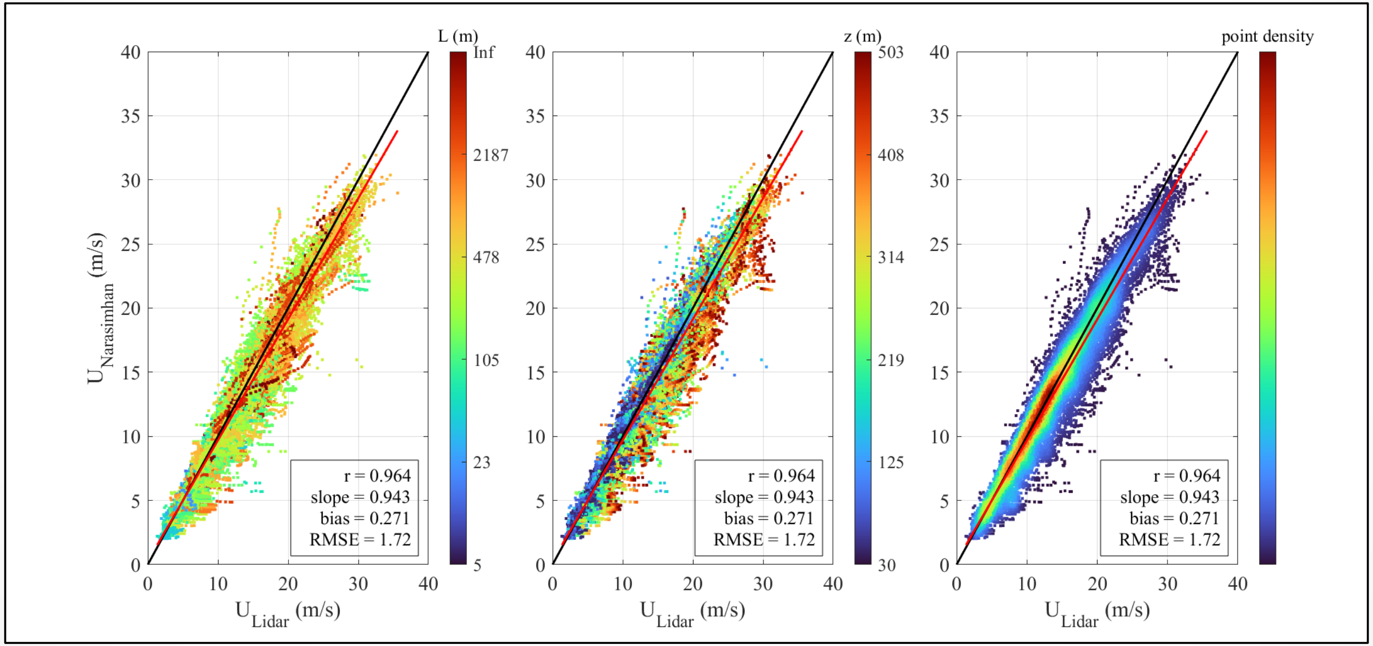
Gryning Velocity Profile vs. Observations

Data from FINO1 for $L \geq 0$ and $z \leq \min(z_i, 500\ \mathrm{m})$.



Narasimhan Velocity Profile vs. Observations

Data from FINO1 for $L \geq 0$ and $z \leq \min(z_\mathrm{i}, 500\ \mathrm{m})$.



