Karlsruhe Institute of Technology

KIT-Campus Alpin
IMK-IFU: Atmospheric Environmental Research

WindForS
Wind Energy Research Cluster

Meteorological aspects of wind energy conversion

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Some wind energy-relevant meteorological aspects

modern observational techniques (wind, turbulence and temperature profiles)

low-level jets (nocturnal boundary-layer wind maxima)

flow over complex terrain (description – simulation – measurement)

marine boundary layer (offshore wind farms)

wind farms, onshore and offshore (analytical model for yields and wakes)

Emeis, S., 2014: Current issues in wind energy meteorology. Meteorol. Appl., 21, 803-819.

1

modern observational techniques

ground-based remote sensing devices at IMK-IFU

SODAR, acoustic
Doppler analysis ➔ wind, turbulence

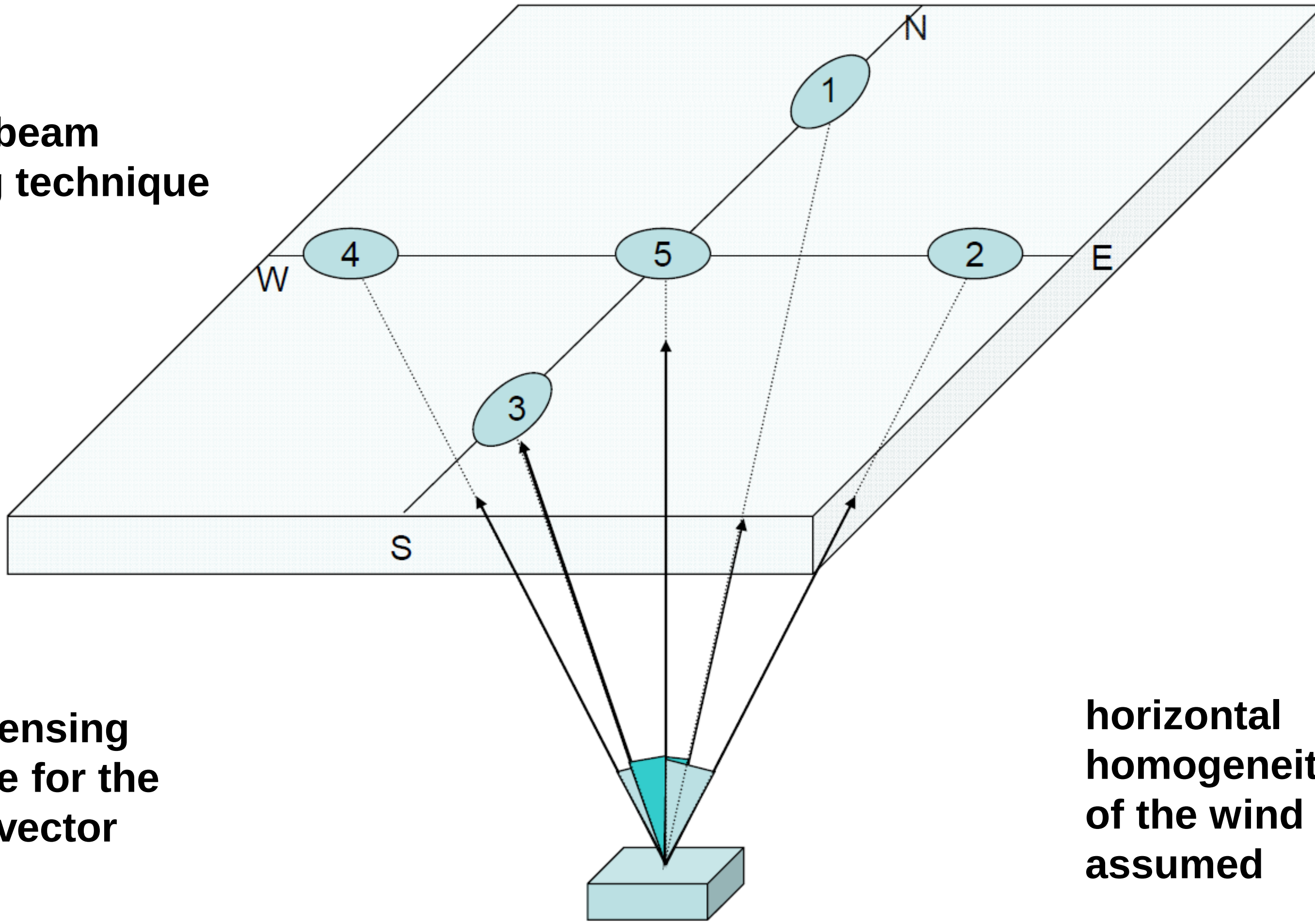
SODAR-RASS (Doppler-RASS), acoustic, electro-magnetic backscatter, ➔ sound speed ➔ wind and temperature profiles

Ceilometer,
optical pulses, wave length ~ 0.9 µm
➔ aerosol profiles, mixed-layer height, clouds

Wind-LIDAR, optical backscatter, Doppler analysis, wave length ~ 1.5 µm ➔ wind and aerosol profiles

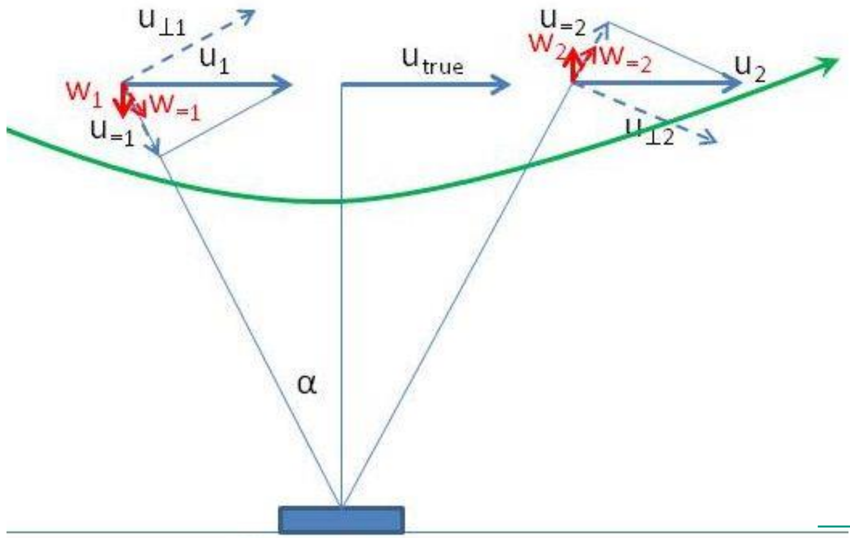
image:
Halo Photonics

Doppler beam swinging technique (DBS)



remote sensing technique for the 3D wind vector

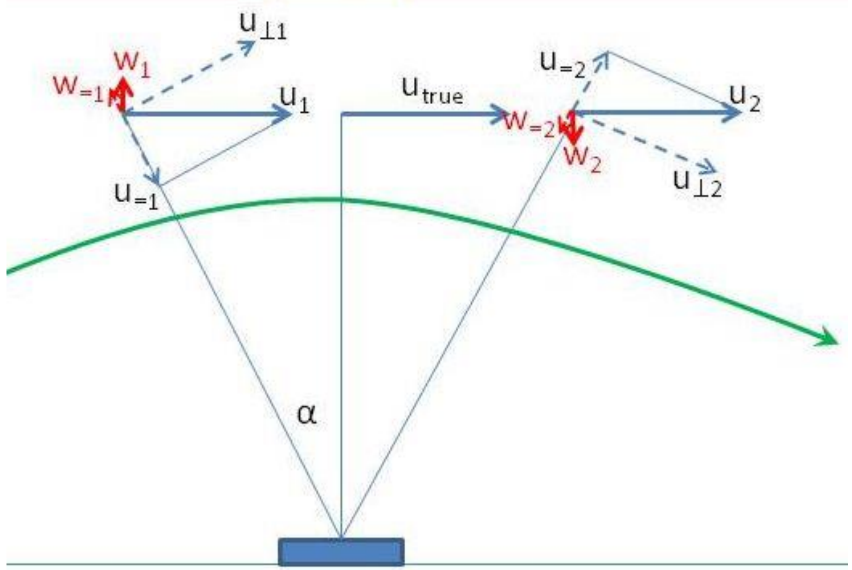
horizontal homogeneity of the wind field assumed



valley:

vertical component adds to horizontal component

➔ SODAR/LIDAR measures too much wind



hill top:

vertical component reduces horizontal component

➔ SODAR/LIDAR measures less wind

➔ in either case: correction needed

Summary – remote sensing

advantages

- cheaper measurements for great hub heights

- full profile information

- instrumentation is more movable than instrumented masts

- delivers volume-averaged information (more suitable for wind energy)

disadvantages

- assumption of horizontal homogeneity is not fulfilled in complex terrain ➔ correction needed

- data quality may depend on atmospheric conditions

- verification/validation of measurements is still discussed

- not easily comparable to point measurements (e.g., cup anemometers)

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low-level jets

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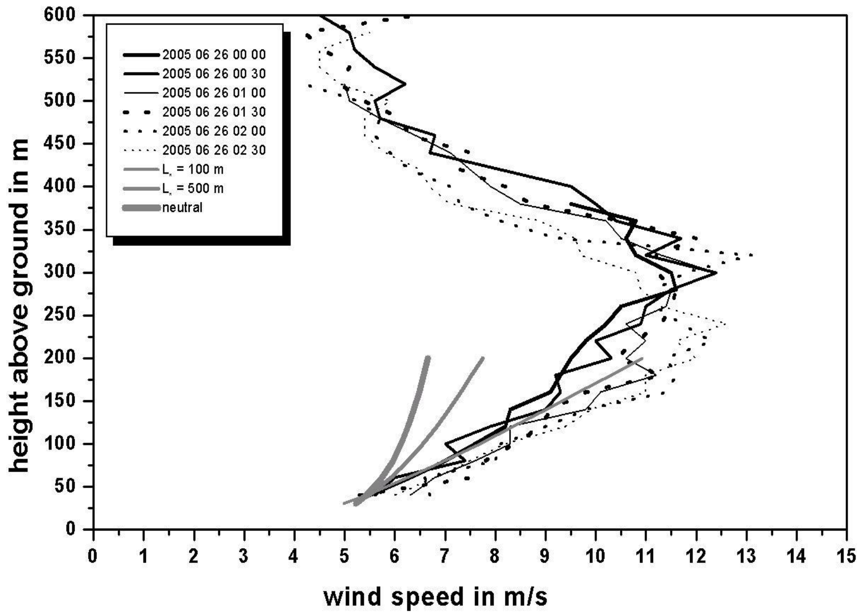
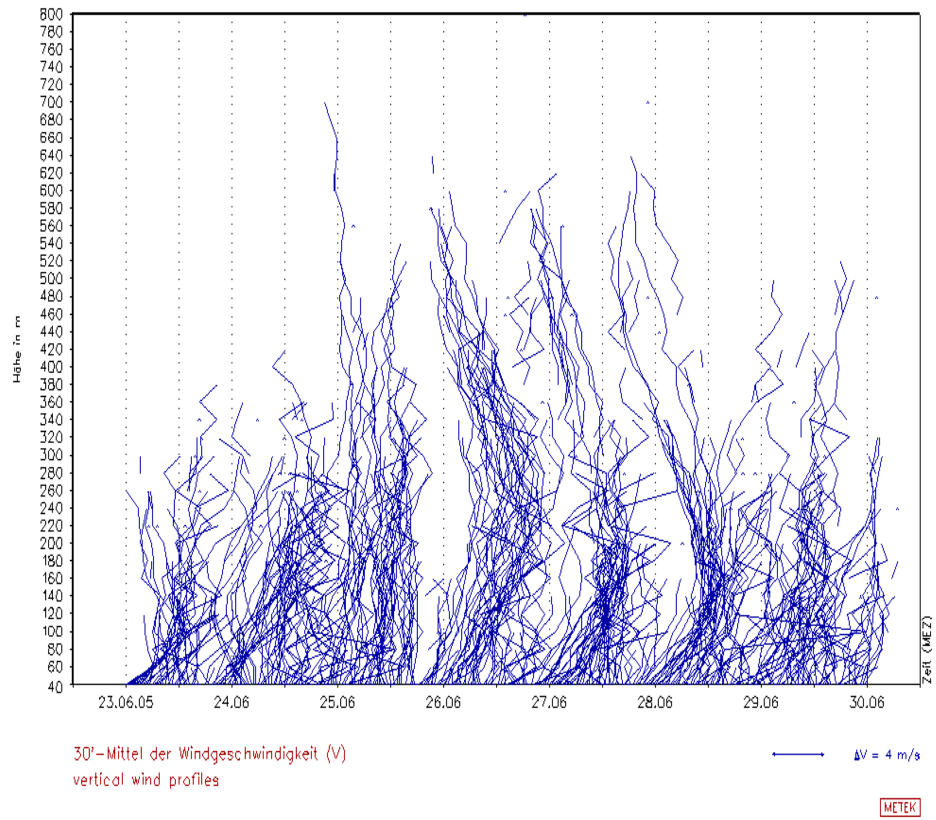
Sodar observation of a low-level jet

