Karlsruhe Institute of Technology

WindForS Wind Energy Research Alliance

Remote Sensing for the derivation of the mixing-layer height and detection of low-level jets

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Introduction

-definition of mixing layer

- definition of low-level jets

- remote sensing techniques and results

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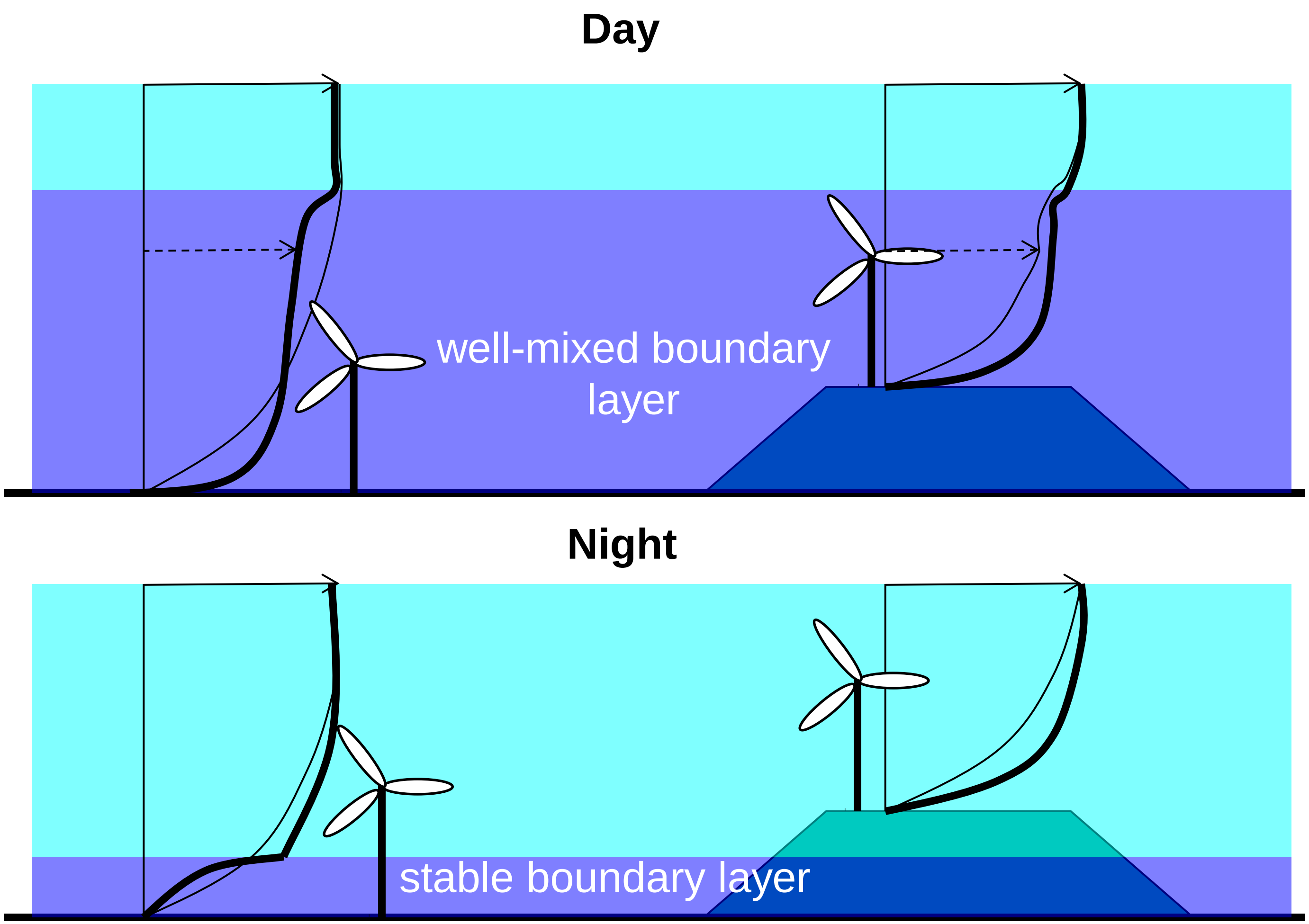
Mixing-layer height

Inversion height	literally: inversion in the temperature profile, increase of temperature with height, strong decrease of moisture, radiation inversions, sinking inversions, surface inversions, lifted inversions
Mixing-layer height (mixing height, mixed-layer height)	upper boundary for vertical exchange (mixing), upper boundary of the well-mixed layer, entrainment, defined by the turbulence profile or by the vertical distribution of a tracer (aerosol, pot. temperature)
Boundary layer height	SBL: at night, height of the near-surface layer influenced by surface friction CBL: at day, height of convective plumes

boundary layer height ≈ mixing-layer height

boundary layer height ≥ inversion height

Mixing-layer height influences diurnal variation of vertical wind profiles



Relevance for wind energy

The vertical wind profile (equilibrium conditions)

logarithmic law
(with stability correction) $u(z) = (u_*/\kappa)\,(\ln(z/z_0) - \psi(z/L_*))$

power law $u(z) = u(z_A)\,(z/z_A)^n$

New proposal
(Gryning et al. 2007)

$$u(z) = \frac{u_{*0}}{\kappa}\left(\ln\left(\frac{z}{z_0}\right) + \frac{z}{L_{MBL,N}} - \frac{z}{z_i}\left(\frac{z}{2L_{MBL,N}}\right)\right)$$

needs information on the PBL or mixing-layer height

Gryning, S.-E., E. Batchvarova, B. Brümmer, H. Jørgensen, S. Larsen, 2007: On the extension of the wind profile over homogeneous terrain beyond the surface boundary layer. Bound.-Lay. Meteorol., **124**, 251–268.

Peña, A., S.-E. Gryning, C.B. Hasager, 2010: Comparing mixing-length models of the diabatic wind profile over homogeneous terrain. Theor. Appl. Climatol., **100**, 325-353.

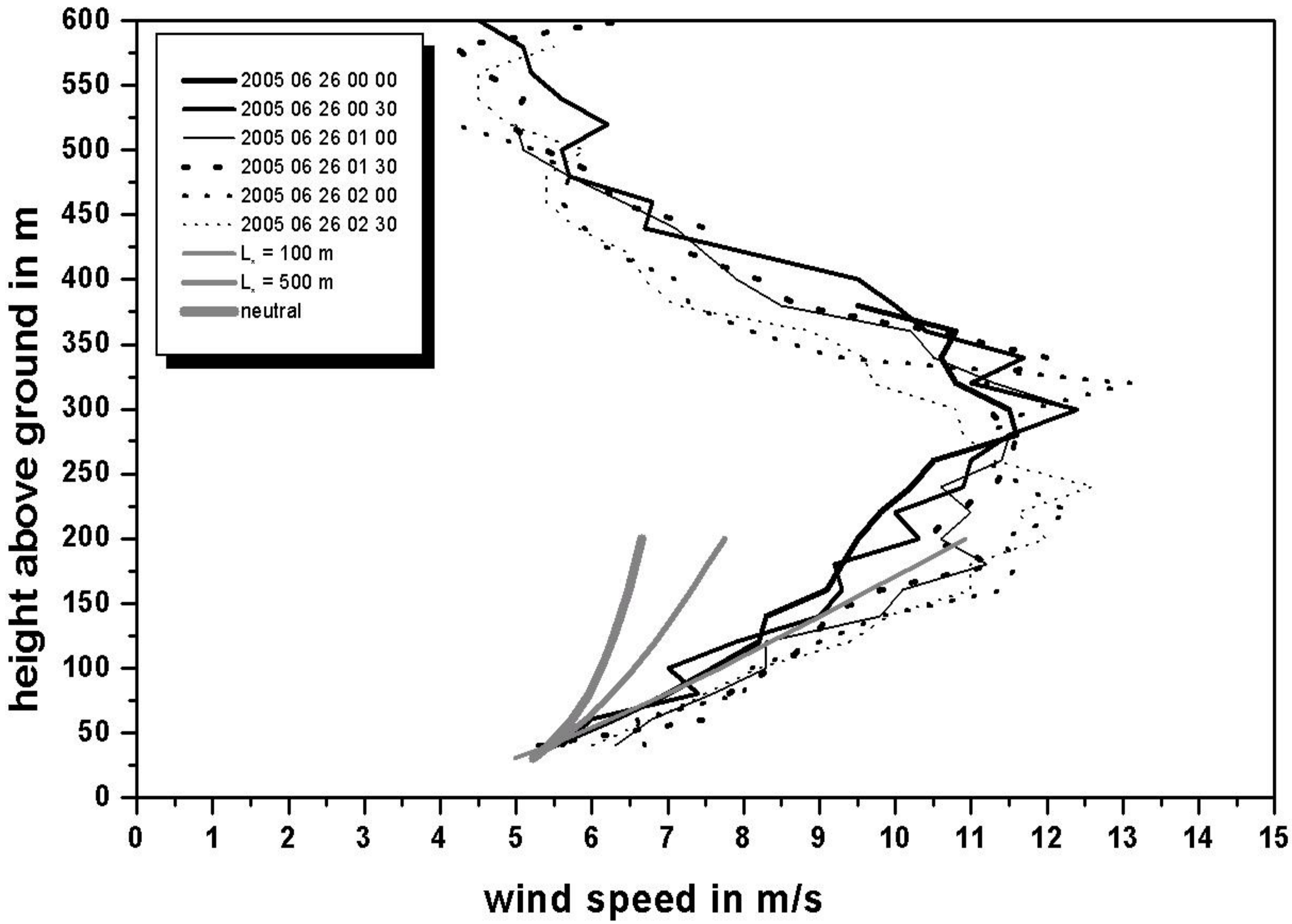
LLJ can only be described by time-dependent equations!