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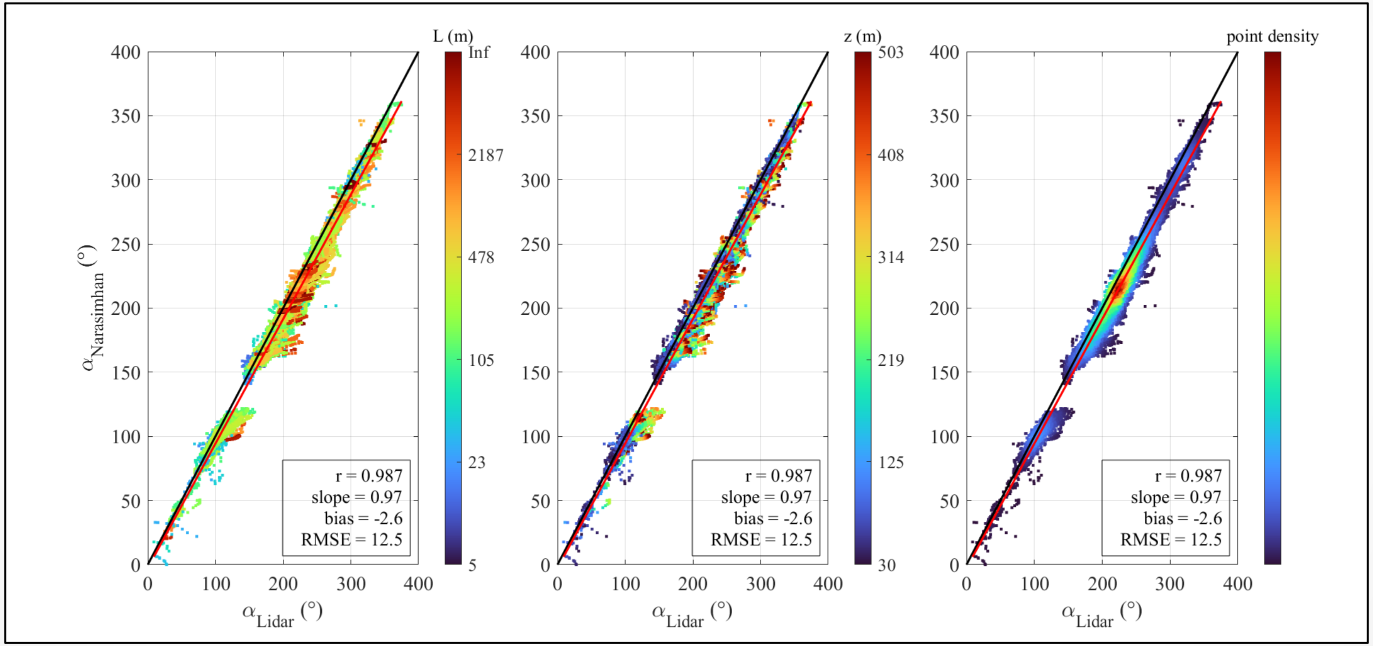
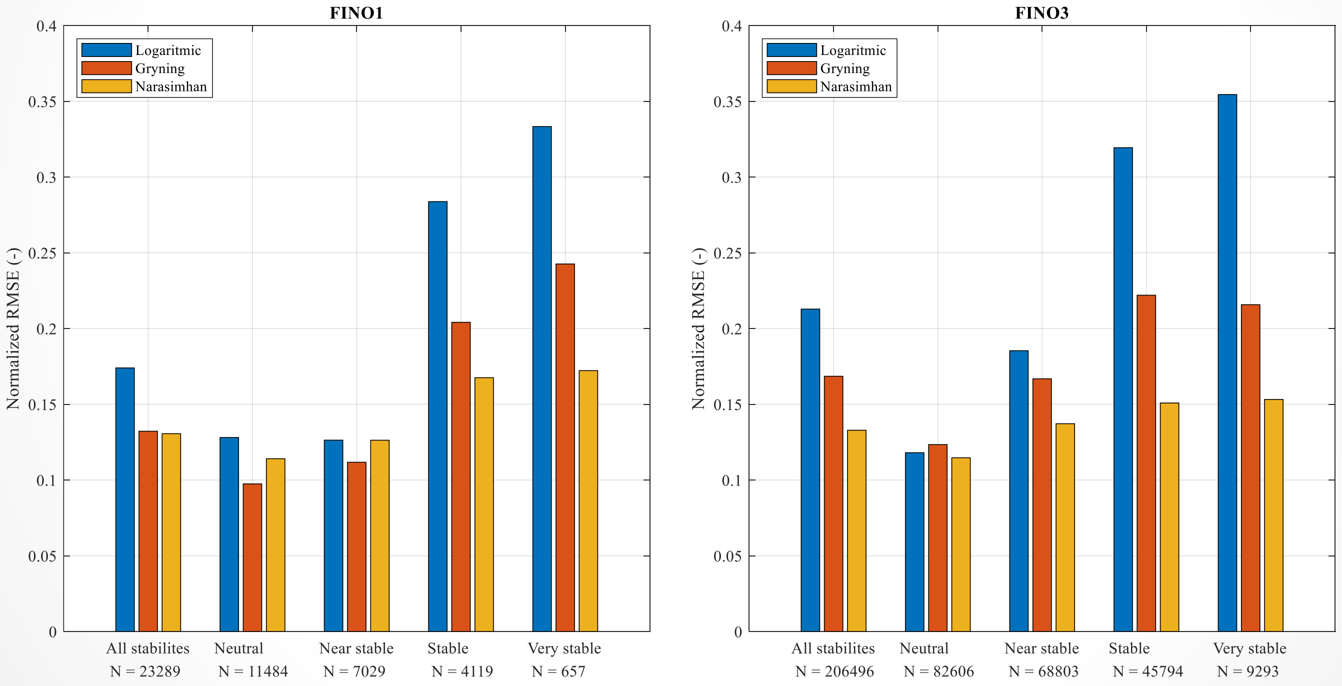
Narasimhan Direction Profile vs. Observations