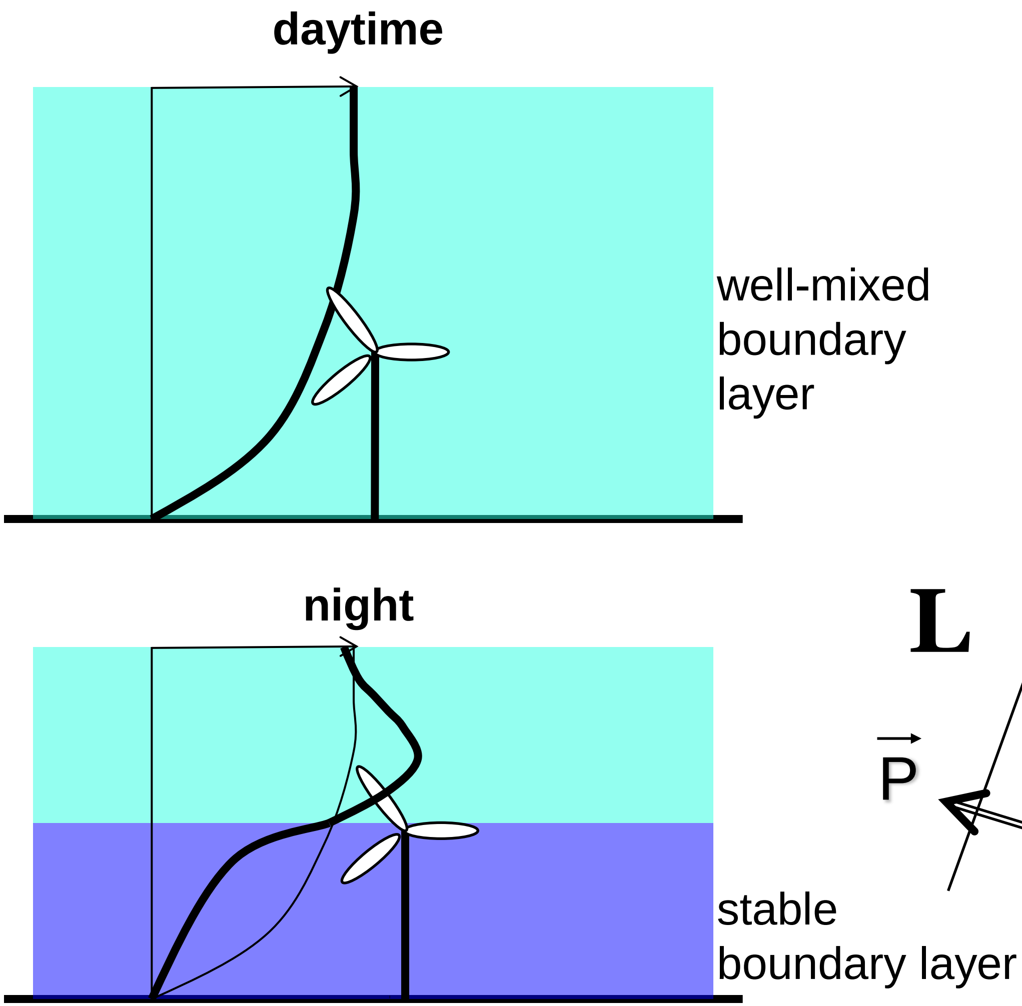
vertical wind profiles (30 min mean)

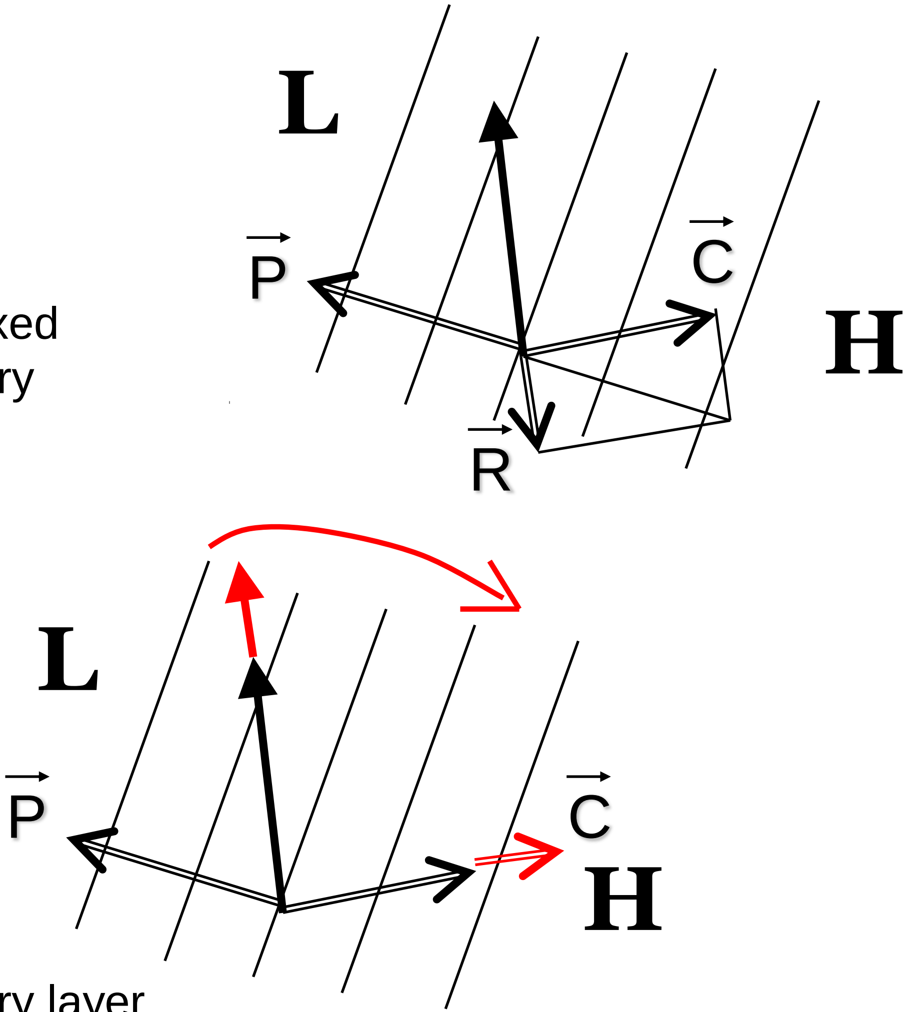
26 June 2005, 00 – 02:30 CET



23-30 June 2005




daytime
well-mixed boundary layer
night
stable boundary layer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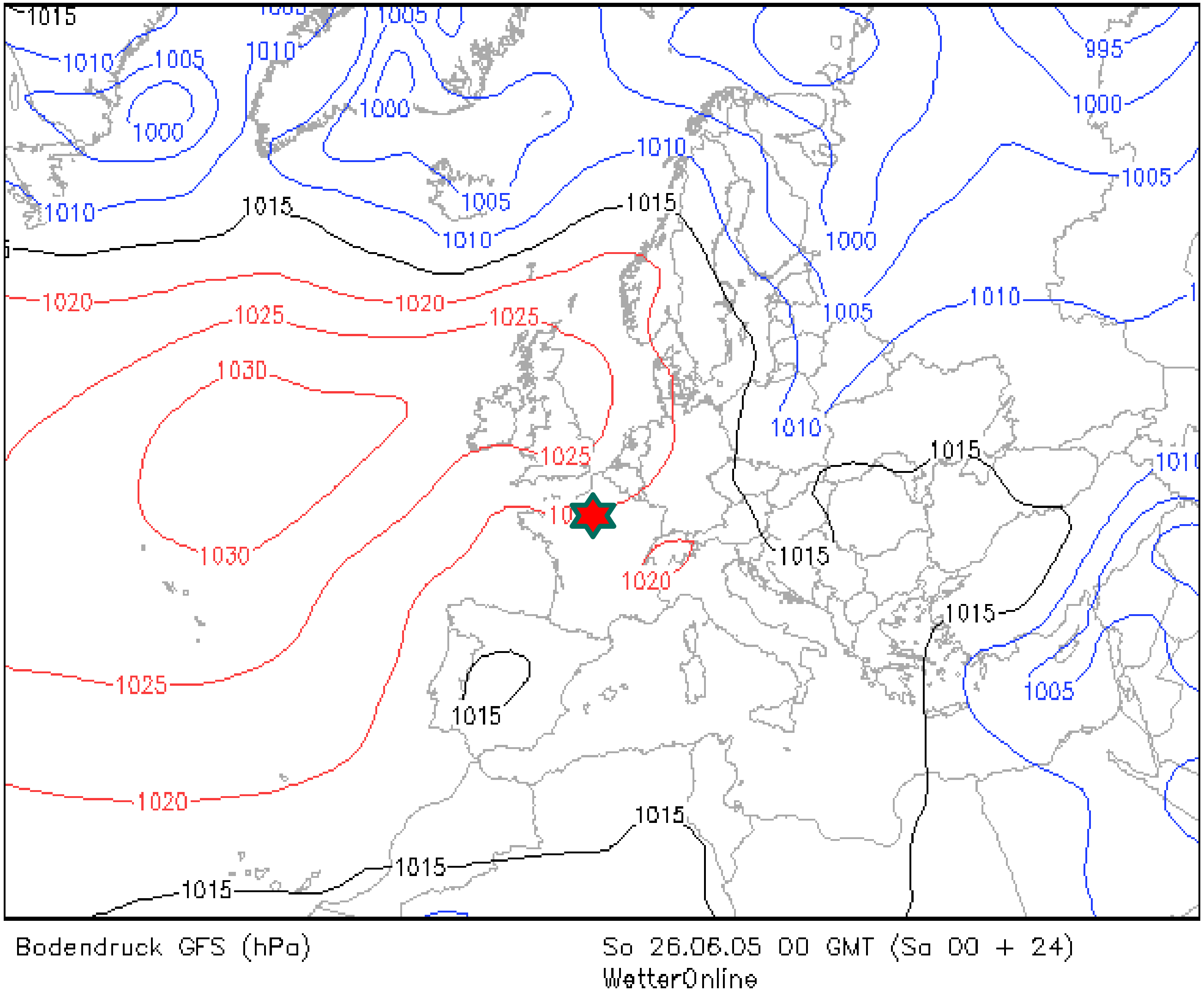
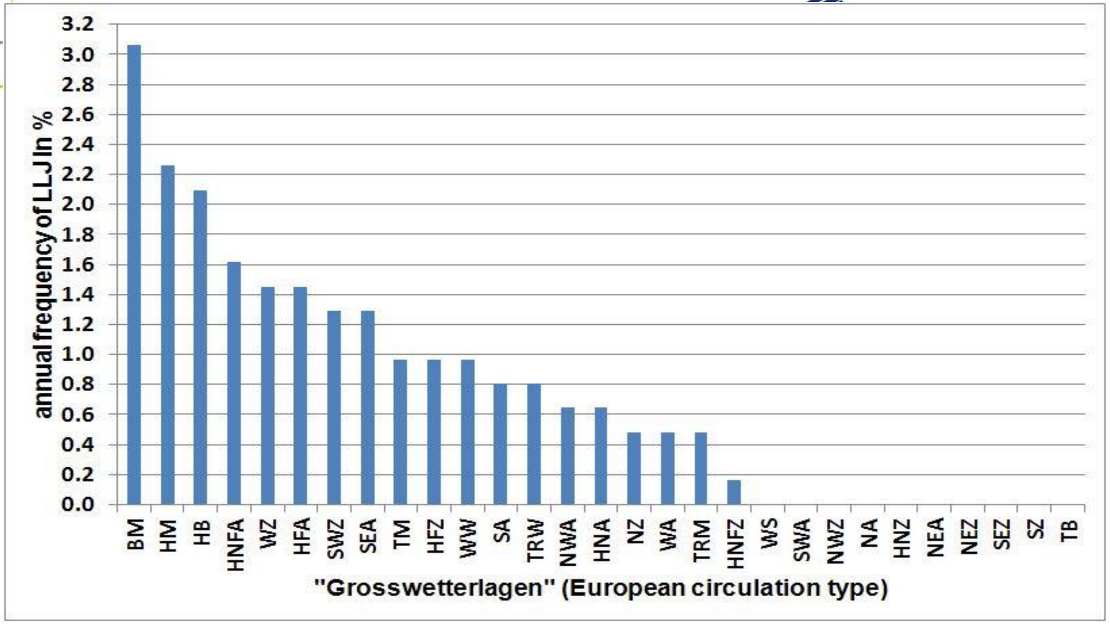
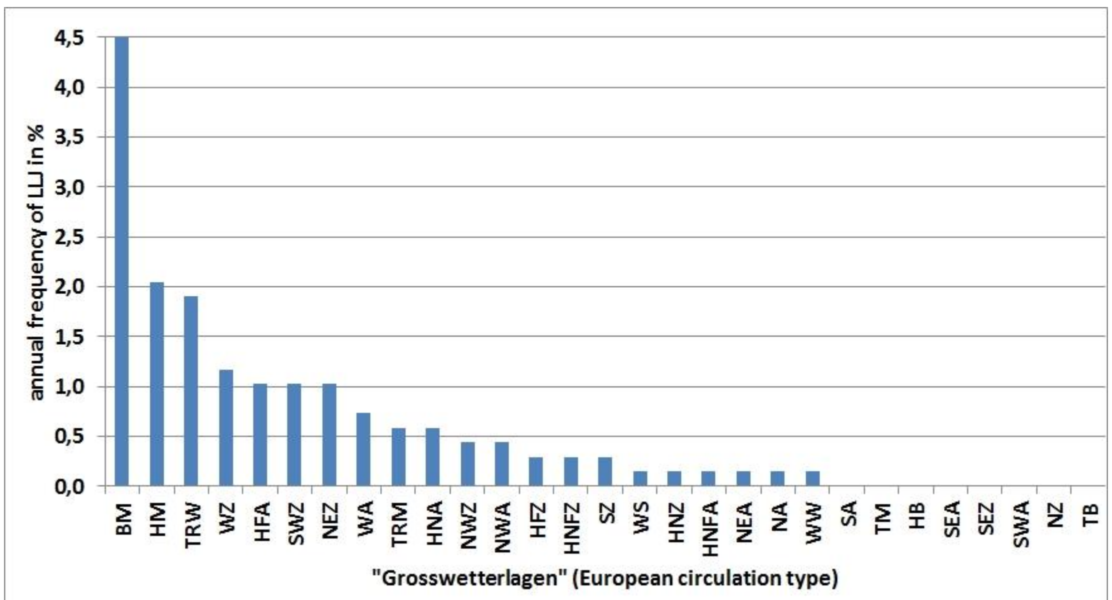
sea-level pressure
00 GMT