Low-level jet

vertical profiles of wind speed

26 June 2005

AdP Ch d G



Prof. Dr. Stefan Emeis – Low-level jets stefan.emeis@kit.edu

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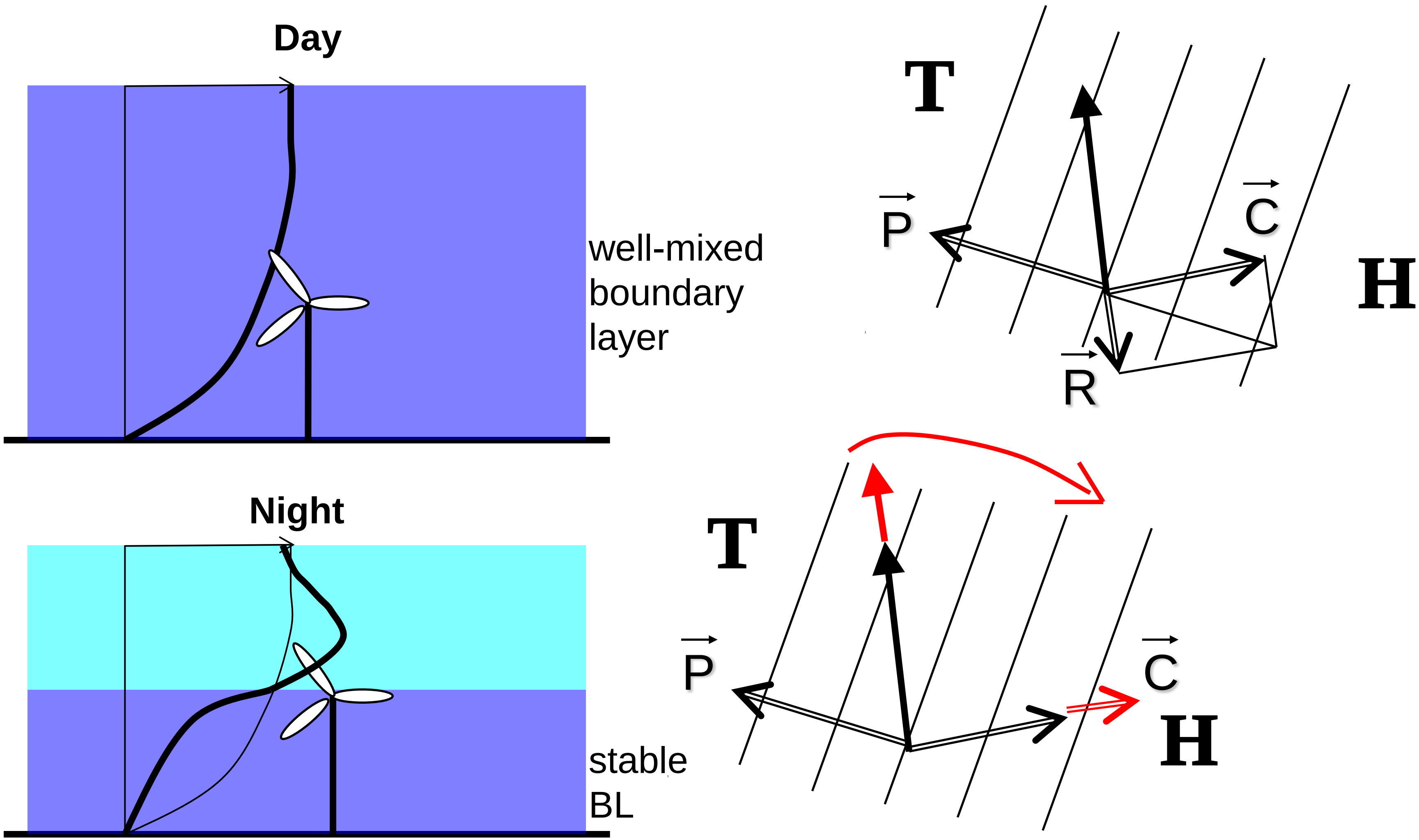
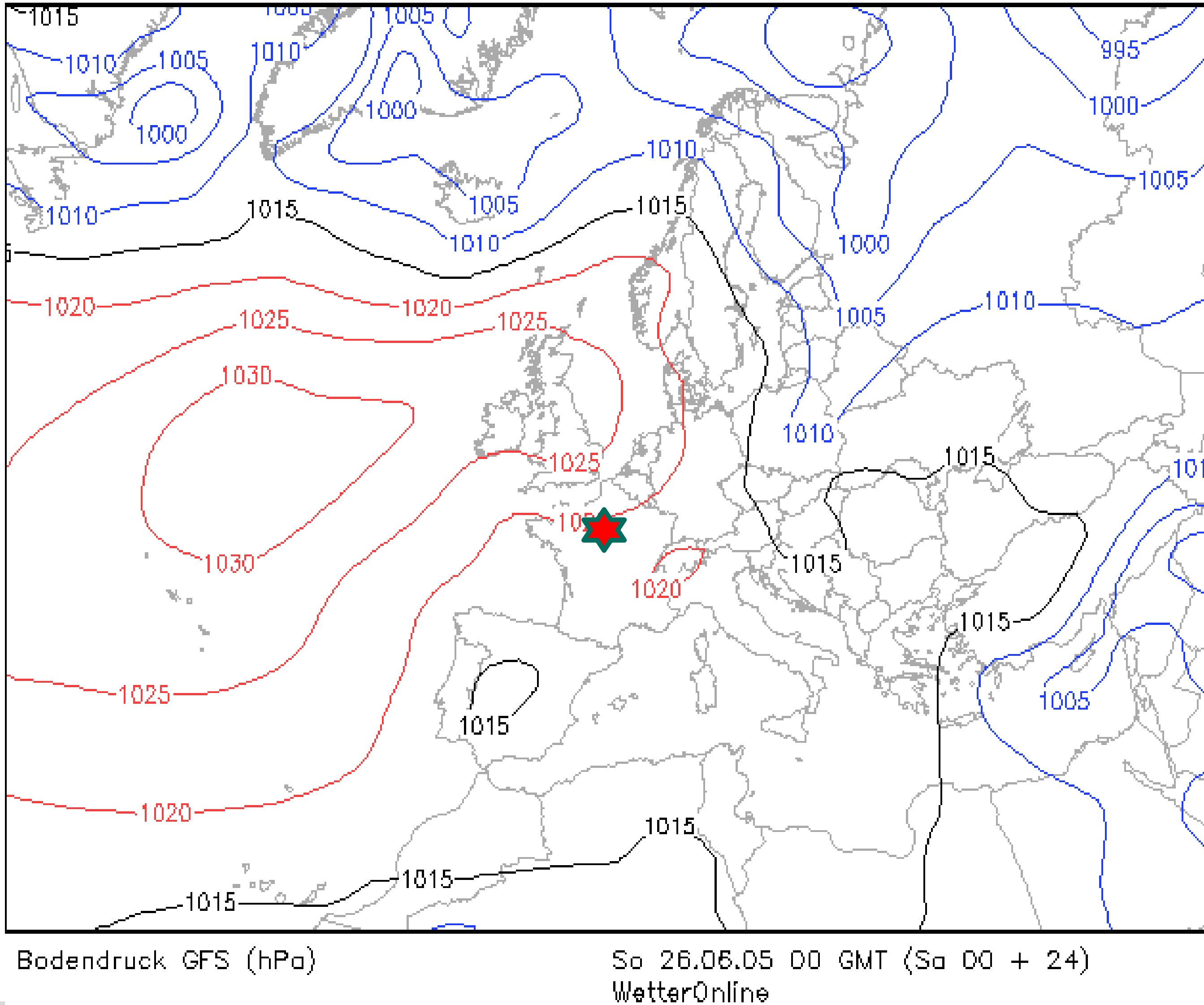
Nocturnal low-level jet and the turning of wind direction with height

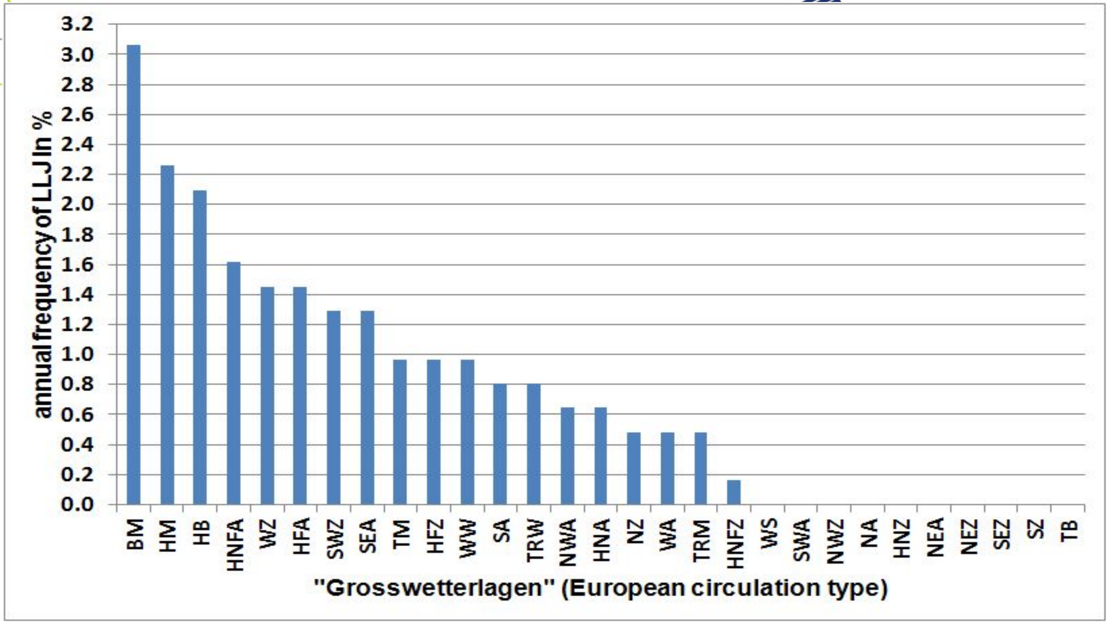


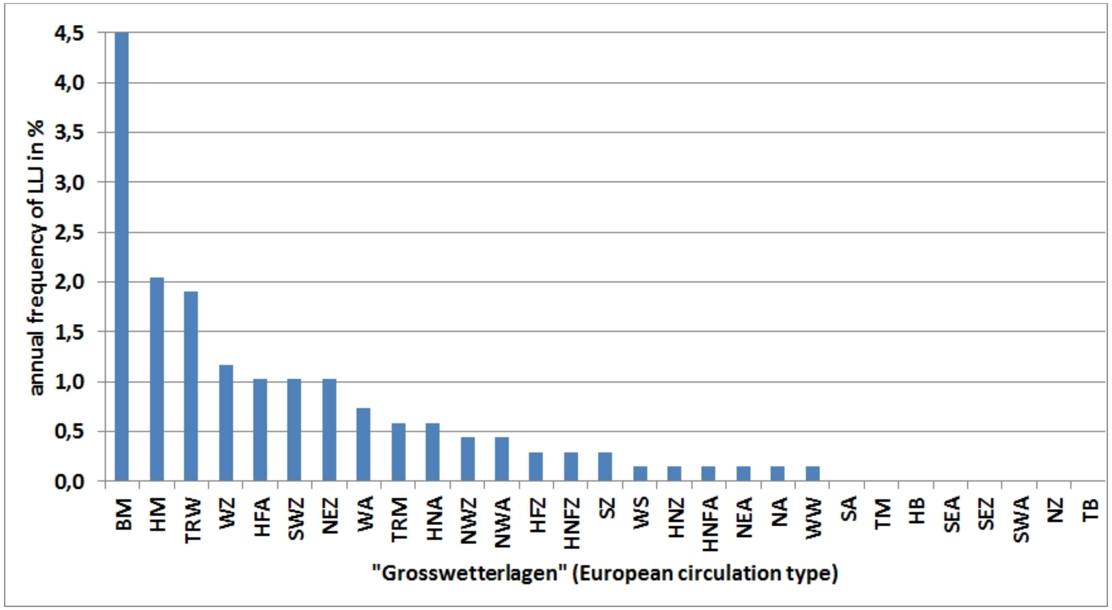
surface pressure
00 GMT

26 June 2005

asterisk denotes location where LLJ was observed







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

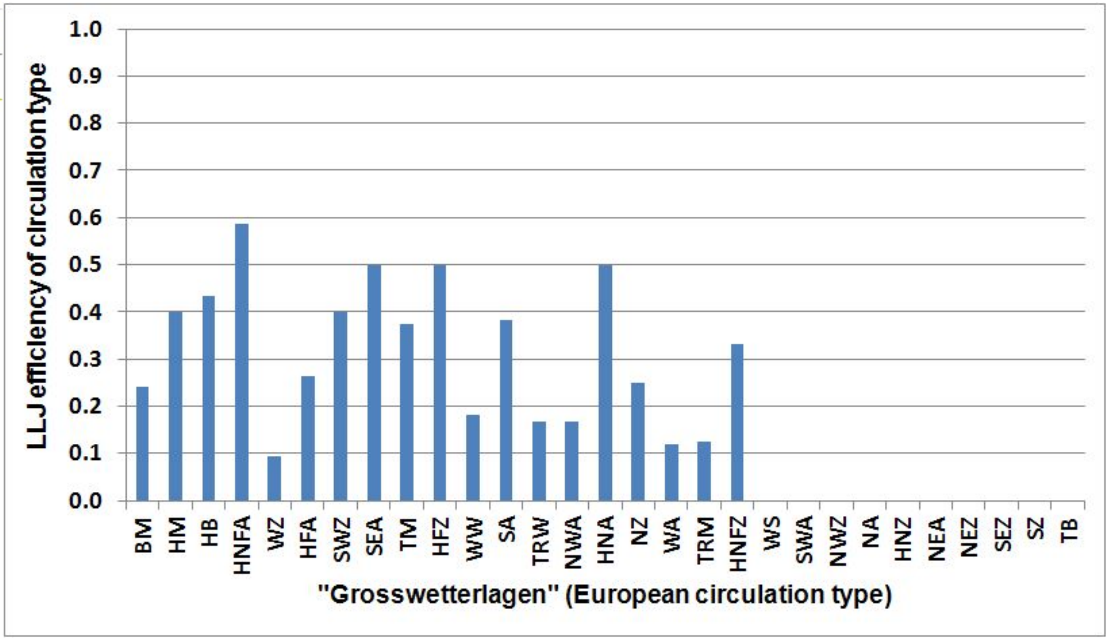
roughly 22 % of all nights

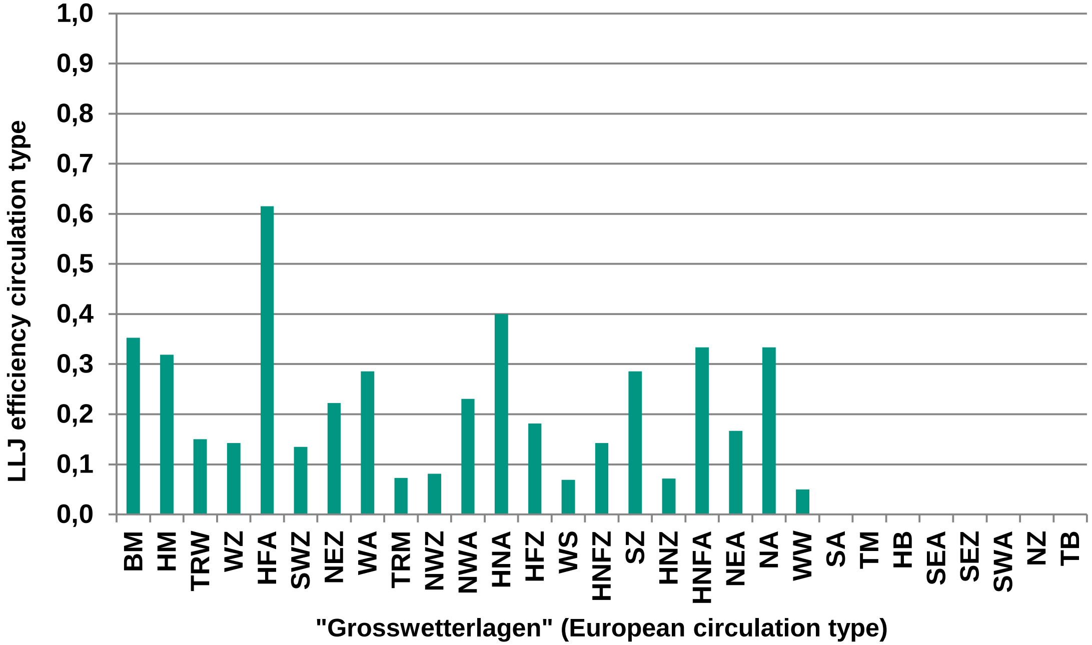
over Augsburg in the years 2008-2010, 2014

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**
...	