Data from FINO1 for $L \geq 0$ and $z \leq \min(z_\mathrm{i}, 500\ \mathrm{m})$.



Deviations Between Modelled and Observed Profiles

Normalized RMSE across wind profile models and atmospheric stability.



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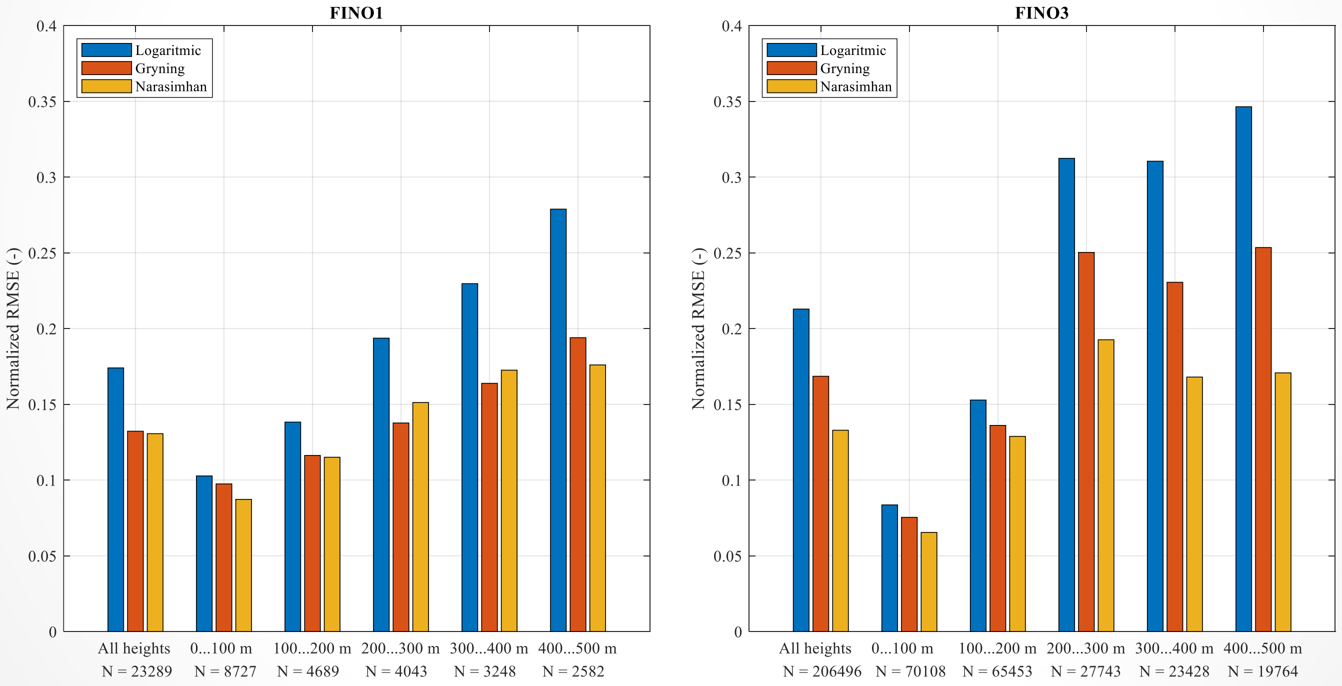
Deviations Between Modelled and Observed Profiles