26 June 2005

asterisk:
observation site







frequency of LLJ over Hannover for 20 months in the years 2001 to 2003

roughly 22 % of all nights

over Augsburg in the years 2008-2010, 2014

roughly 17,5 % of all nights

Circulation types:

BM **bridge Central Europe**
HB **high Brit. Isles**
HM **high Central Europe**
...

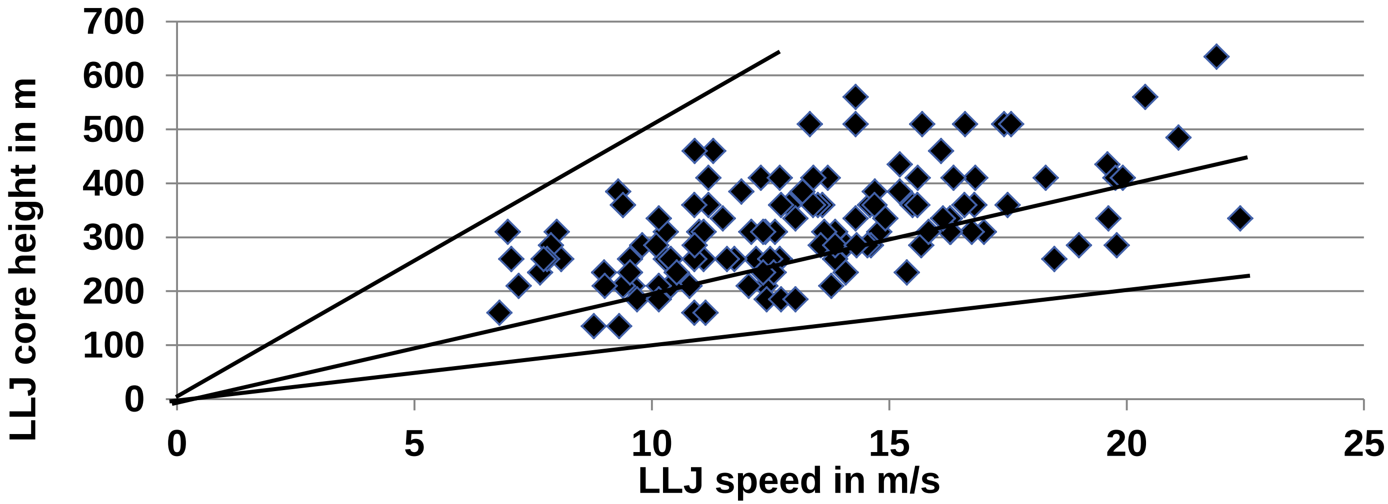
HFA/HFZ high Scandinavia
HNFA **high Northern Atlantic**
...

Critical Richardson number is limiting condition for vertical shear

(mechanical turbulence is generated if Ri falls below Ri_{krit})

$$Ri_{krit} = \frac{g \partial \Theta / \partial z}{\Theta (\partial u / \partial z)^2} \approx 0.25$$

Θ (z)	potential temperature
g	gravitational acceleration
u (z)	wind speed
z	vertical coordinate



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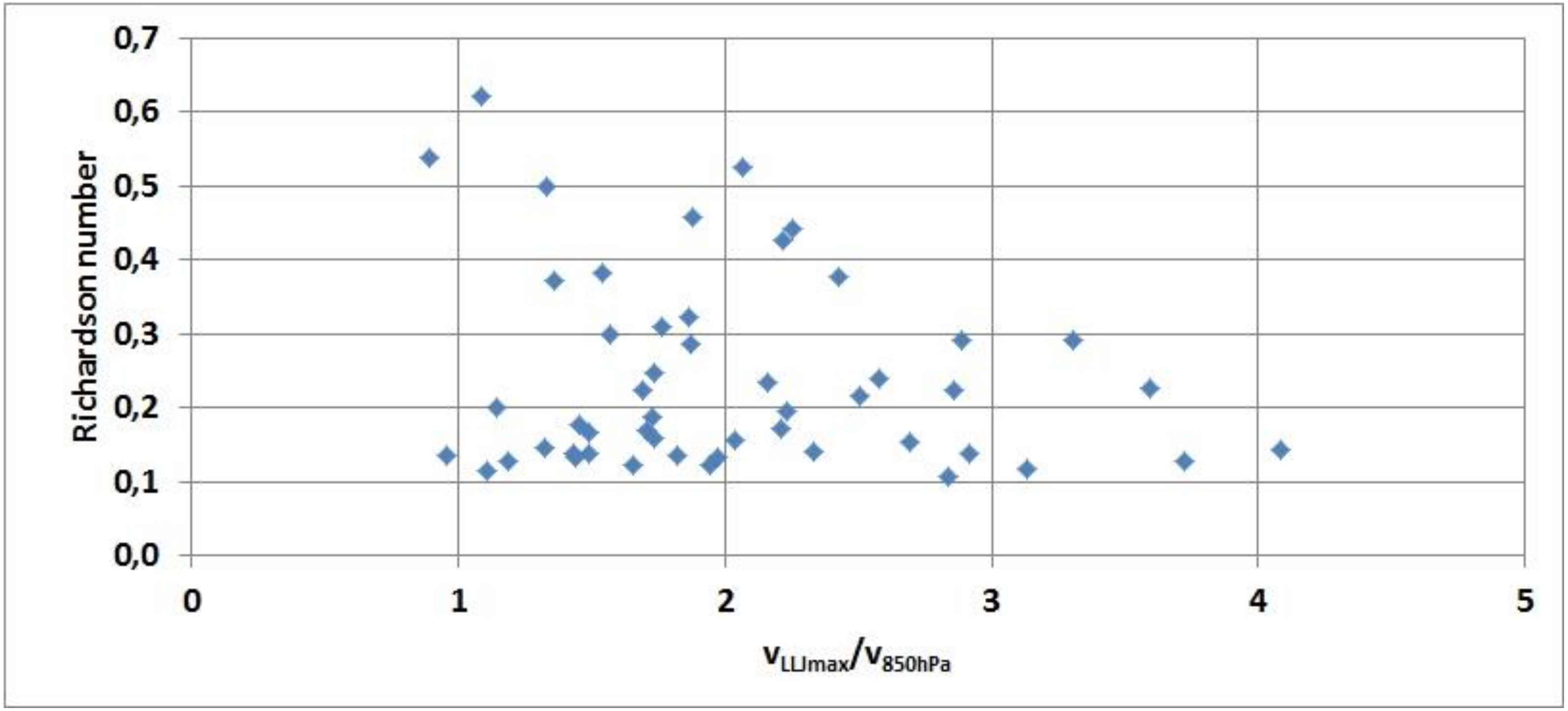
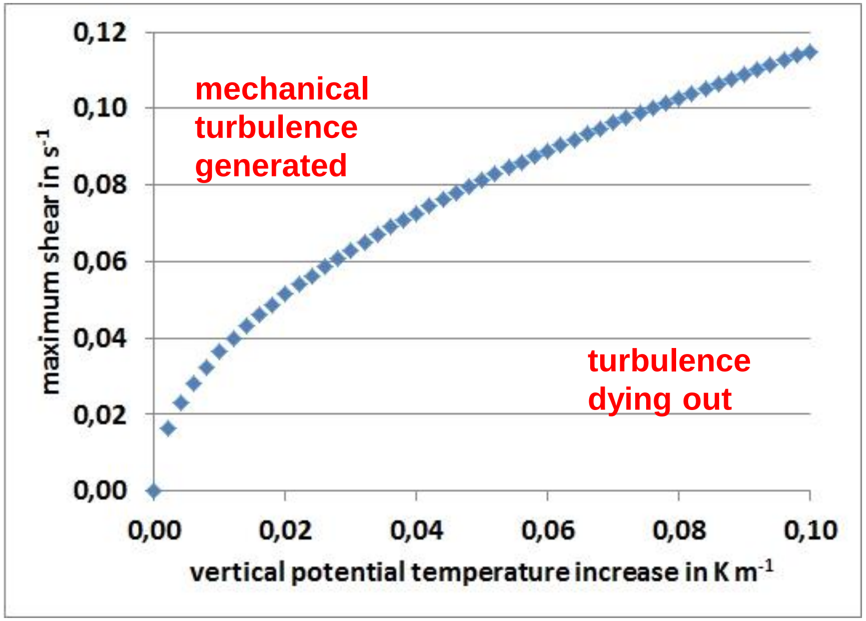
RASS observations Augsburg