"effectivity" for forming a low-level jet

top: Hannover
bottom: Augsburg

Circulation types:

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

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

Remote sensing of mixing-layer height and low-level jets

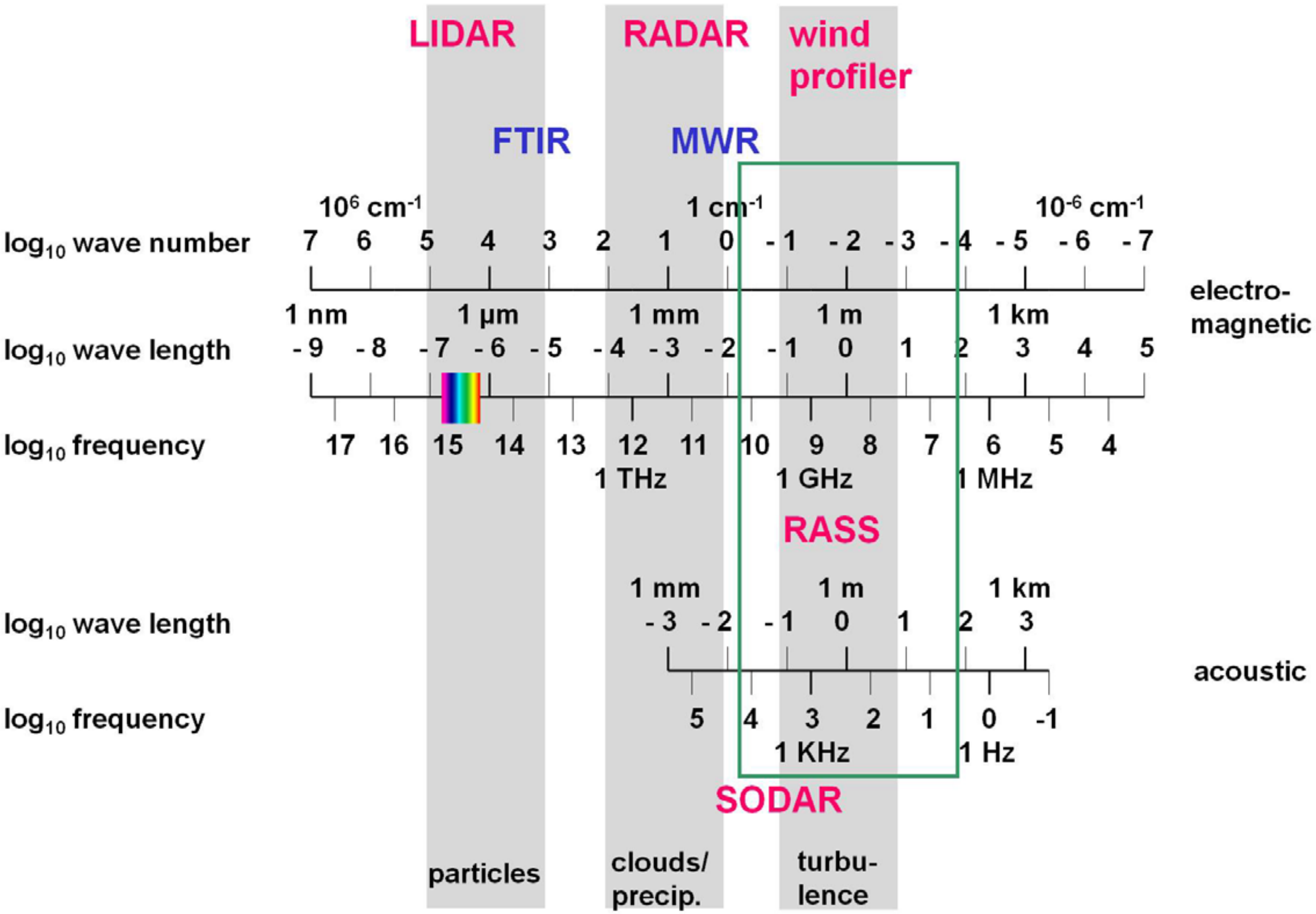
Basic remote sensing techniques

name	princple	spatial resolution	direction	type
RADAR	backscatter, electro-magnetic pulses, fixed wave length	profiling	scanning, slanted	active, monostatic
SODAR	backscatter, acoustic pulses, fixed wave length	profiling	fixed, slanted, vertical	active, usually monostatic
LIDAR ceilometer	backscatter, optical pulses, fixed wave length(s)	profiling	scanning, fixed, horizontal, slanted, vertical	active, monostatic
RASS	backscatter, acoustic, electro-magnetic, fixed wave length	profiling	fixed, vertical	active, monostatic
FTIR	absorption, infrared, spectrum	path-averaging	fixed, horizontal, slanted	active, bistatic or passive
FTIR	emission, infrared, spectrum	path-averaging	fixed, horizontal, slanted	passive
DOAS	absorption, optical, fixed wave lengths	path-averaging	fixed, horizontal	active, bistatic
radiometry	electro-magnetic, fixed wave length(s)	averaging, profiling	fixed, scanning, slanted, vertical	passive
tomography	travel time, acoustic, fixed wave length	horizontal distribution	fixed, horizontal	active, multiple emitters and receivers

subject of this lecture

subject of this lecture

Frequencies for atmospheric remote sensing



Emeis, S., 2010: Measurement Methods in Atmospheric Sciences - In situ and remote. Borntraeger, Stuttgart, 272 pp., 103 figs, 28 tables, ISBN 978-3-443-01066-9.

Surface-based Remote Sensing Systems

at IMK-IFU

SODAR (Large system), acoustic backscatter, Doppler shift analysis ➔ wind, turbulence

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

Ceilometer, backscatter, optical pulses, wave length ~ 0.9 µm ➔ aerosol profiles

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

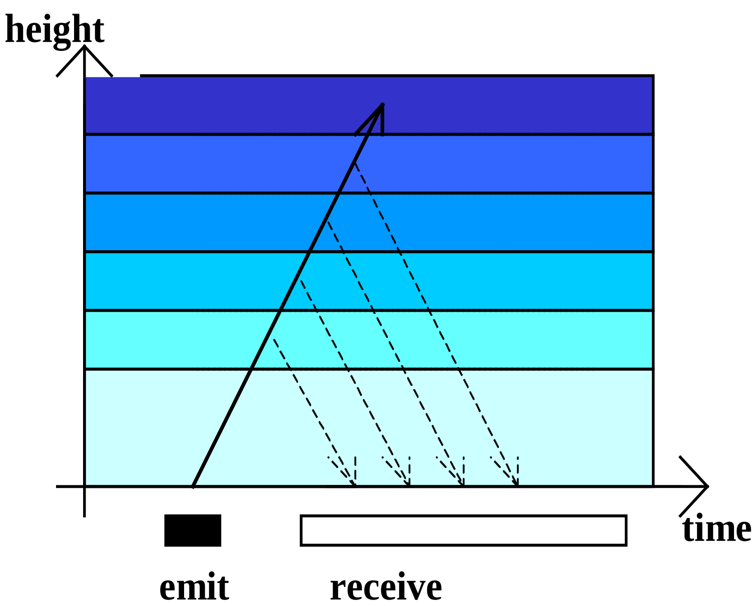
image: Halo Photonics

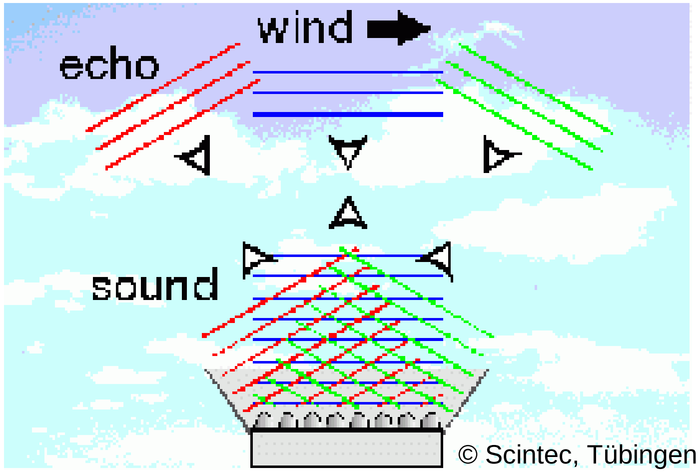
SODAR

algorithms for the determination of mixing-layer height

and low-level jet observations

monostatic SODAR: measuring principles





deduction:

sound travel time	=	height
backscatter intensity	=	turbulence
Doppler-shift	=	wind speed

Emission of sound waves into three directions:

in order to measure all three components of the wind (horizontal and vertical)

The SODAR equation:

$$P_R = r^{-2} (c_s \tau A \varepsilon/2) P_0 \beta_s e^{-2\sigma r} + P_{bg}$$

P_R received power,
P_0 emitted power,
ε antenna efficiency,
A effective antenna area,
σ sound absorption in air due to classical and molecular absorption due to the collision of water molecules with the oxygen and nitrogen molecules of the air,
r distance between the scattering volume and the instrument,
τ pulse duration (typically between 20 and 100 ms),
β_s backscattering cross-section (typically in the order of 10^{-11} m^{-1} sr^{-1}),
c_s sound speed,
P_{bg} background noise.

Emitted power: ~ 10^3 W, received (backscattered) power: 10^{-15} W

The SODAR equation:

$$P_R = r^{-2} (c_s \tau A \varepsilon/2) P_0 \beta_s e^{-2\sigma r} + P_{bg}$$

The ratio of the two terms on the right-hand side of the SODAR equation is called signal-to-noise ratio (usually abbreviated as SNR).

The backscattering cross-section β_s is a function of the temperature structure function C_T^2 (Tatarskii 1961).

For a monostatic SODAR we find (Reitebuch 1999) when using the wave number $k = 2\pi/\lambda$:

$$\beta_s(180°) = 0{,}00408\, k^{1/3}\, C_T^2 / T^2$$

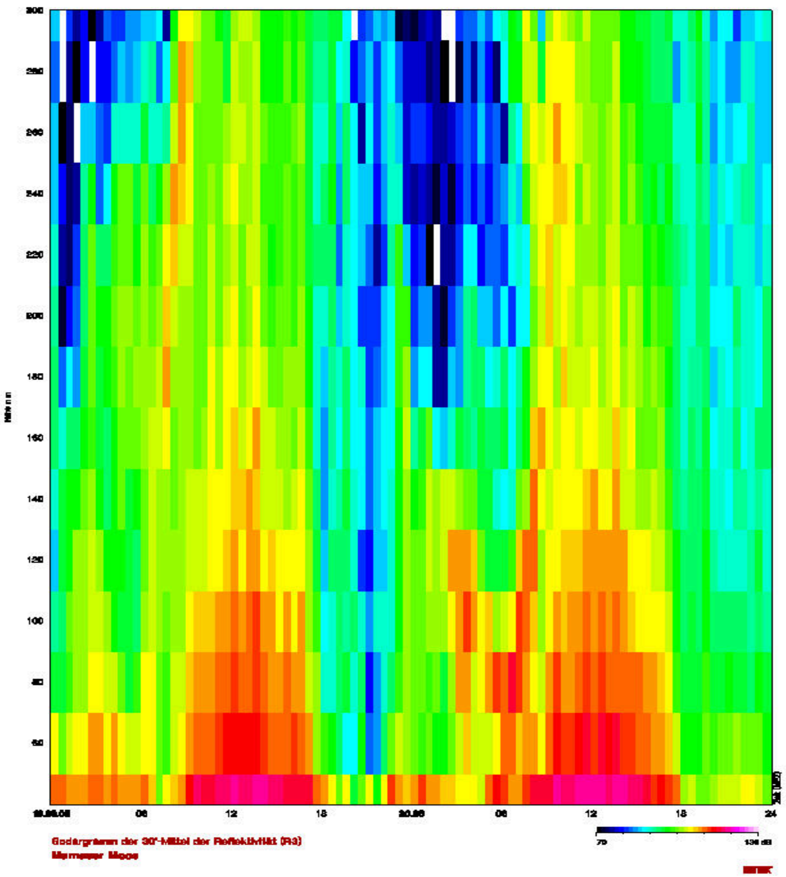
Reitebuch, O., 1999: SODAR-Signalverarbeitung von Einzelpulsen zur Bestimmung hochaufgelöster Windprofile. Schriftenreihe des Fraunhofer-Instituts für Atmosphärische Umweltforschung, Shaker Verlag GmbH Aachen, Bd. 62, 178 S.