Normalized RMSE across wind profile models and height.



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Conclusion

- Tall lidar profiles observed at FINO1 and FINO3…
  - … supplemented with mast data.
  - … classified using ERA5 Obukhov length estimate.
- 3 analytical profile models parameterized and compared with observations.
- Neutral to near-stable conditions:
  - All models perform similarly well.
  - Logarithmic profile shows slightly larger deviations.
- Stable to very stable conditions:
  - Narasimhan profile shows lowest deviations.
  - Logarithmic profile shows largest deviations.
- Deviations further increase with height for all models.

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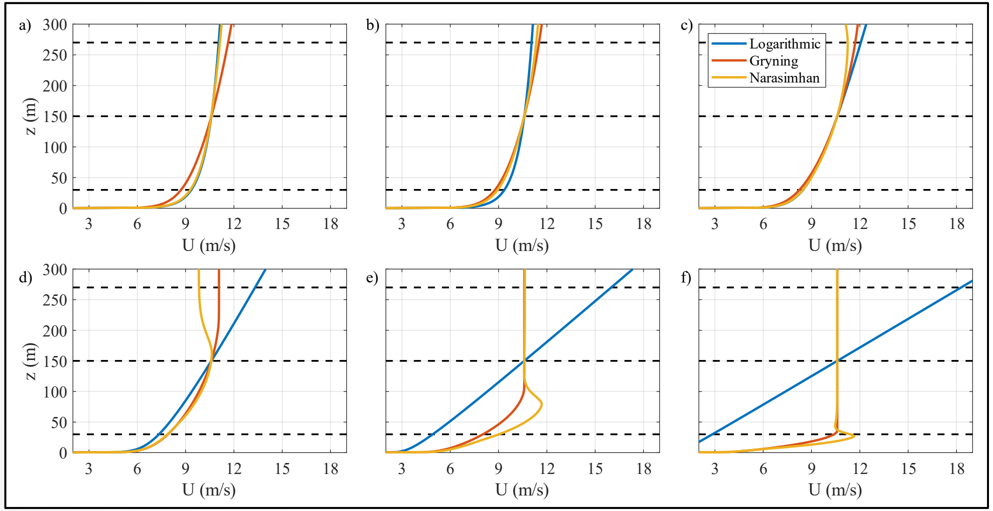
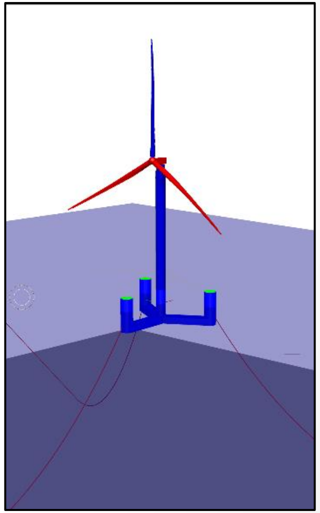
Outlook

Subsequent study: L Vogt, J B Jakobsen, J B de Vaal: “Sensitivity of Floating Wind Turbine Response to Stable Boundary Layer Wind Profiles”





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