Richardson number during LLJ events



maximum possible shear for a given $Ri_{krit} = 0.25$



$$Ri_{krit} = \frac{g \partial\Theta/\partial z}{\Theta(\partial u/\partial z)^2} \approx 0.25$$

Summary – low-level jets

climatology

- LLJ in 17 - 21% of all nights
- core height between 135 and 650 m
- core wind speed between 7 and 23 m/s

correlation with driving forces

- LLJ form for 850 hPa wind speeds between 1 and 18 m/s
- LLJ core speed positively correlated with 850 hPa wind speed (maximum at 13 m/s)
- LLJ core speed slightly negatively correlated with 850 hPa relative humidity

shear

- shear is limited by critical Richardson number

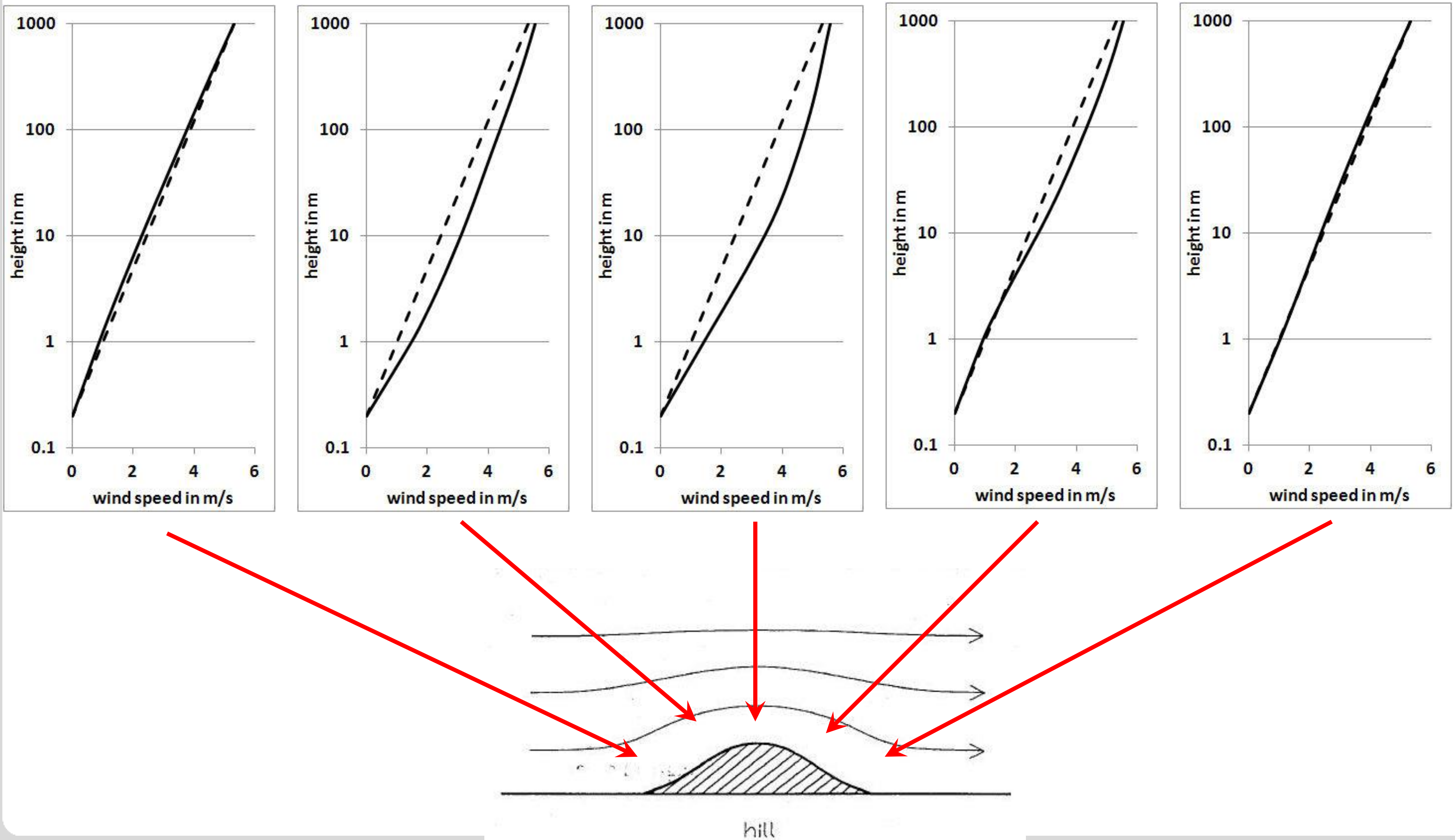
impact on wind turbines

- shear over the rotor plane is about 0.04 to 0.08 1/s during LLJ events
- directional shear is about 0.1 to 0.2 degrees/m

3

flow over complex terrain (description – simulation – measurement)

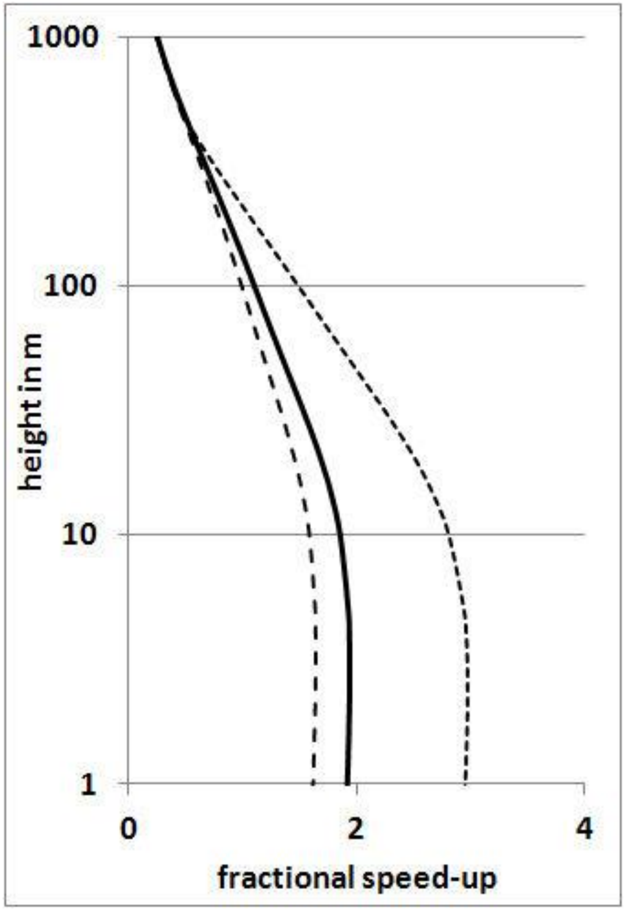
speed-up over a hill (analytical – potential flow - model)



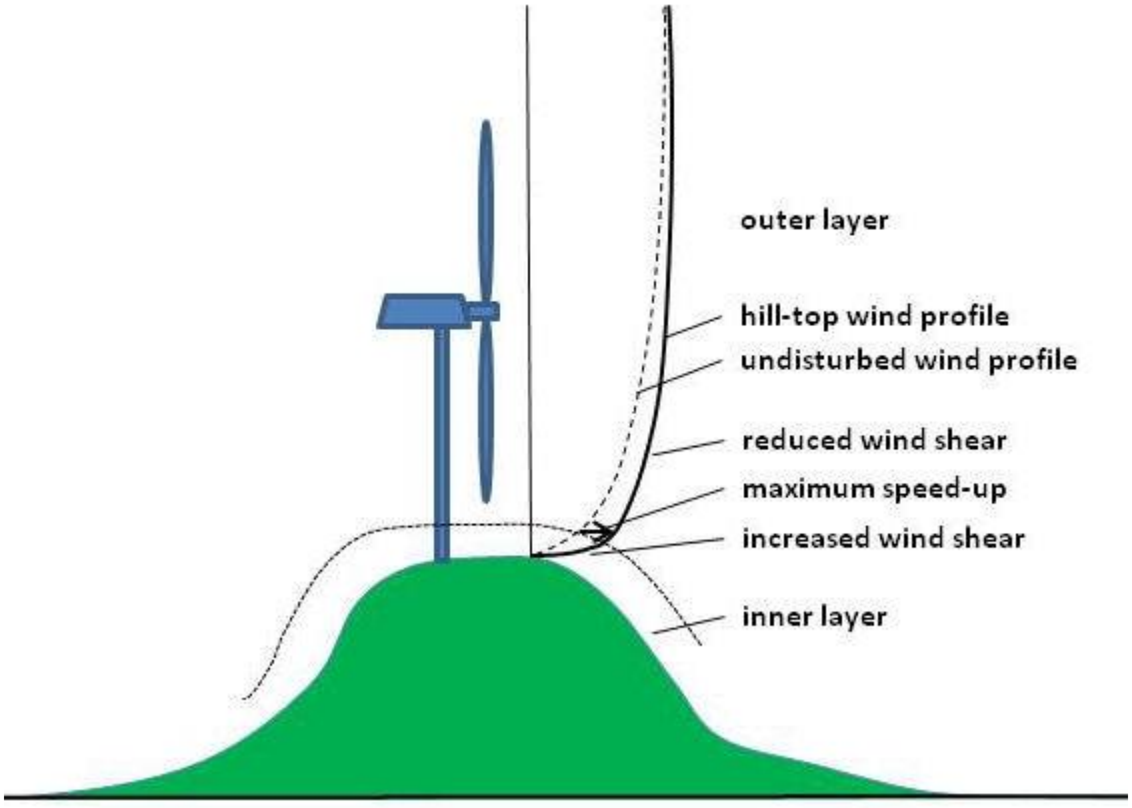
speed-up over a hill
(analytical model)

as function of thermal stability

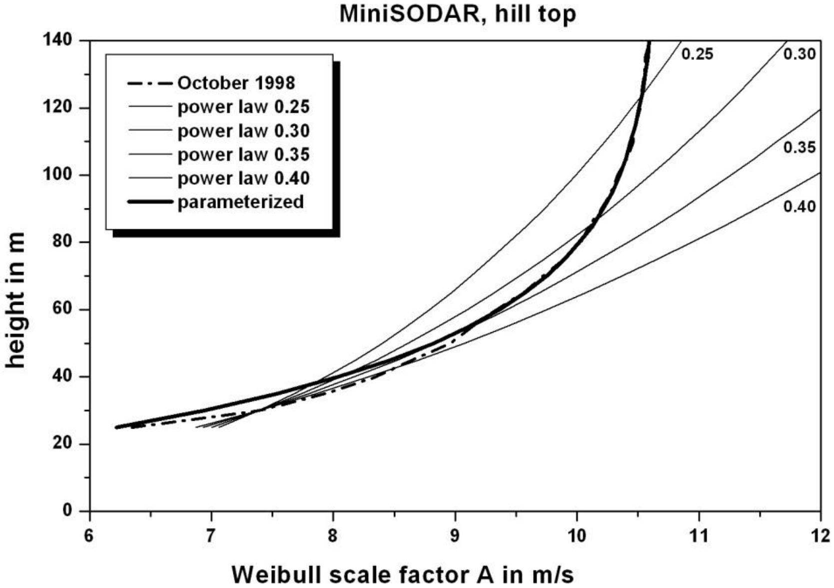
dotted: **stable**
full: **neutral**
dashed: **unstable**