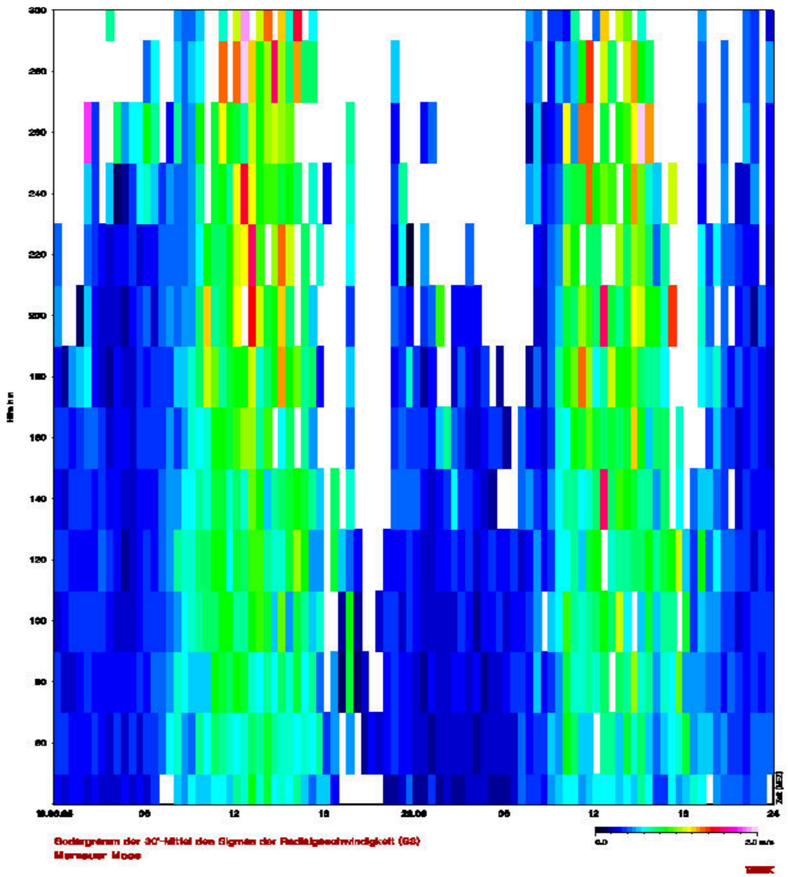
Tatarskii, V.I., 1971: The effect of the turbulent atmosphere on wave propagation. Kefer Press, Jerusalem, 472 S.

SODAR sample plot (daytime convective BL)

acoustic backscatter intensity — **sigma w**

40 – 300 m





2 days, midnight to midnight

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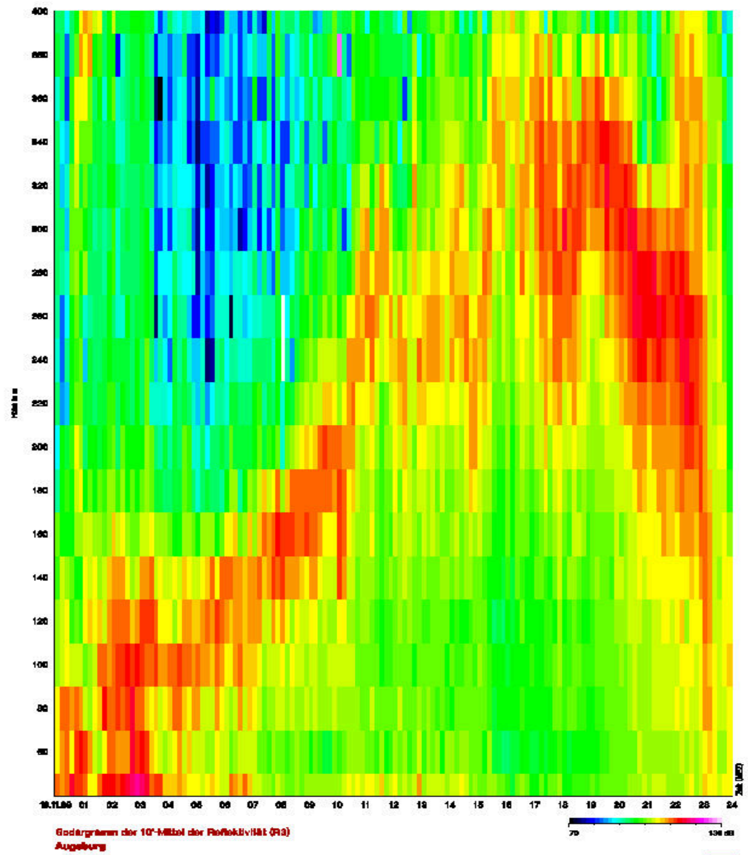
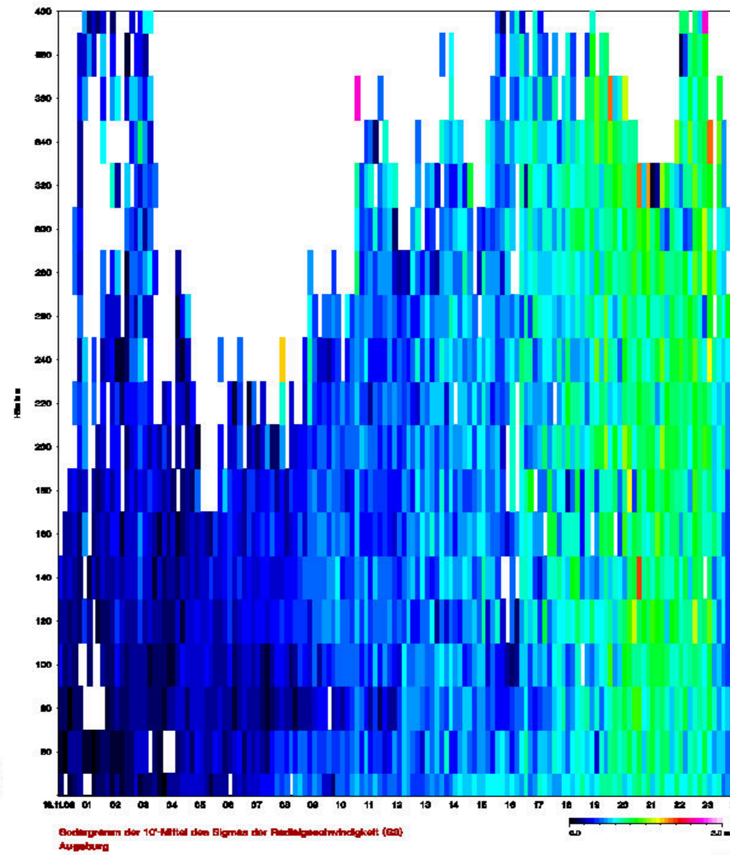
SODAR sample plot (lifted inversion)

acoustic backscatter intensity



sigma w



40 – 400 m

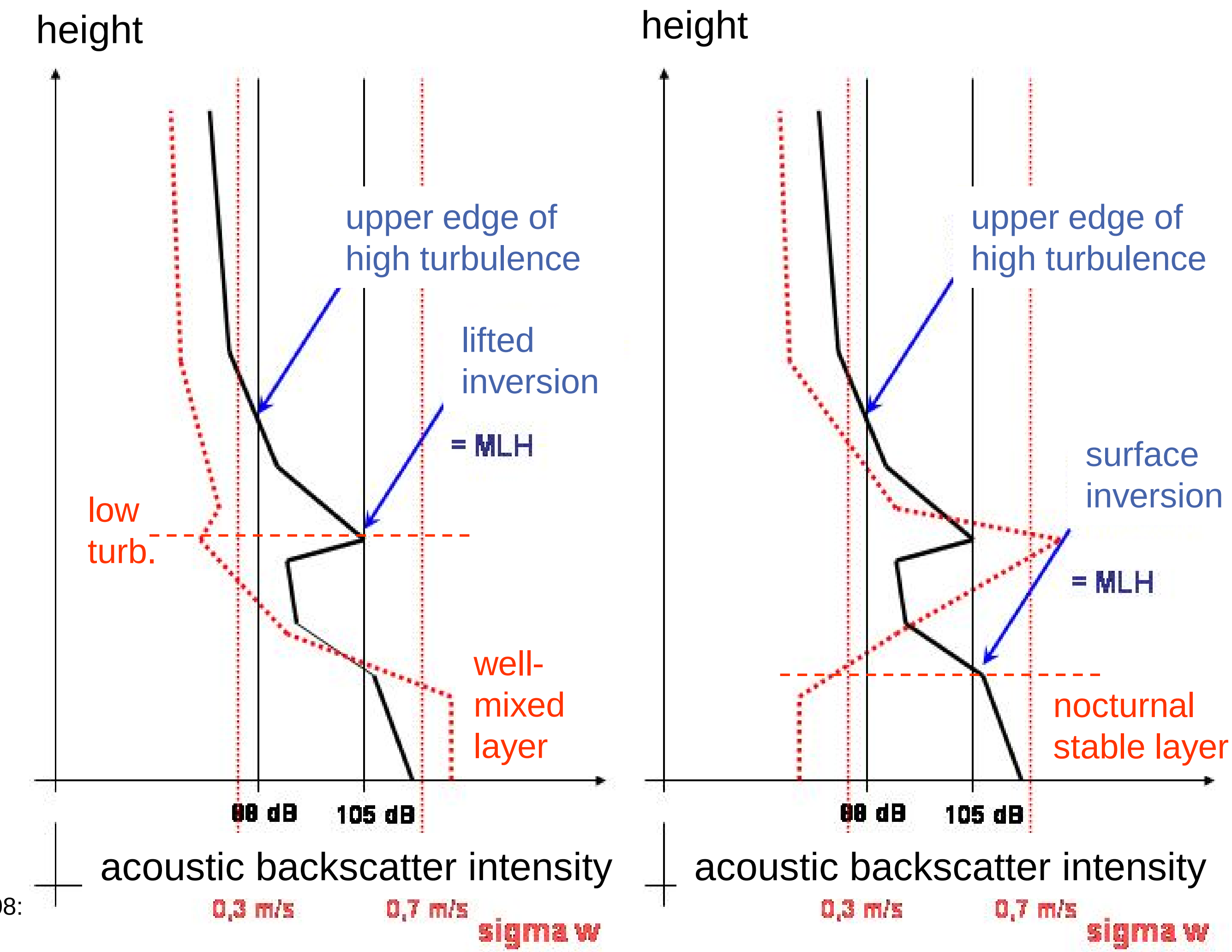
1 day, midnight to midnight

Algorithms to detect MLH from SODAR data

criterion 1:
upper edge of high turbulence

criterion 2:
surface and lifted inversions

MLH = Min (C1, C2)



example 1: daytime   example 2: night-time

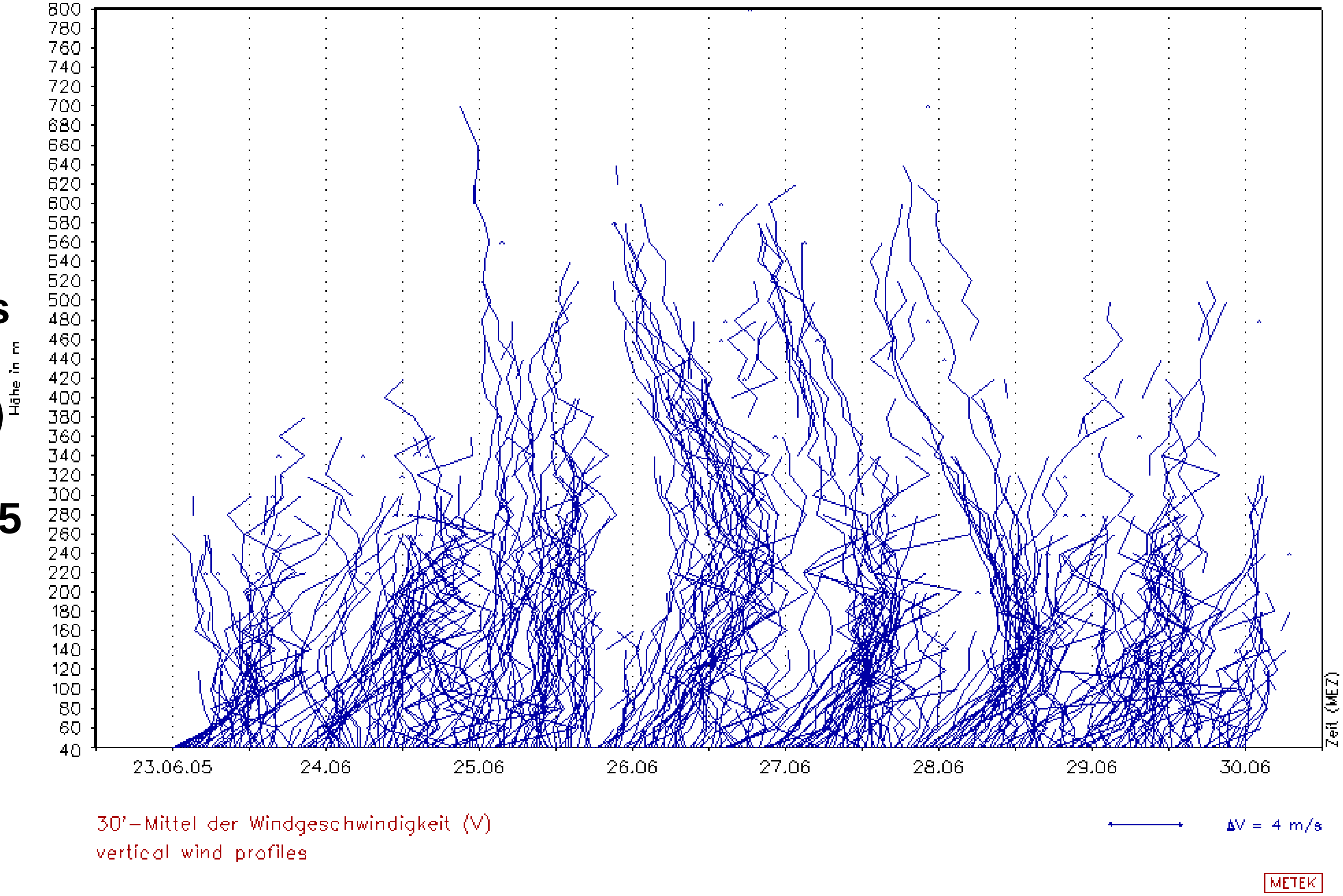
Emeis, S., K. Schäfer, C. Münkel, 2008: Surface-based remote sensing of the mixing-layer height – a review. Meteorol. Z., **17**, 621-630.