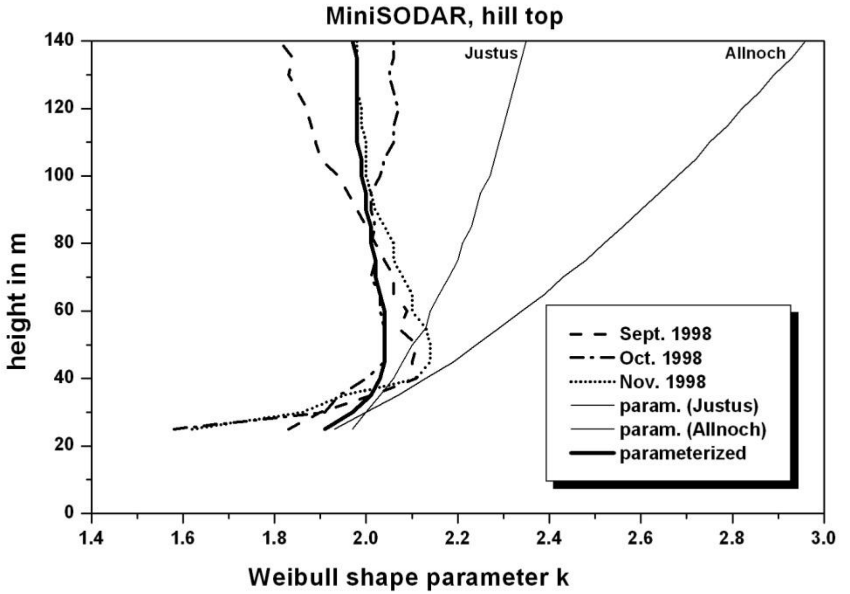


speed-up over a hill



Weibull-Parameter over a crest





Weibull scale parameter
(A_0 = 10.67 m/s, γ = 0.035)

$$A(z) = A_0\left(1 - e^{-\gamma z}\right)$$

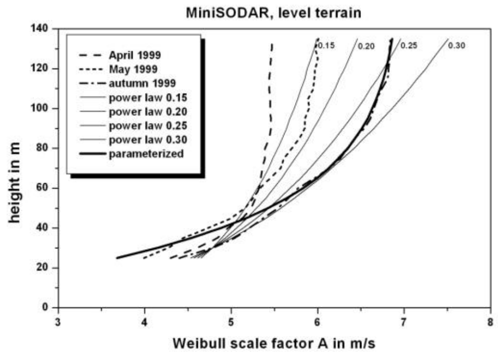
Weibull form parameter
(z_A = 10 m, z_m = 50 m, c_2 = 0.01)

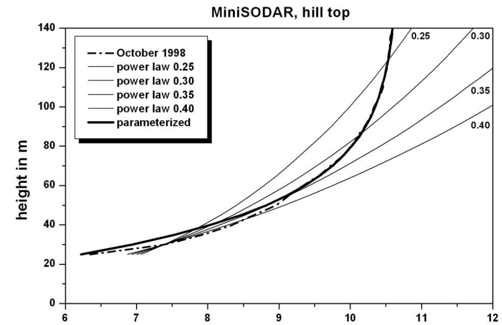
$$k(z) - k_A = c_2 (z - z_A) \exp\left(-\frac{z - z_A}{z_m - z_A}\right)$$

Wieringa (1988)

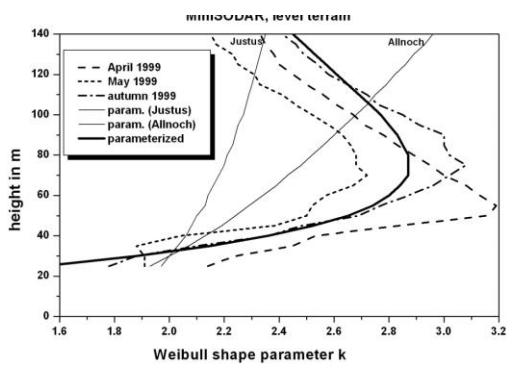
flat terrain

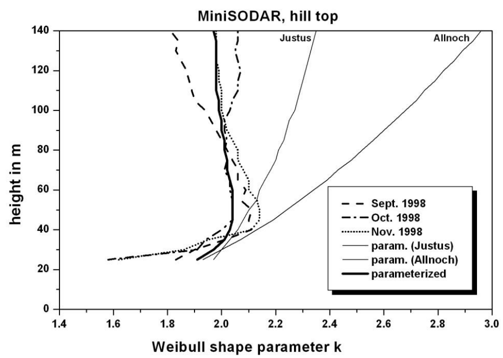
hill top





scale parameter





form parameter

Summary – complex terrain

wind speed

- speed-up over hill tops
- strong horizontal gradients in wind speed characteristics (remote sensing needs corrections)

vertical profiles

- maximum is reached at lower heights over hill tops

shear

- shear is lower in greater heights but higher close to the ground over hill tops

impact on wind turbines

- large turbines experience less shear over hill tops
- increase in hub heights give less benefits
- wind assessment much more difficult than over flat terrain

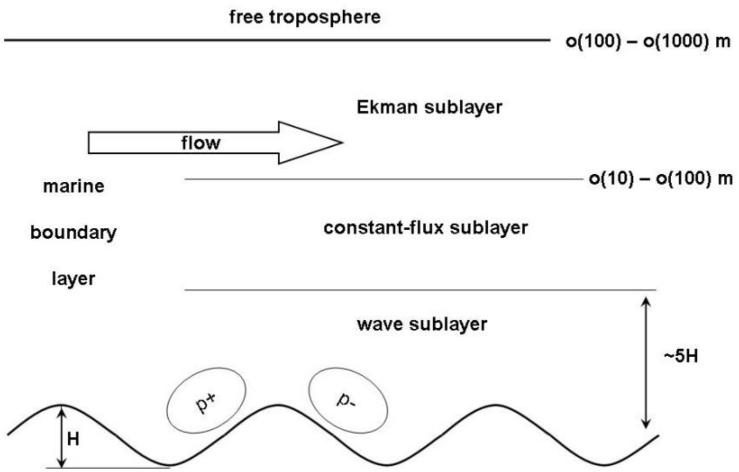
Supported by:
Federal Ministry
for Economic Affairs
and Energy
on the basis of a decision
by the German Bundestag

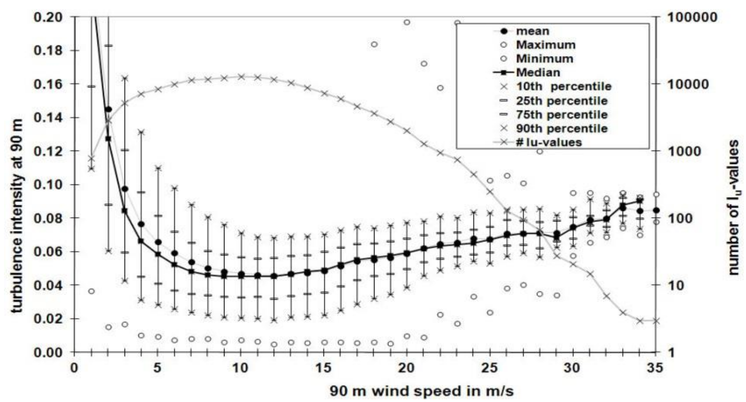
4

marine boundary layer (offshore winds)

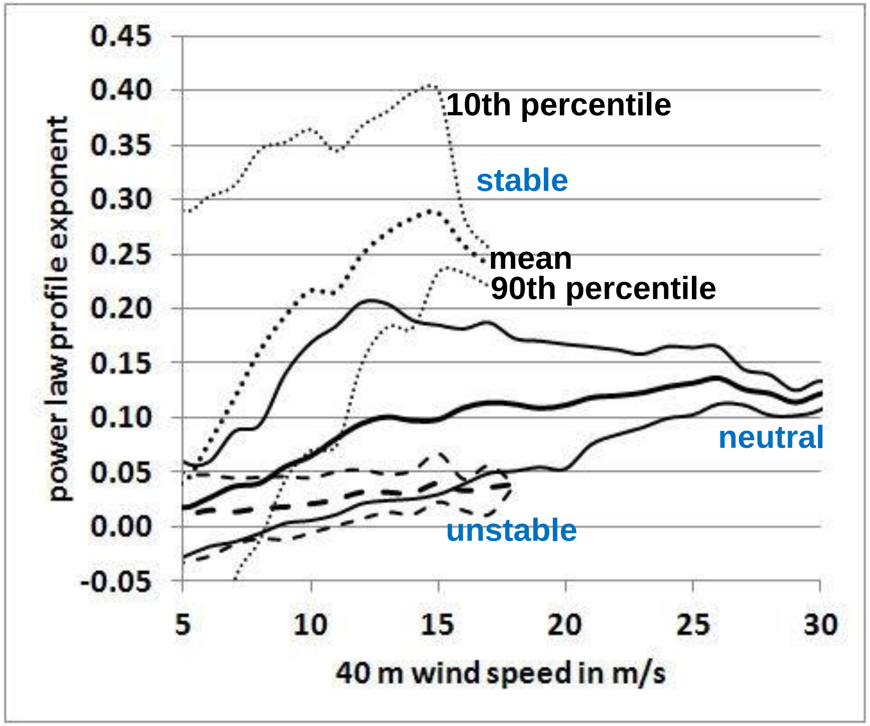
vertical structure of boundary layer is different
turbulence intensity depends on wind speed