examples for low-level jet observations with SODAR

vertical profiles of wind speed (30 min means)

23-30 June 2005

AdP Ch d G

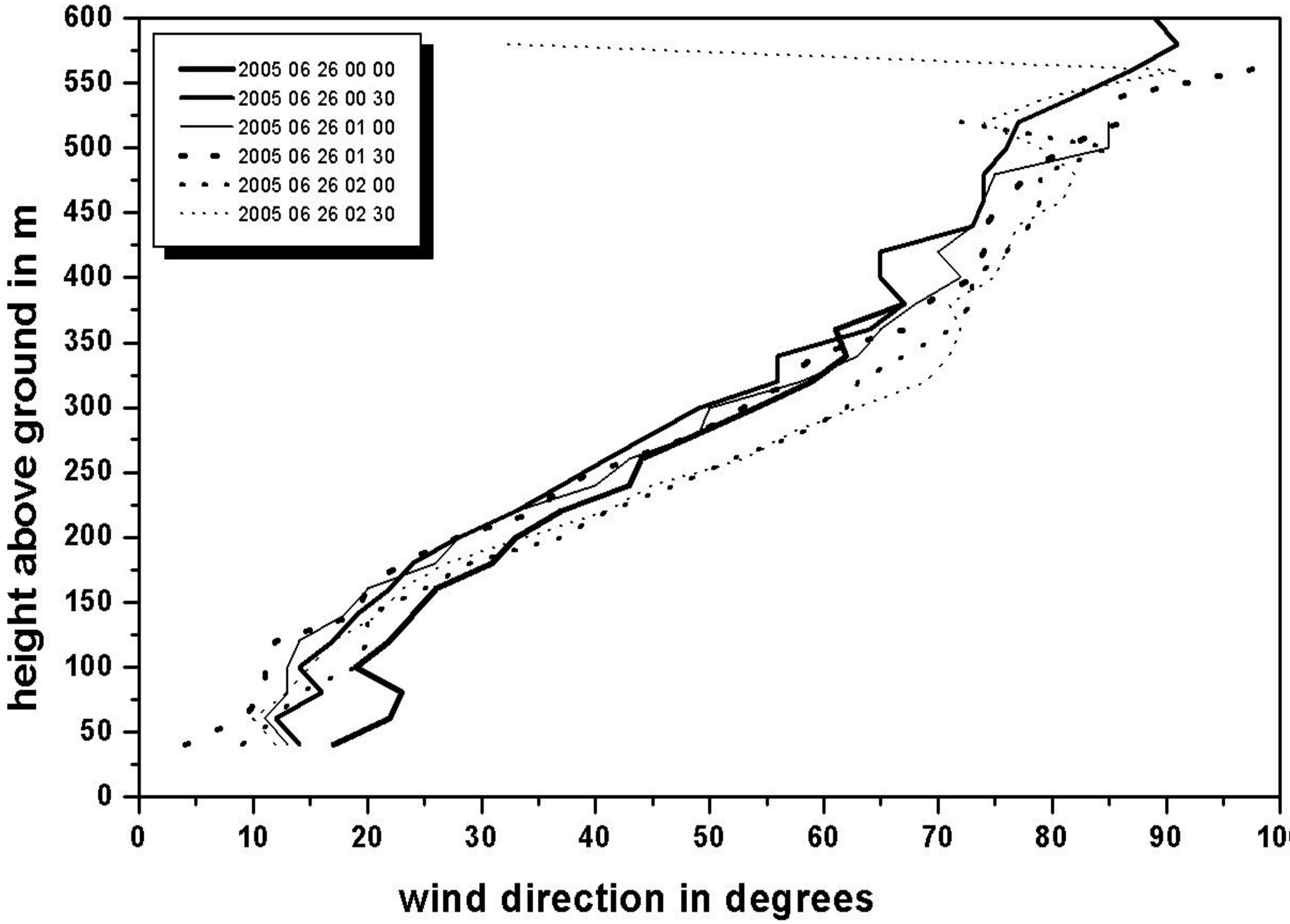


examples for low-level jet observations with SODAR

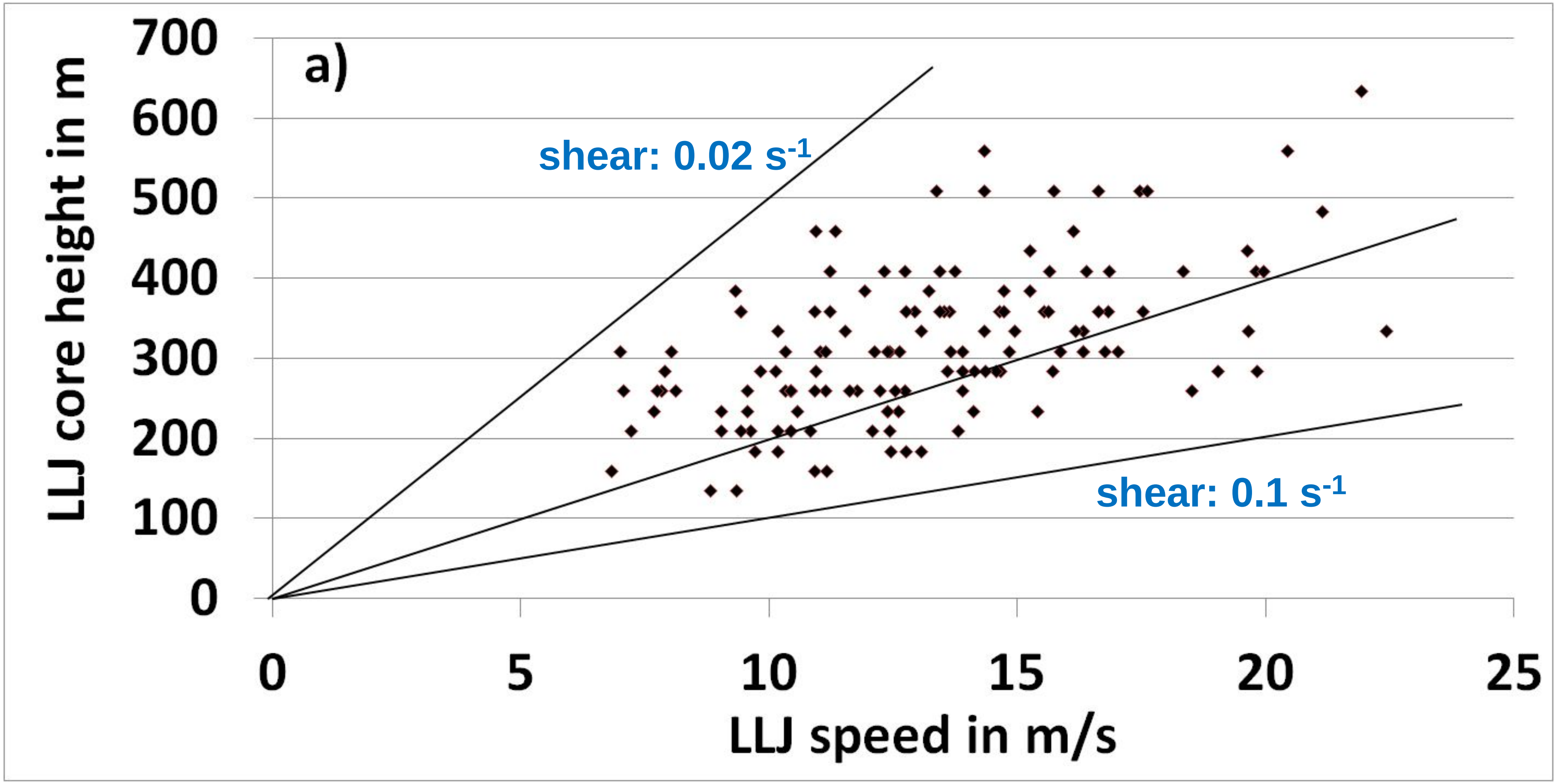
vertical profiles of wind direction

26 June 2005

AdP Ch d G



height in m and core-speed in m/s of LLJ
Hannover 5.2001 – 4.2003



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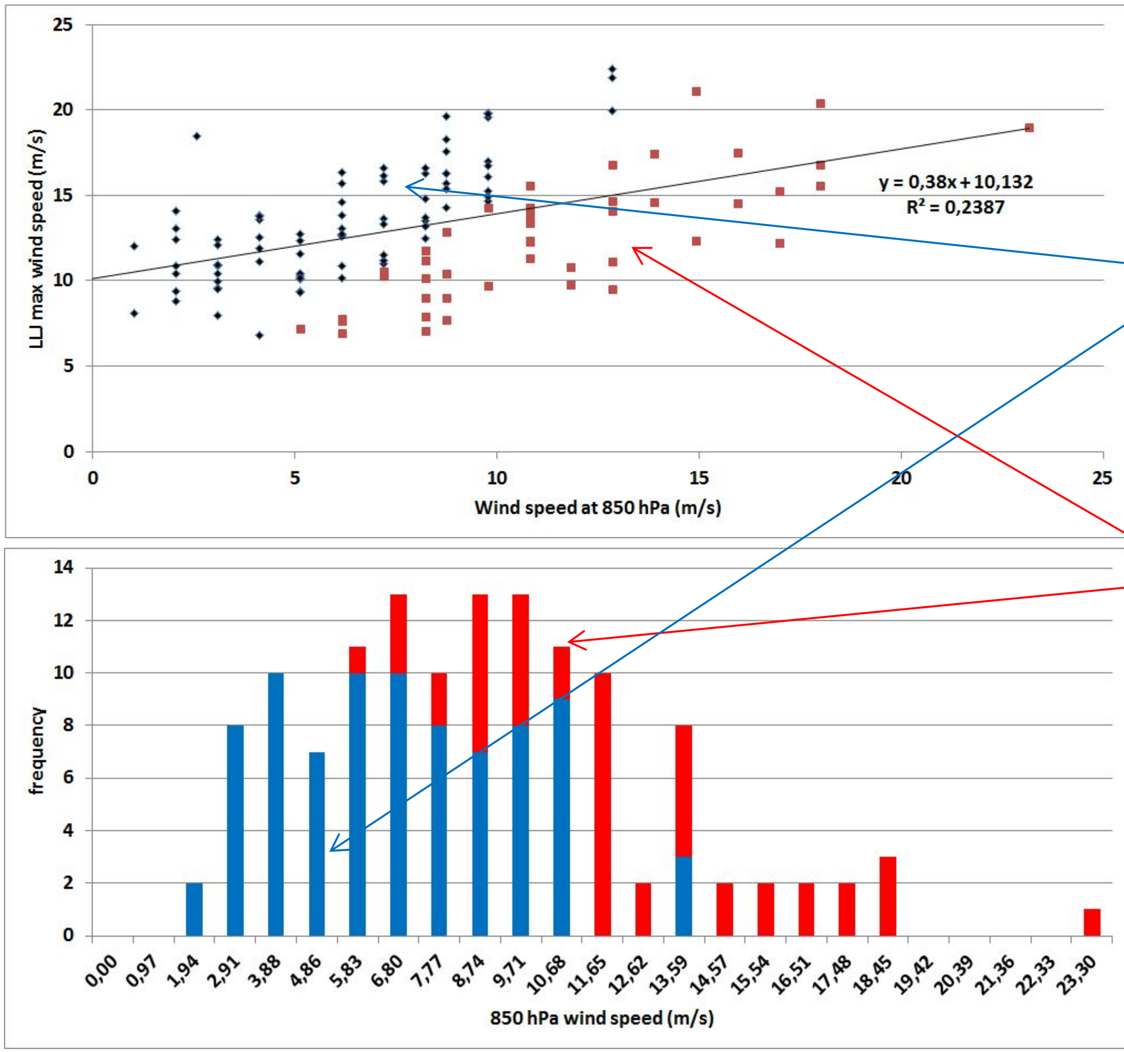
LLJ wind speed and frequency as function of 850 hPa wind speed