offshore

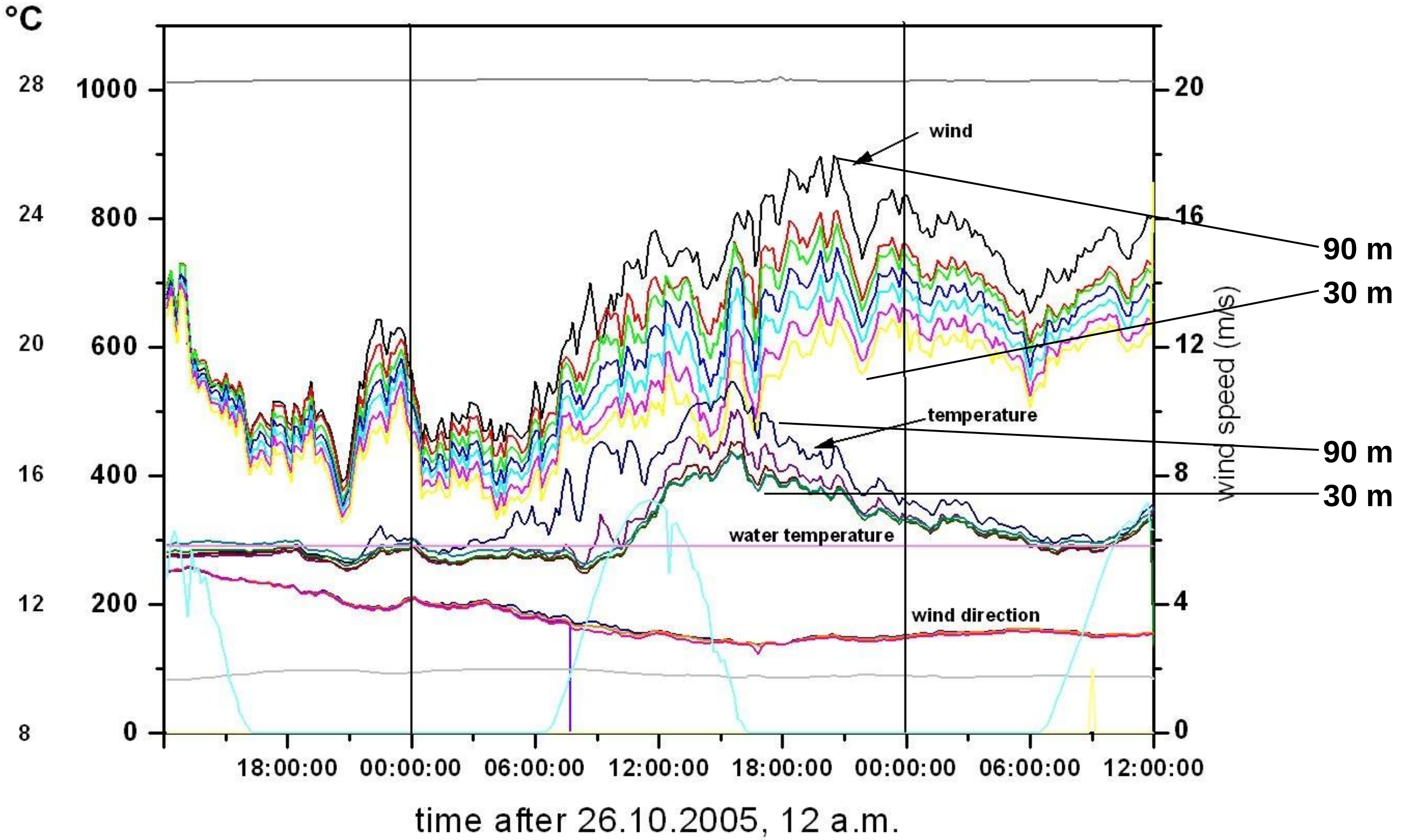




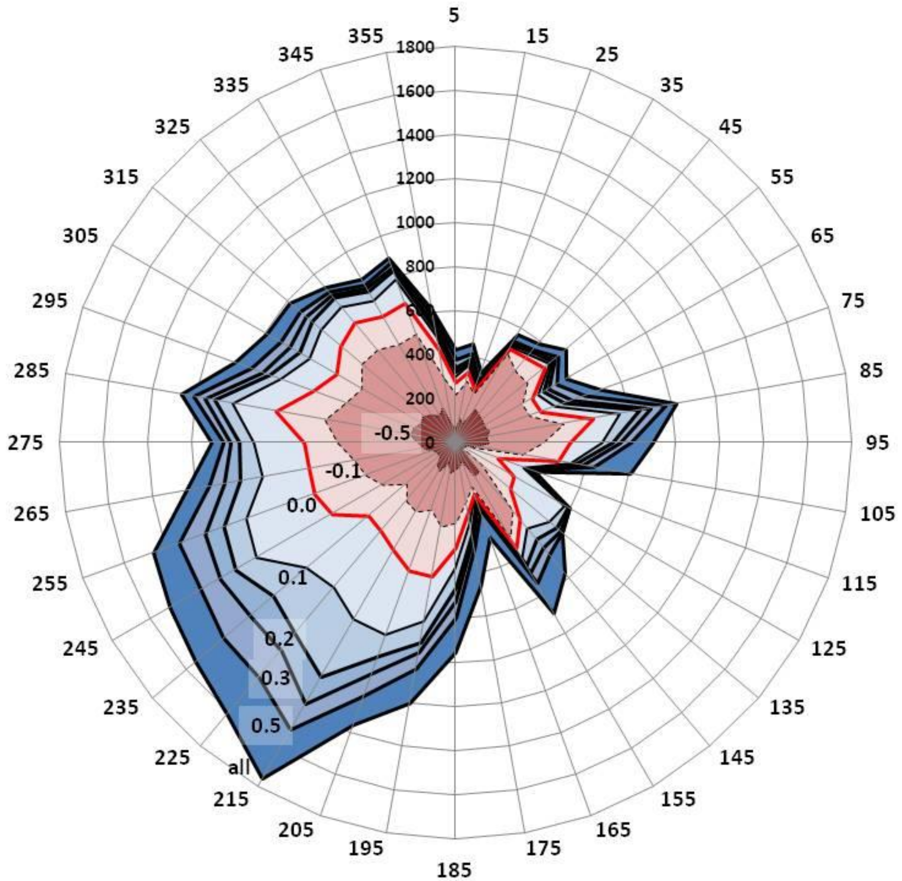
Hellmann exponent depends on wind speed and thermal stability

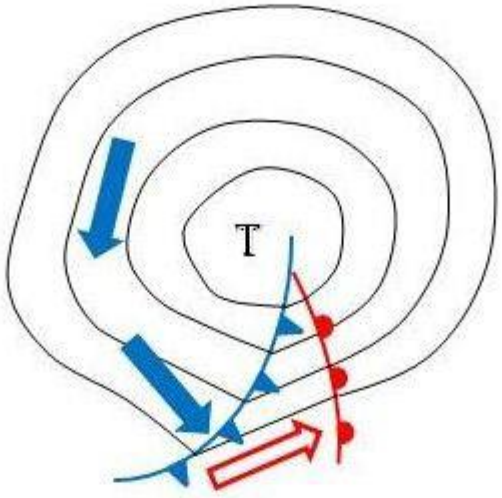


offshore:
vertical wind shear depends on the difference between air and water temperature



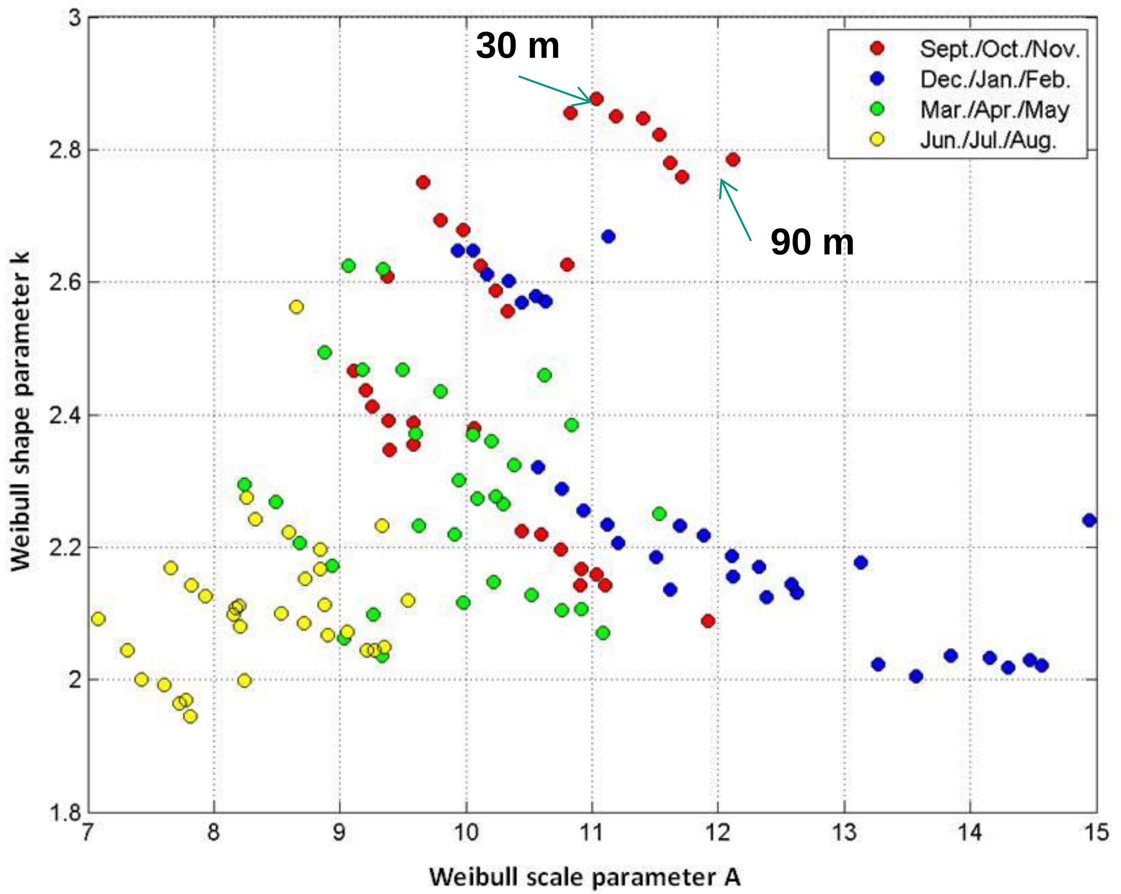
offshore: wind direction and thermal stability are correlated



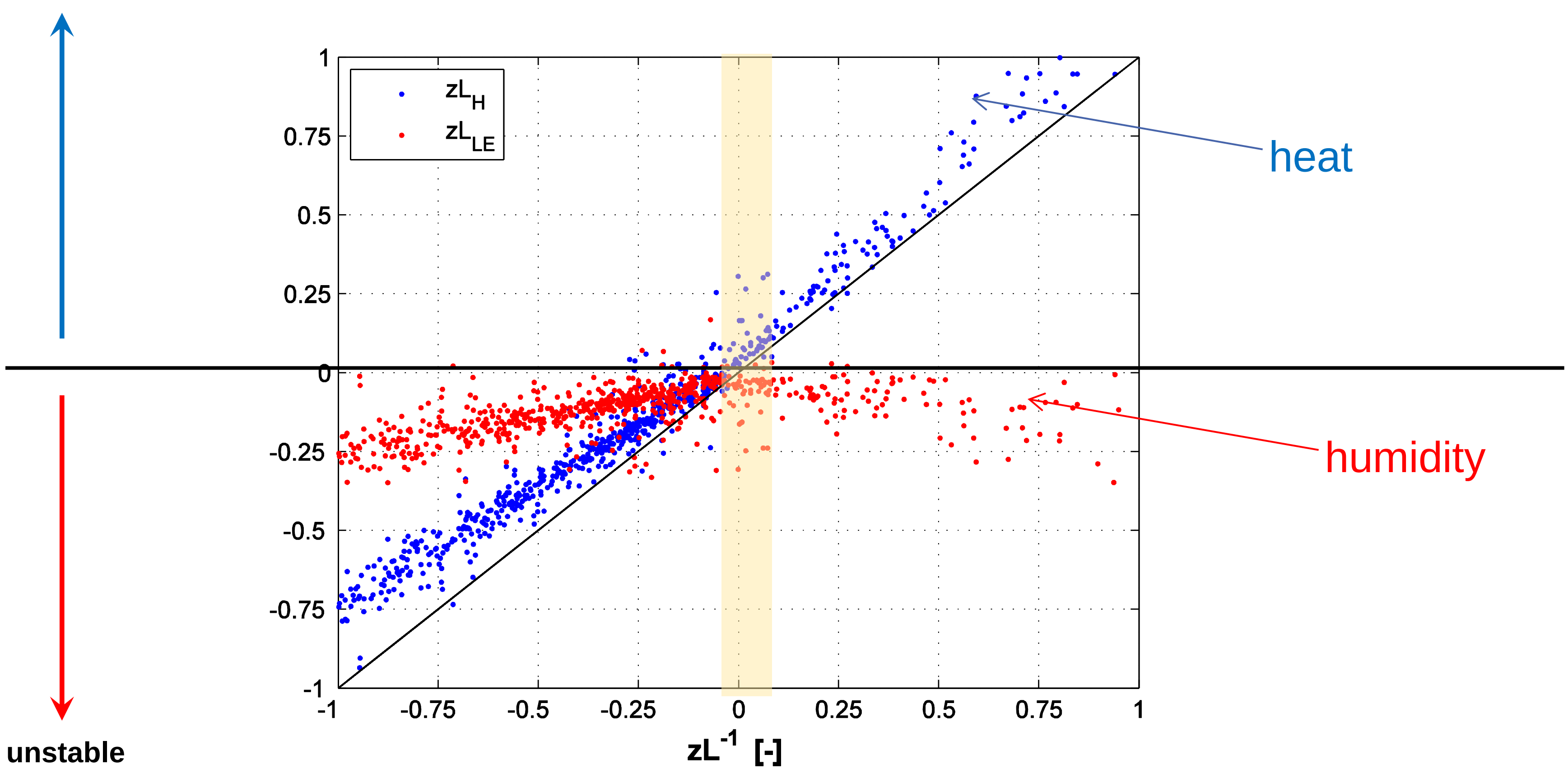


data: FINO1, 2005, wind direction at 80 m, stability at 60 m

offshore: Weibull parameter observed at FINO1



offshore: vertical gradient in humidity ➔ less stability (FINO1 41.5 m data for turbulent heat and humidity fluxes