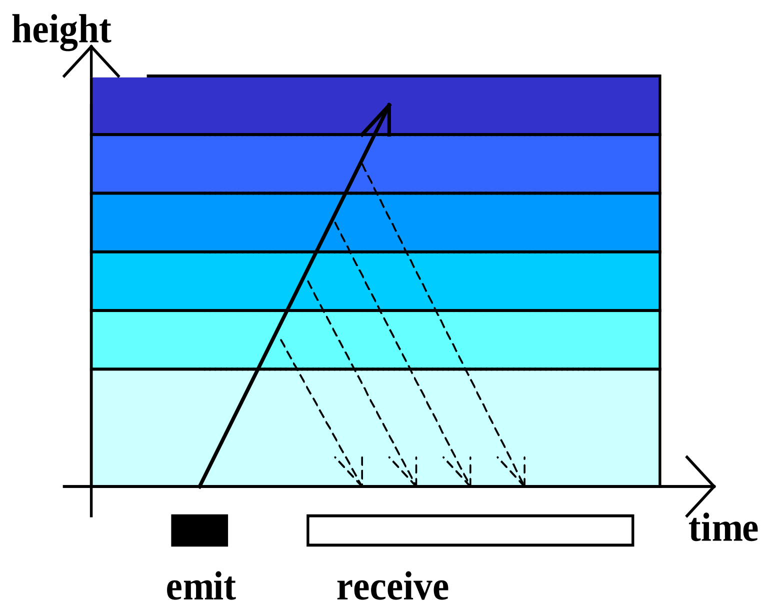
blue: LLJ core speed more than 1.5 times 850 hPa wind speed

red: LLJ core speed less than 1.5 times 850 hPa wind speed

Ceilometer

algorithms for the determination of mixing-layer height

Ceilometer/LIDAR measuring principle



detection:

travel time of signal = height
backscatter intensity = particle size and number distribution
Doppler-shift = cannot be analyzed from ceilometer data
(available only from a Wind-LIDAR: velocity component in line of sight)

The LIDAR equation:

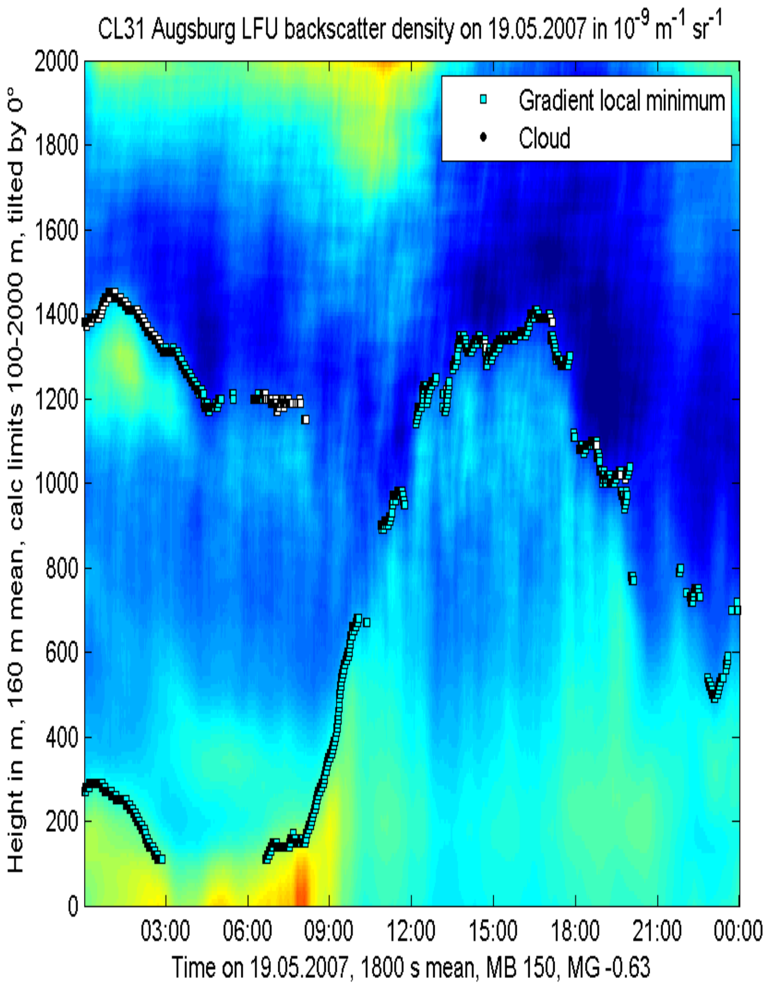
$$P_R(\lambda,r) = r^{-2}\ (c\tau A\varepsilon/2)\ P_0\ [\beta_m(\lambda,r) + \beta_p(\lambda,r)]\ e^{-2\sigma r} + P_{bg}$$

- r distance between the LIDAR and the backscattering object,
- c speed of light,
- τ pulse duration,
- A antenna area,
- ε correction term for the detector efficiency and losses due to the lenses,
- P_0 emitted energy,
- β_m backscatter coefficient for molecules
- β_p backscatter coefficient for particles,
- σ absorption of light in the atmosphere,
- P_{bg} background noise.

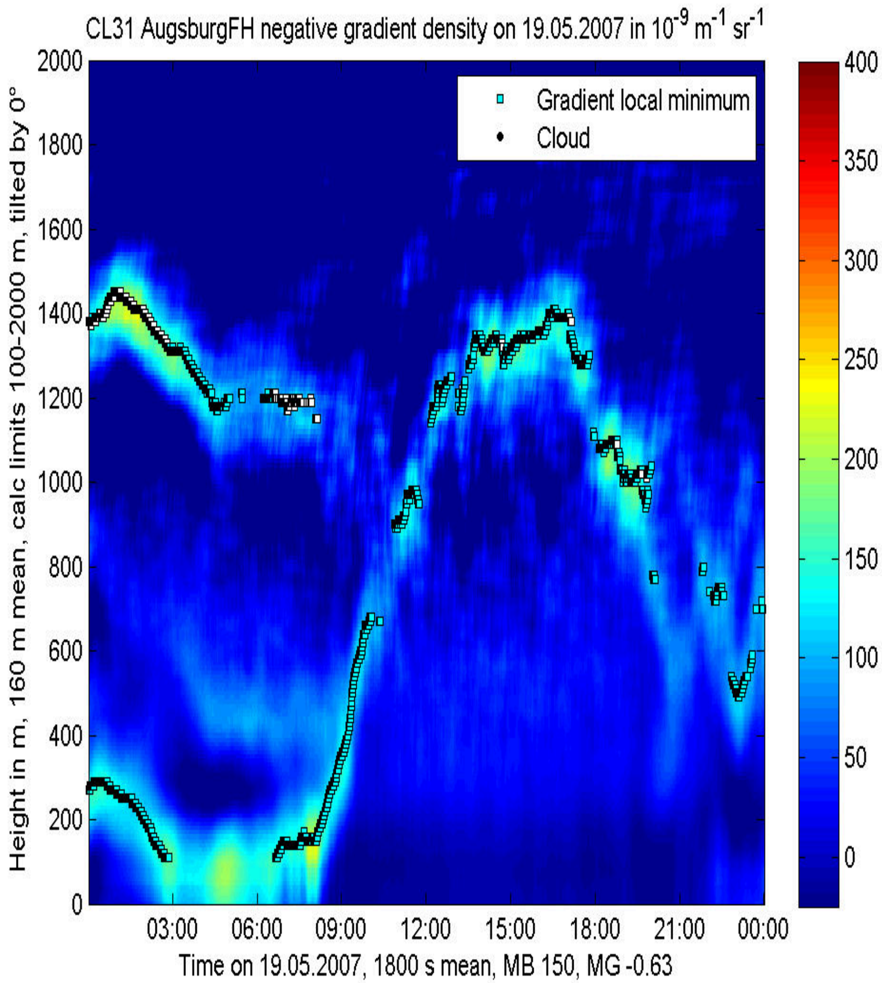
For a ceilometer β_m is negligible and only β_p is important

ceilometer sample plot (daytime convective BL)

optical backscatter intensity



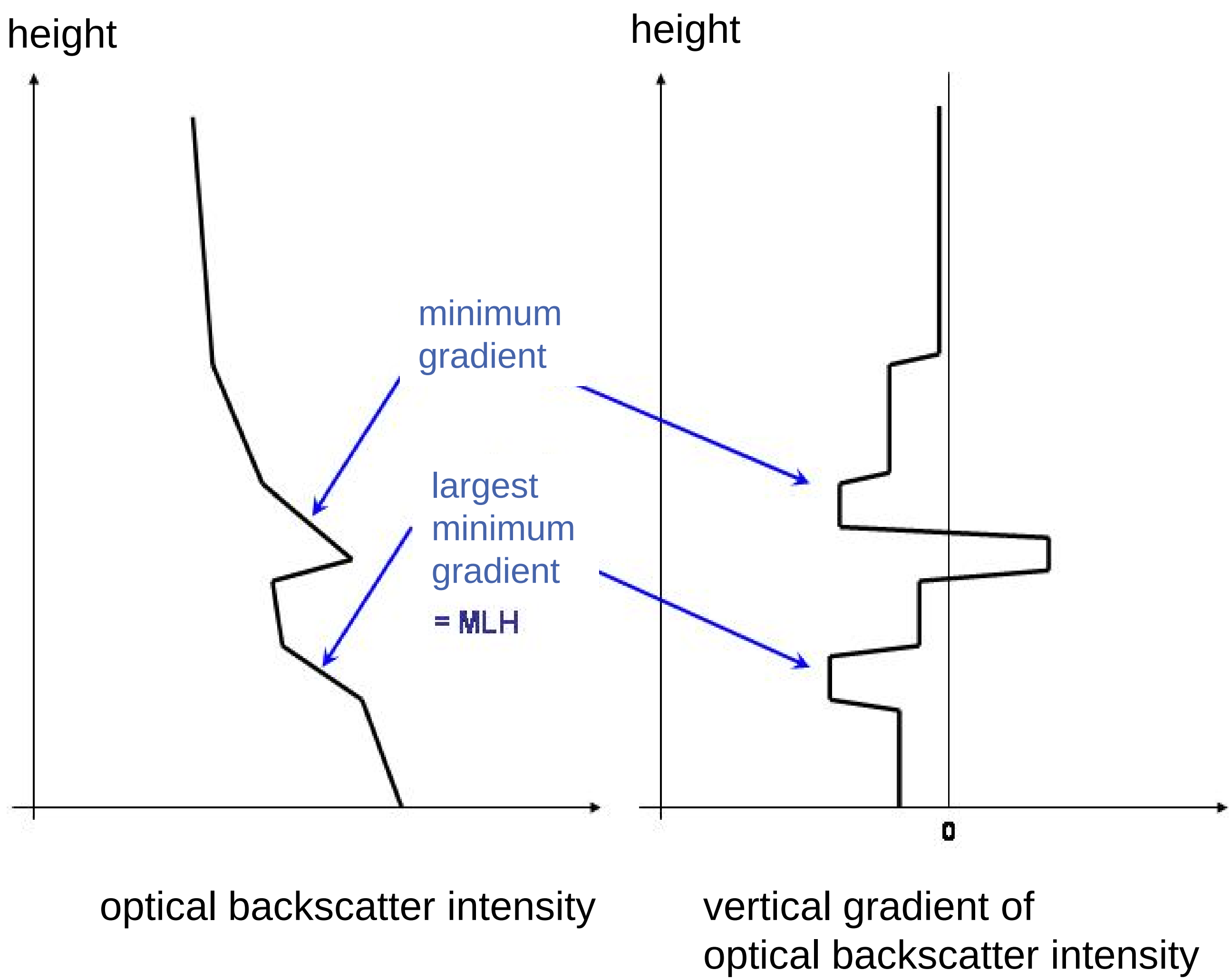
negative vertical gradient of optical backscatter intensity



Algorithm to detect MLH from Ceilometer-Daten

criterion

minimal vertical gradient of backscatter intensity (the most negative gradient)

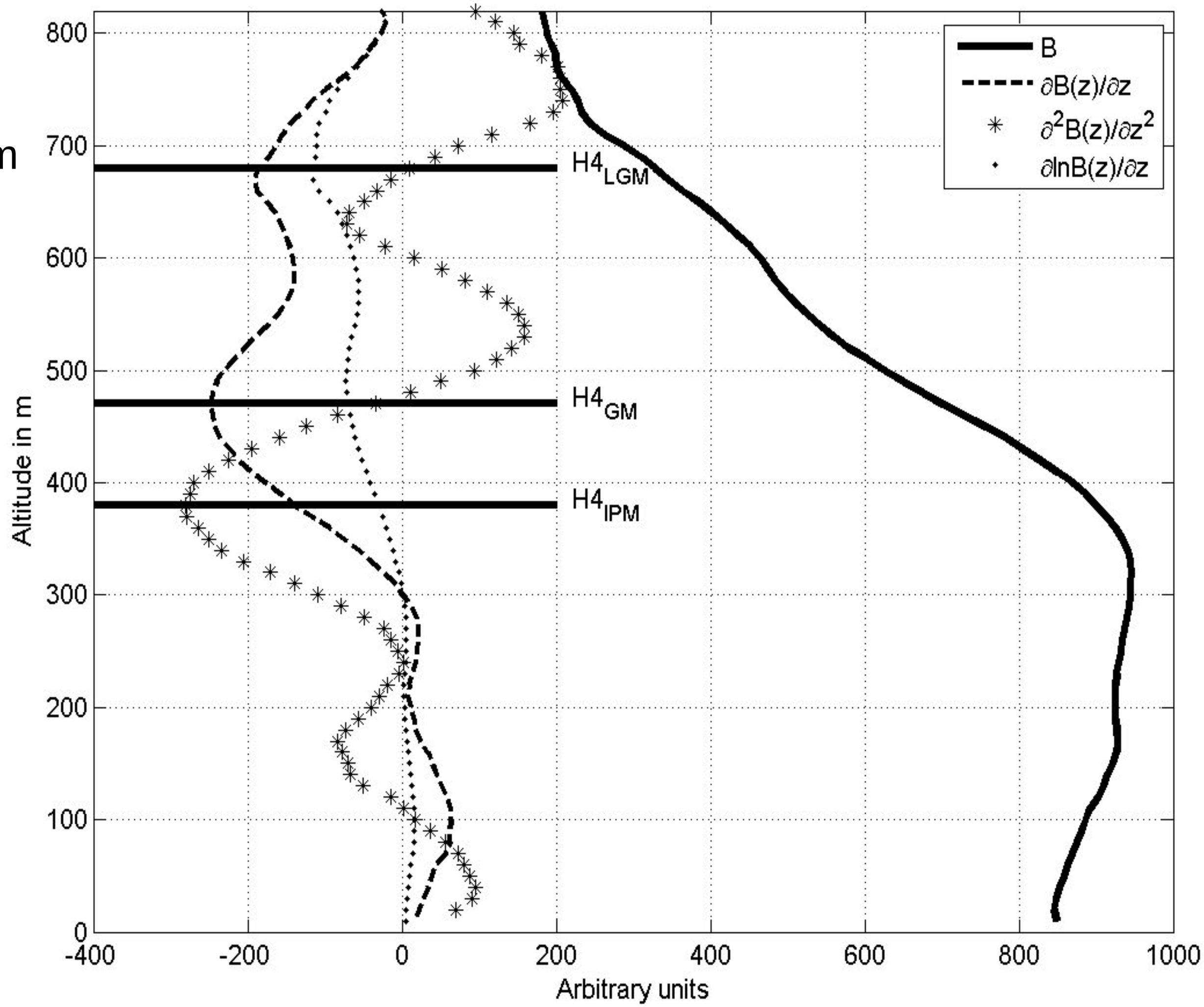


Different gradient methods (see Sicard et al. 2006, BLM 119, 135-157)

logarithmic gradient minimum

gradient minimum

inflection point method (minimum of 2nd derivative)



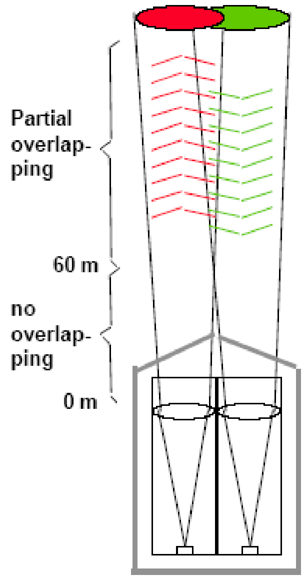
comparison of two different ceilometers

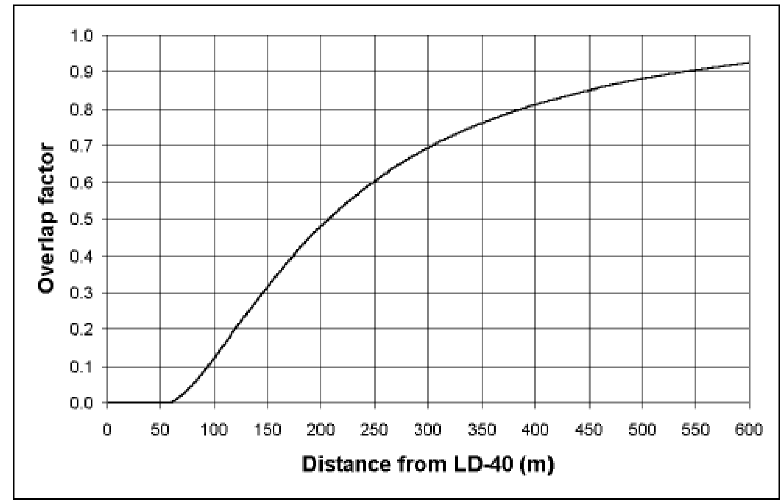
LD40

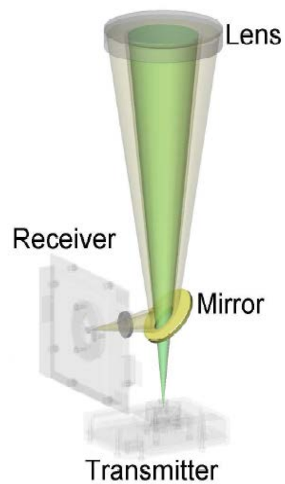
two optical axes
- wave length: 855 nm
- height resolution: 7.5 m
- max. range: 13000 m

CL31 / CL51

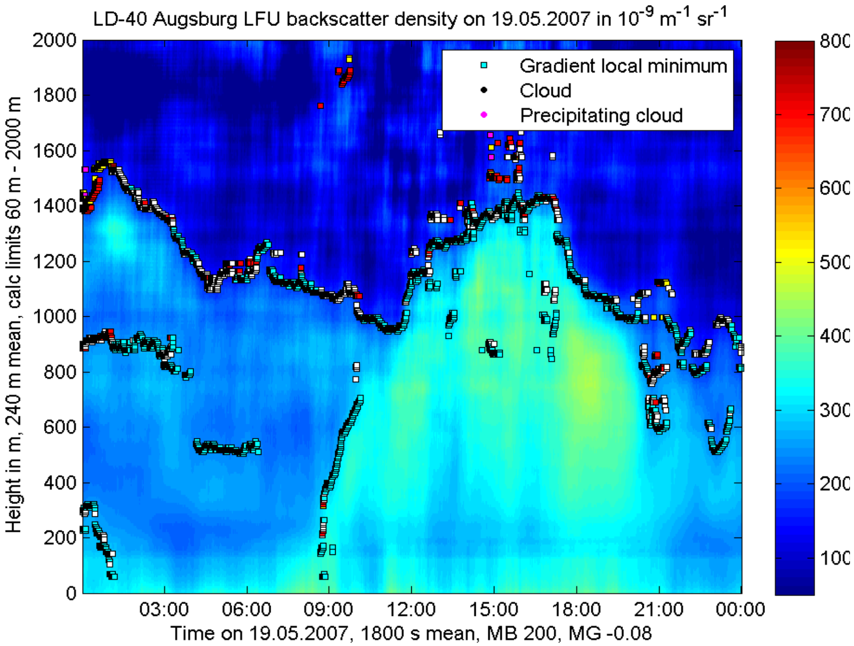
one optical axis
- wave length: 905 nm
- height resolution: 5 m
- max. range: 7500 m