Summary – offshore

wind/turbulence

- higher wind speeds – less turbulence
- no diurnal variation but seasonal variation

shear

- depends on temperature difference between air and water

thermal stability

- coupled (highest wind speeds with stable stratification)

humidity

- humidity usually decreases with height ➔ less stable stratification

impact on wind turbines

- higher yields
- less loads
- longer wakes

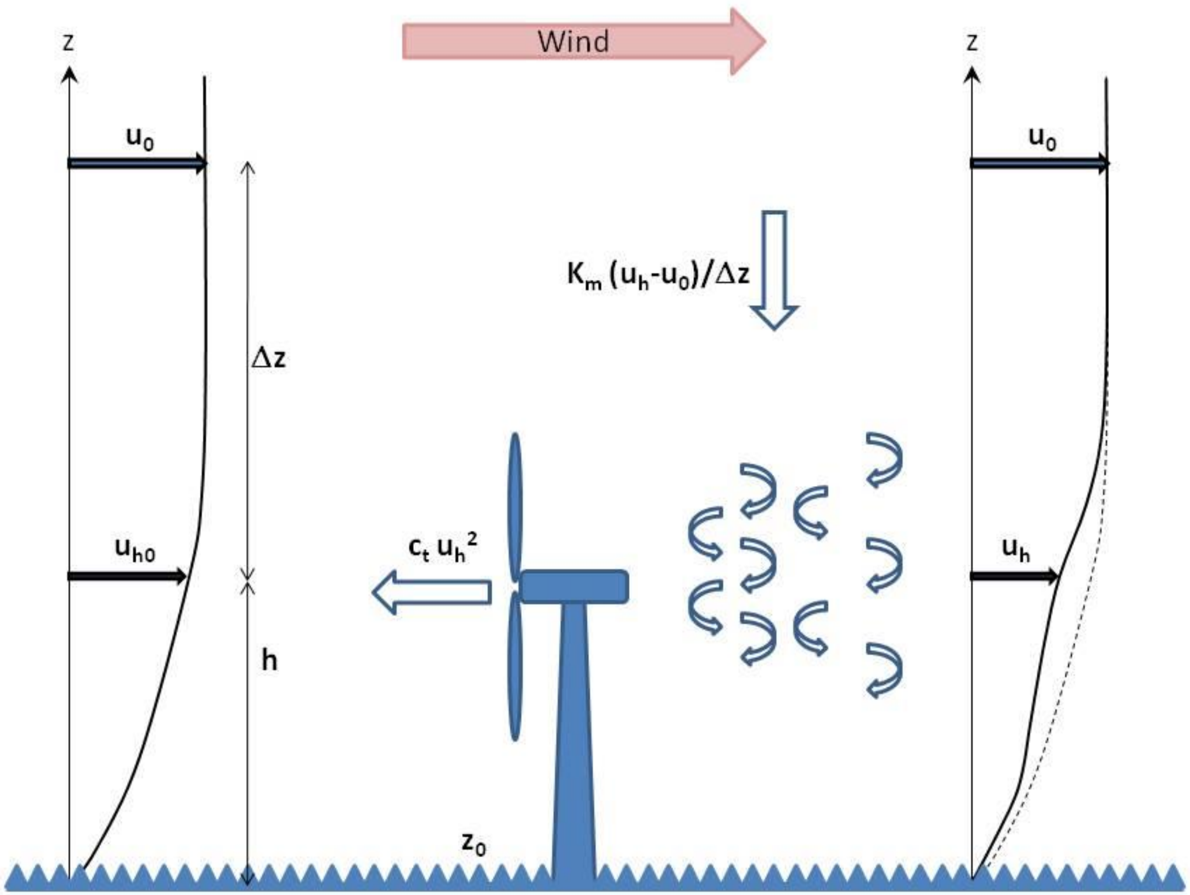
5

wind farms, onshore and offshore

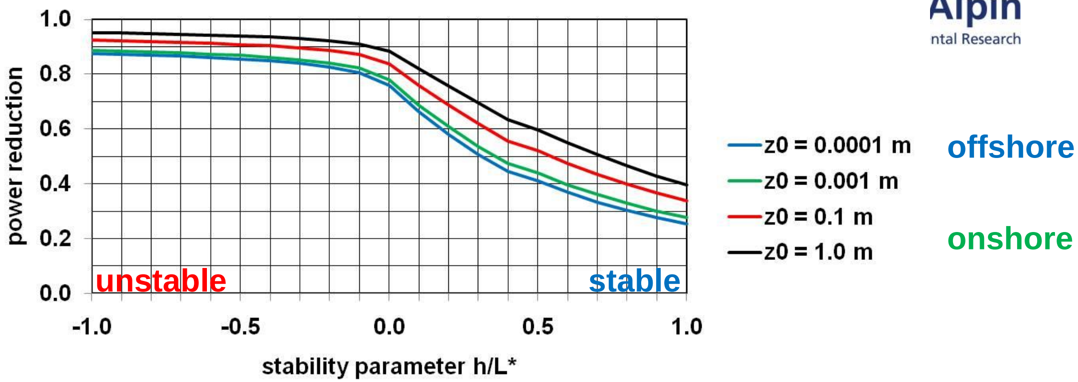
Chapter 6 in Emeis, S., 2012: Wind Energy Meteorology - Atmospheric Physics for Wind Power Generation. Series: Green Energy and Technology. Springer, Heidelberg etc., XIV+196 pp., 94 illus., 16 in colour, H/C, ISBN 978-3-642-30522-1

Emeis, S., 2010: A simple analytical wind park model considering atmospheric stability. Wind Energy, **13**, 459-469.

simple analytic wind farm model

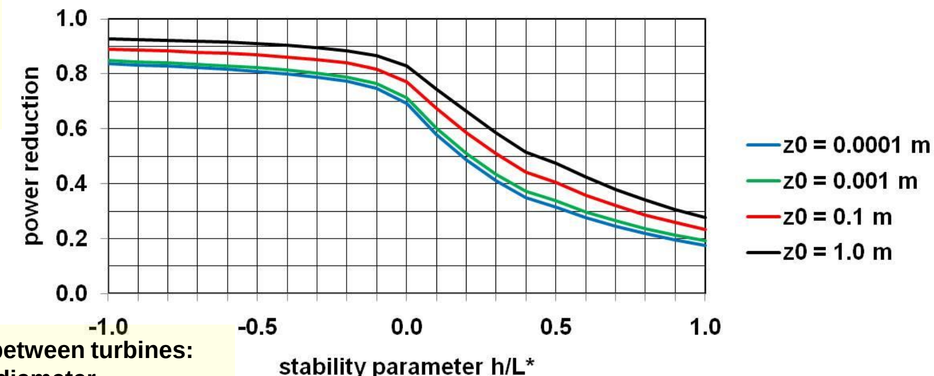


power reduction in wind farms



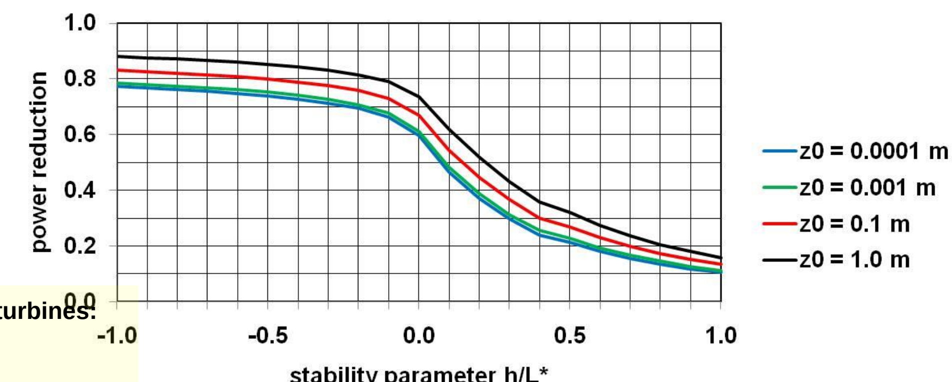
mean distance between turbines:
10 rotor diameter

➔ turbine-induced turbulence 10.1%



mean distance between turbines:
8 rotor diameter

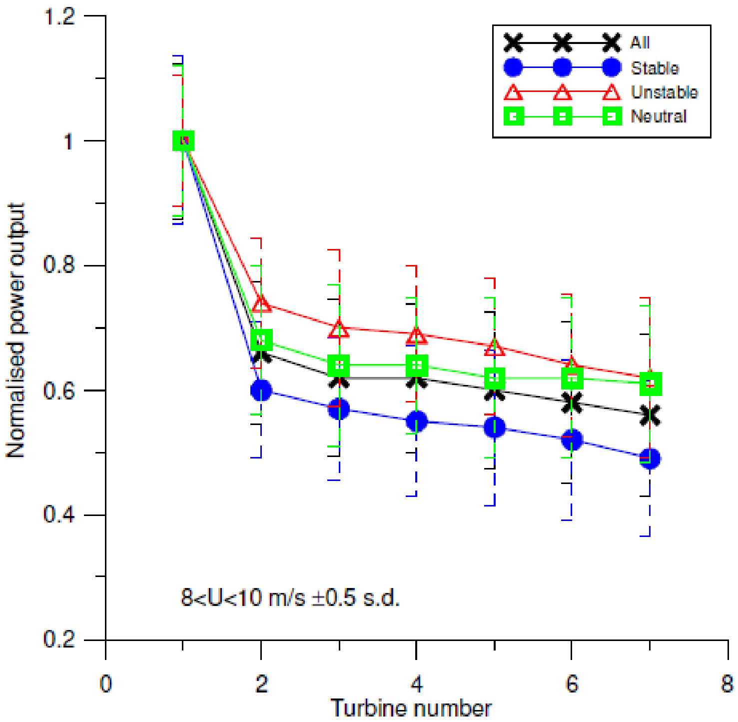
➔ turbine-induced turbulence 12.6%



mean distance between turbines:
6 rotor diameter

➔ turbine-induced turbulence 16.8%

observed reduction in wind power
Nysted wind farm (Baltic Sea)

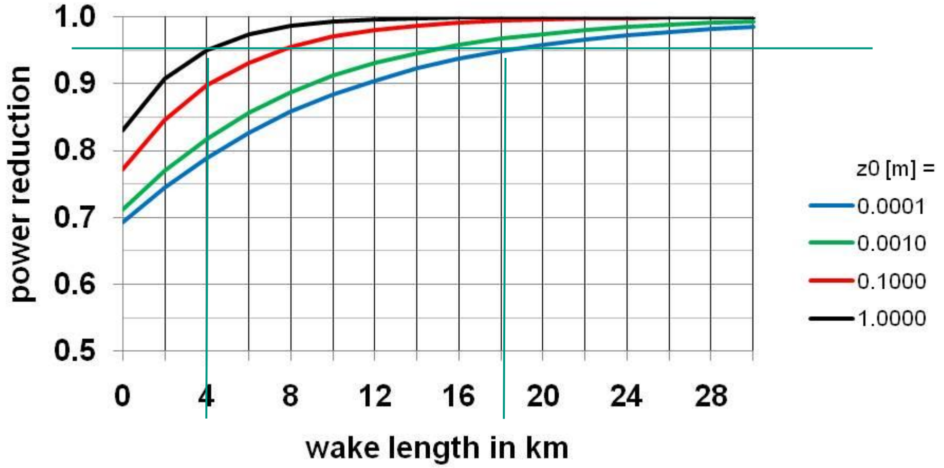


Barthelmie R, Frandsen ST, Rethore PE, Jensen L., 2007: Analysis of atmospheric impacts on the development of wind turbine wakes at the Nysted wind farm. Proceedings of the European Offshore Wind Conference, Berlin 4.-6.12.2007.

wind farm wake length,
mean distance between turbines: 8 rotor diameter

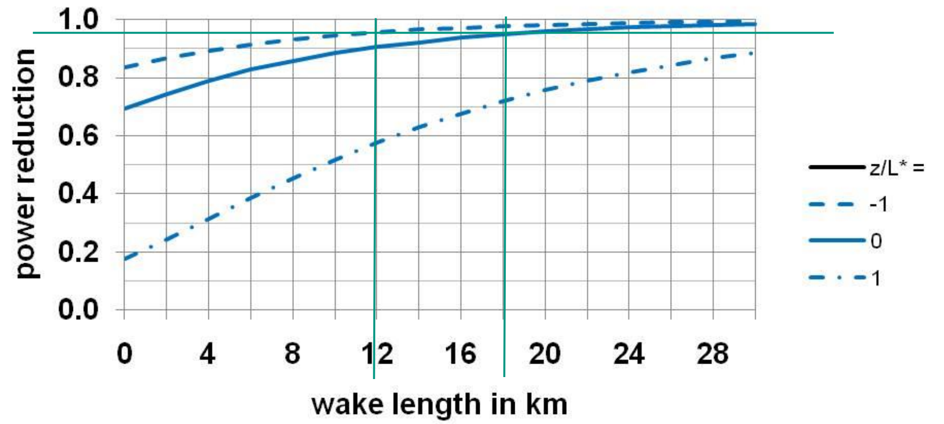
roughness: onshore (z_0 = 1.0 m) – offshore (z_0 = 0.0001 m)

neutral

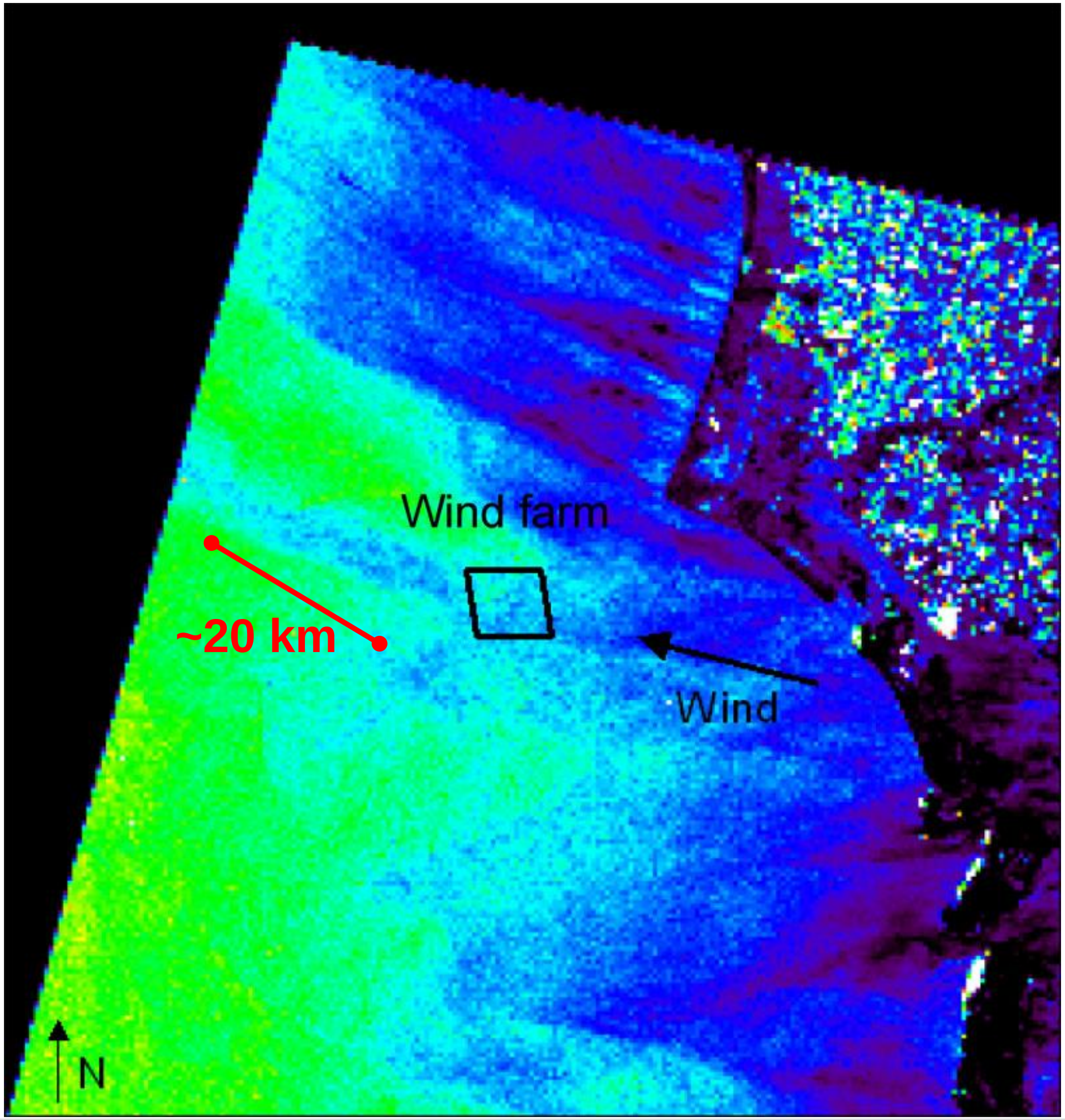


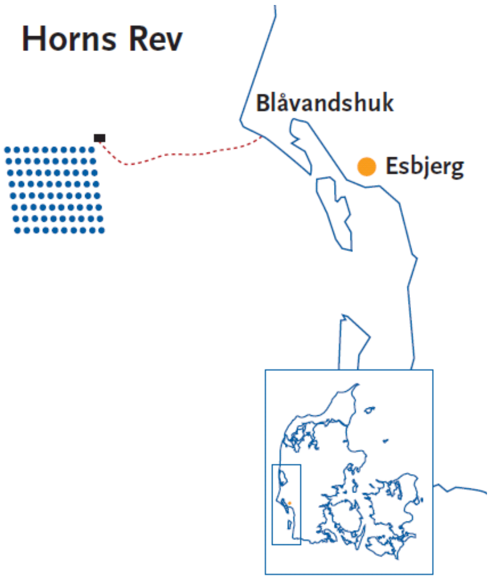
stability: unstable (h/L_* = -1) – neutral – stable (h/L_* = 1)

offshore



SAR image of Horns Rev wind farm (4 km x 5 km)





http://www.hornsrev.dk/nyheder/brochurer/Horns_Rev_TY.pdf

25. 02. 2003

© ERS SAR/Risø
http://galathea3.emu.dk/satelliteeye/projekter/wind/back_uk.html

Summary – wind farms

farm yield

- strong dependence on atmospheric stability,

- dependence on surface roughness,

- dependence on mean distance of turbines

farm wake lengths

- strong dependence on atmospheric stability

- dependence on surface roughness

impact on offshore wind farms (compared to onshore farms)

- turbines need to have larger spacing in offshore farms

- offshore farms needs to have larger spacing between each other

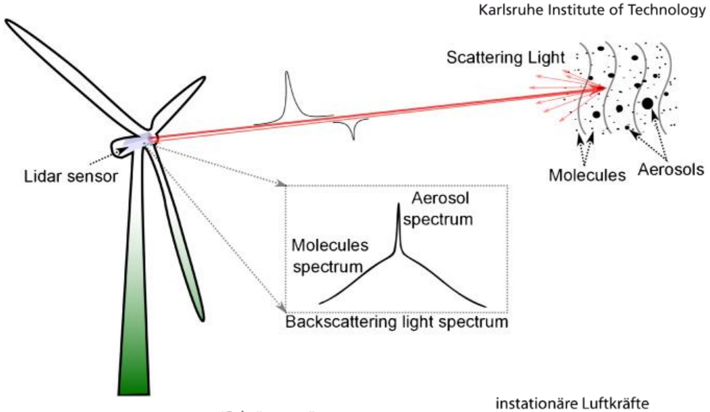
6

coming next in this session

Thorsten Beuth, Camille Porcher, Leilei Shinohara:

Redesign of wind turbines based on LiDAR technology, is it worth it? – A discussion based on a simple model for the tower's initial costs.

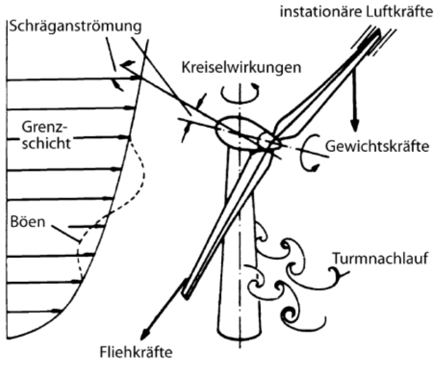
Institute for Information Processing Technologies, Karlsruhe Institute of Technology,
Arts et Métiers ParisTech



Bastian Ritter, Ulrich Konigorski, Mike Eichhorn:

Overview of Advanced Control Design for Optimal Wind Turbine Operation.

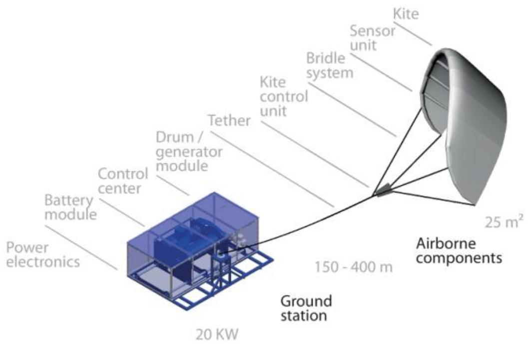
Industrial Science GmbH, Darmstadt,
Chair of Control Systems and Mechatronics, Technische Universität, Darmstadt,
IAV GmbH, Gifhorn



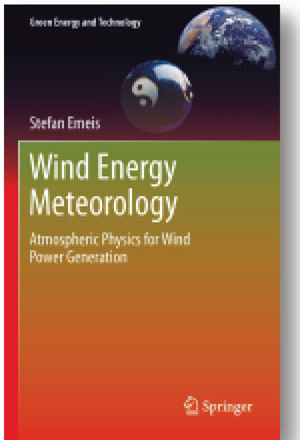
Felix Friedl, Lukas Braun, Roland Schmehl, Matthias Stripf:

Fault-Tolerant and Reliable Design of a Pumping Kite Power System.

Faculty of Aerospace Engineering, Delft University of Technology /
Institute of Aeronautical Engineering, FH Joanneum University of Applied Sciences,
Faculty of Aerospace Engineering, Delft University of Technology /
Institute of Flight System Dynamics, Technical University of Munich,
Faculty of Aerospace Engineering, Delft University of Technology,
Faculty of Mechanical Engineering and Mechatronics, Karlsruhe University of Applied Sciences



Thank you very much for your attention



2013, 2013, XIV, 196 p. 94 illus., 16 in color.

Printed book

Hardcover

- **99,95 € | £90.00 | $129.00**
- ***106,95 € (D) | 109,95 € (A) | CHF 133.50**

S. Emeis, Karlsruher Institut für Technologie, Garmisch-Partenkirchen, Germany

Wind Energy Meteorology

Atmospheric Physics for Wind Power Generation

- First book devoted solely to the meteorological basics of wind power generation
- Presents the meteorological basics for large wind turbines and wind parks
- Gives guidance to plan offshore wind parks

This book is intended to give an introduction into the meteorological boundary conditions for power generation from the wind, onshore and offshore. It is to provide reliable meteorological information for the planning and running of this important kind of renewable energy. This includes the derivation of wind laws and wind profile descriptions, especially those above the logarithmic surface layer. Winds over complex terrain and nocturnal low-level jets are considered as well. A special chapter is devoted to the efficiency of large wind parks and their wakes.