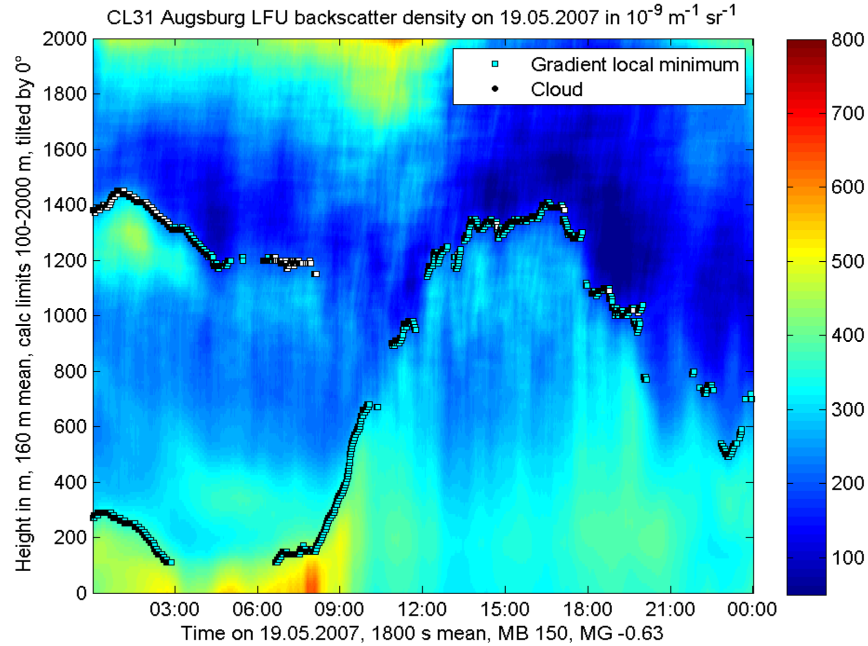


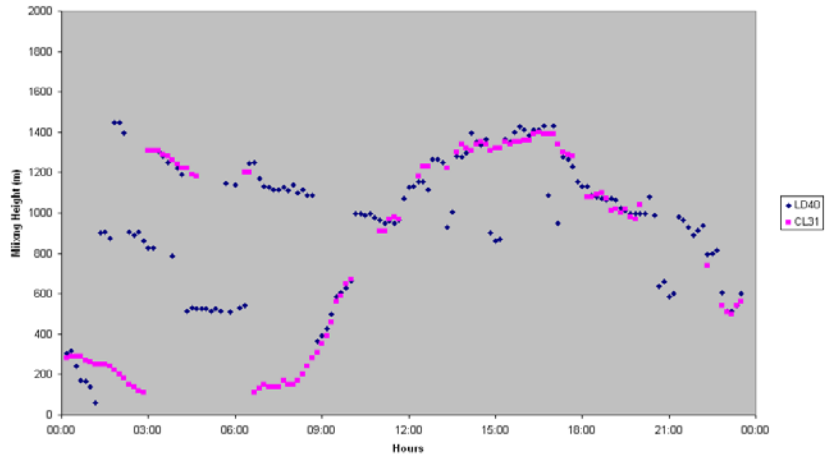




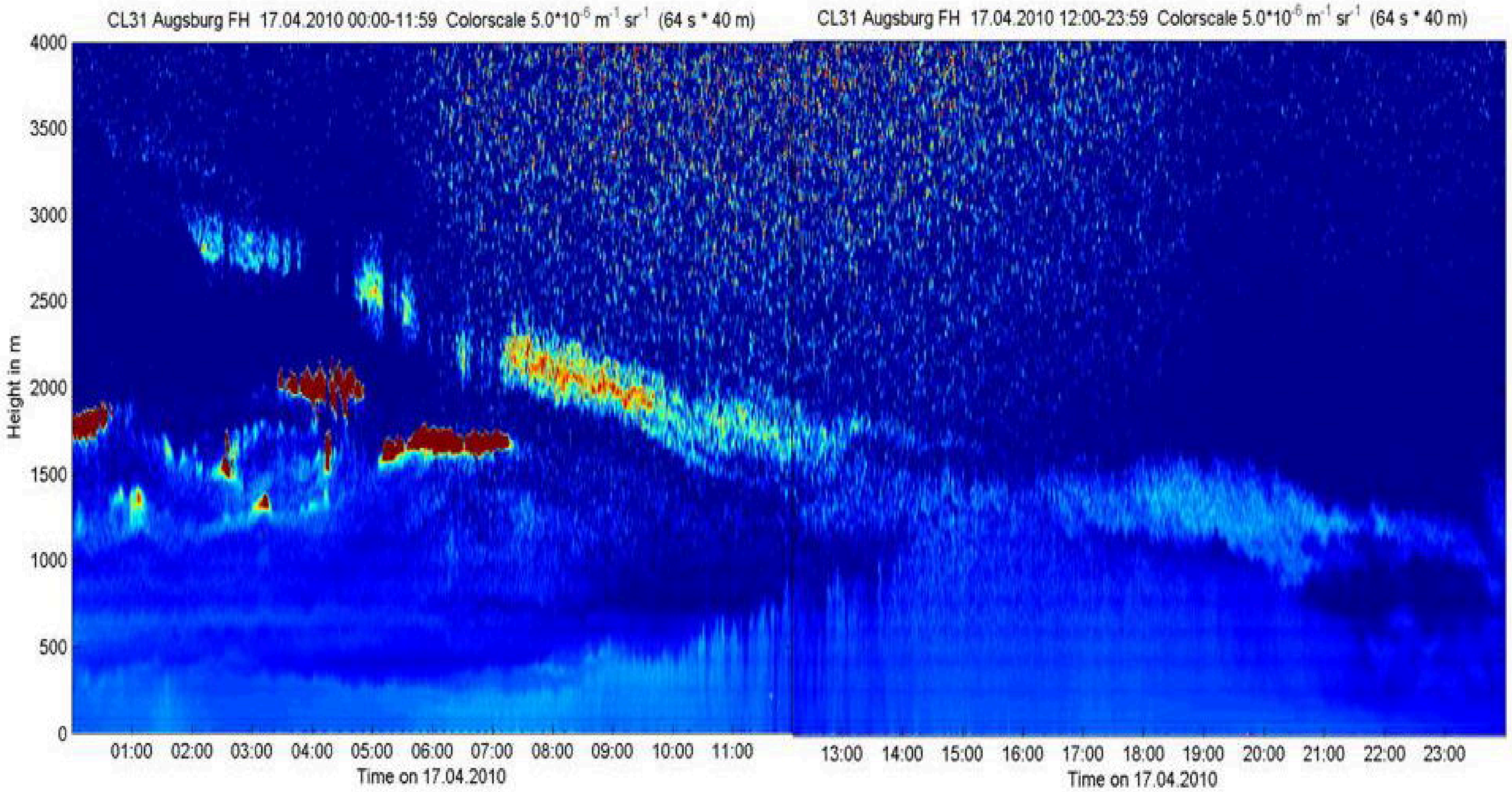
comparison of LD40 and CL31







Eyjafjallajökull ash cloud over Southern Germany



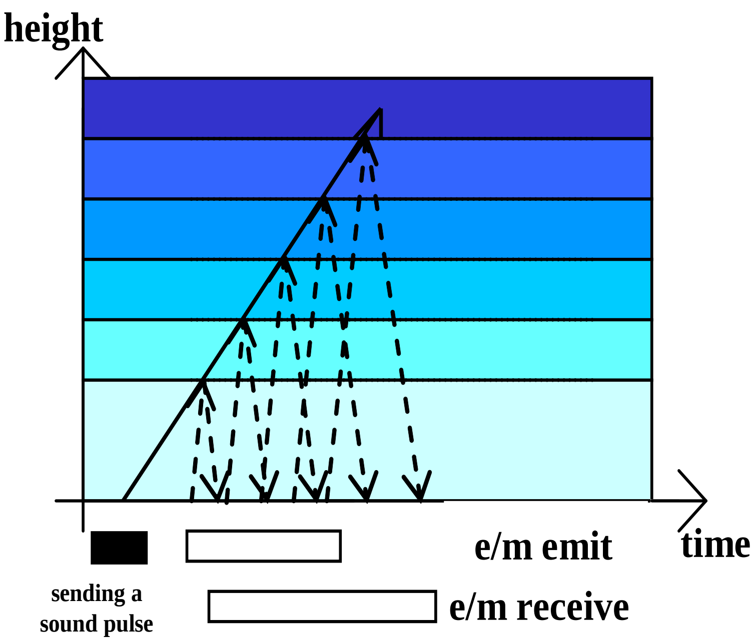
read more: Emeis, S., R. Forkel, W. Junkermann, K. Schäfer, H. Flentje, S. Gilge, W. Fricke, M. Wiegner, V. Freudenthaler, S. Groß, L. Ries, F. Meinhardt, W. Birmili, C. Münkel, F. Obleitner, P. Suppan, 2011: Measurement and simulation of the 16/17 April 2010 Eyjafjallajökull volcanic ash layer dispersion in the northern Alpine region. Atmos. Chem. Phys., 11, 2689–2701

RASS

principles of operation

examples

RASS measuring principle



detection:

travel time of em./ac. signal	= height	
ac. backscatter intensity	= turbulence	(identical to SODAR)
ac. Doppler-shift	= line-of-sight wind speed	(identical to SODAR)
em. Doppler shift	= sound speed ➔ temperature	

RASS (radio-acoustic remote sensing)

measures vertical temperature profiles

Bragg-RASS: windprofiler plus acoustic component

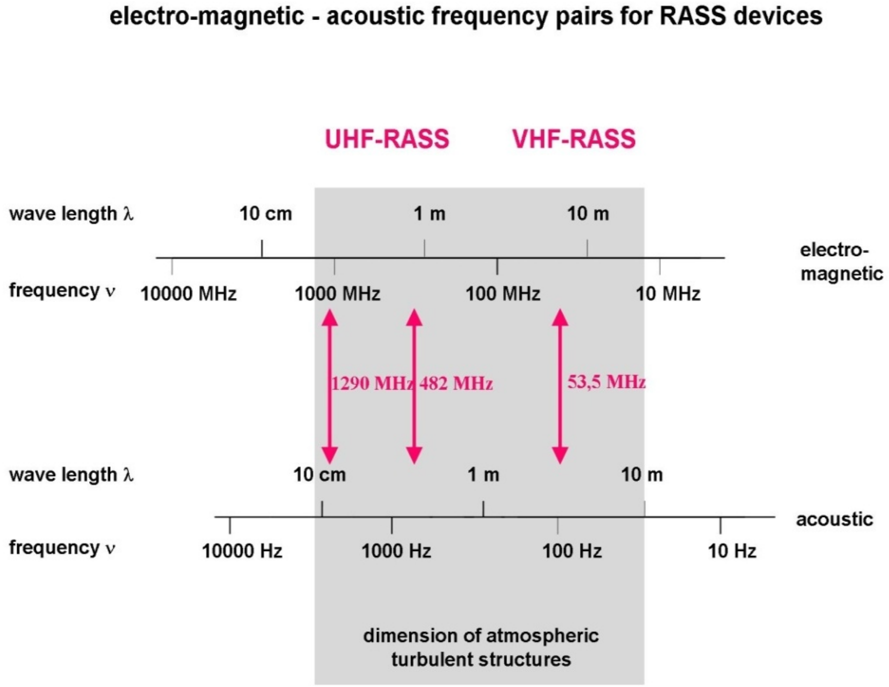
Doppler-RASS: SODAR plus electro-magnetic component

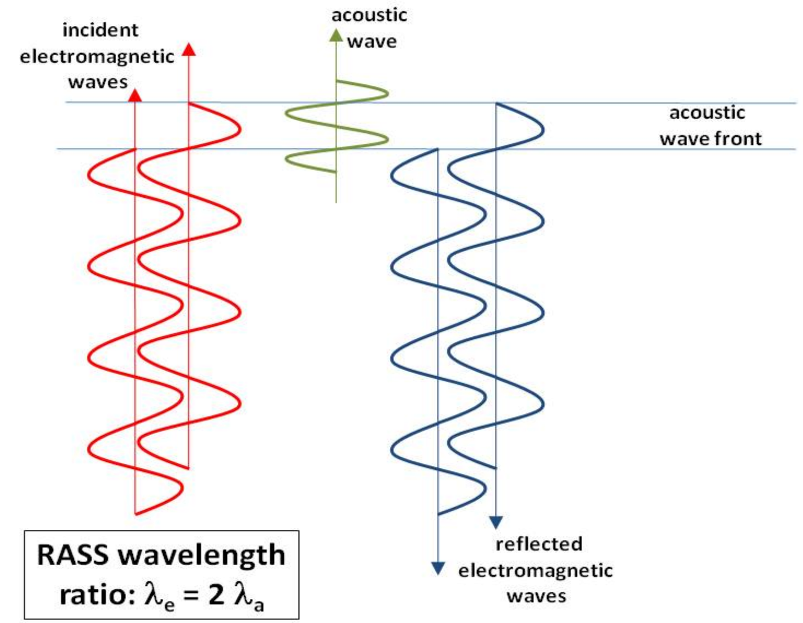
UHF RASS (boundary layer)

VHF RASS (troposphere)

RASS: frequencies

Bragg condition:
acoustic wavelength = ½ electro-magnetic wavelength





Emeis, S., 2010: Measurement Methods in Atmospheric Sciences - In situ and remote. Borntraeger, Stuttgart, 272 pp., 103 figs, 28 tables, ISBN 978-3-443-01066-9.

SODAR-RASS (Doppler-RASS) (METEK)

acoustic frequ.: 1077 Hz
radio frequ.: 474 MHz
resolution: 20 m
lowest
range gate: ca. 40 m

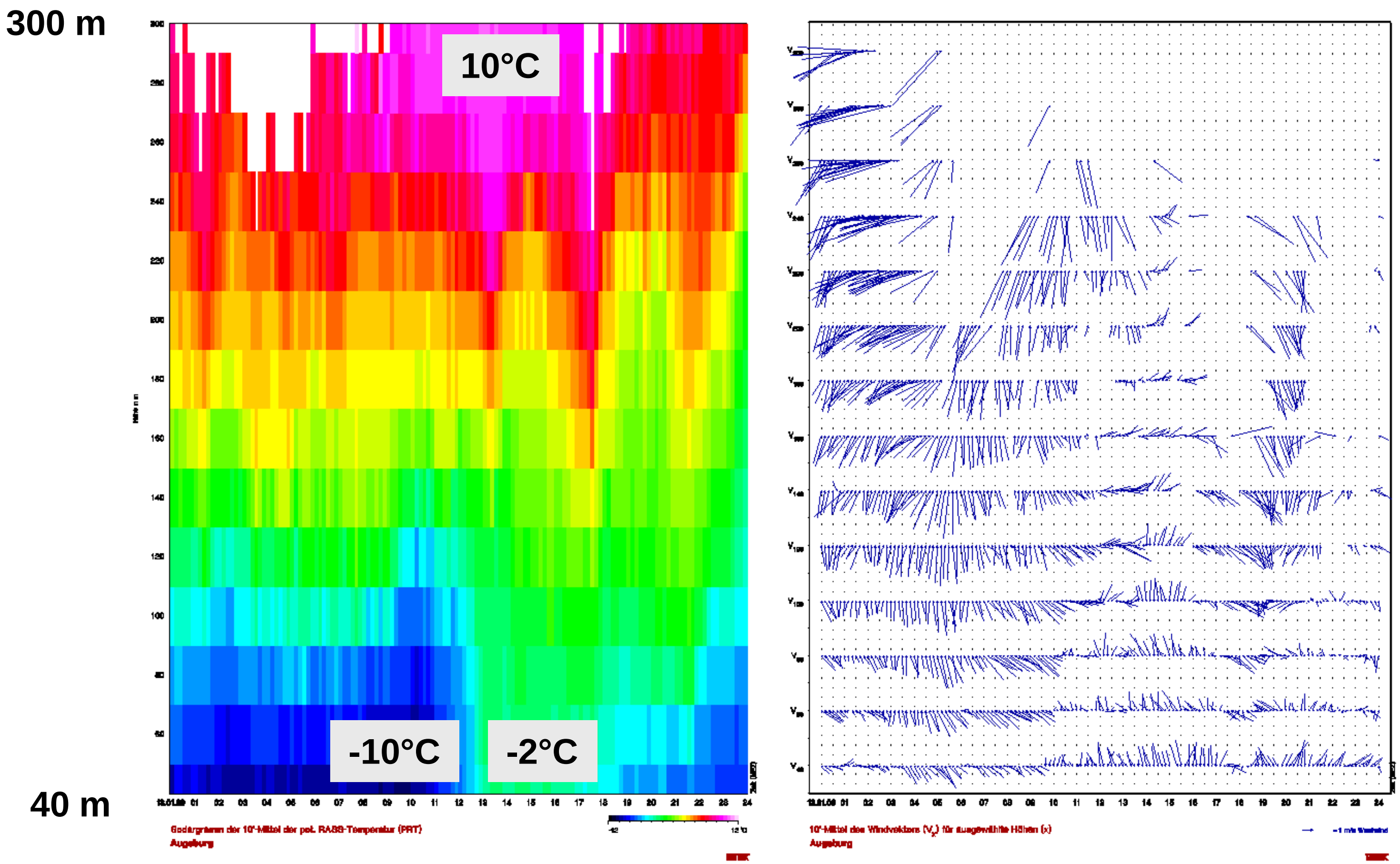
vertical range: 540 m

Bragg-RASS

acoustic frequ.: about 3000 Hz
radio frequ.: 1290 MHz
resolution: 50 m
lowest
range gate: ca. 200 m

vertical range: 1000 m

example RASS data: winter day
potential temperature (left), horizontal wind (right)



Critical Richardson number is limiting condition for vertical shear

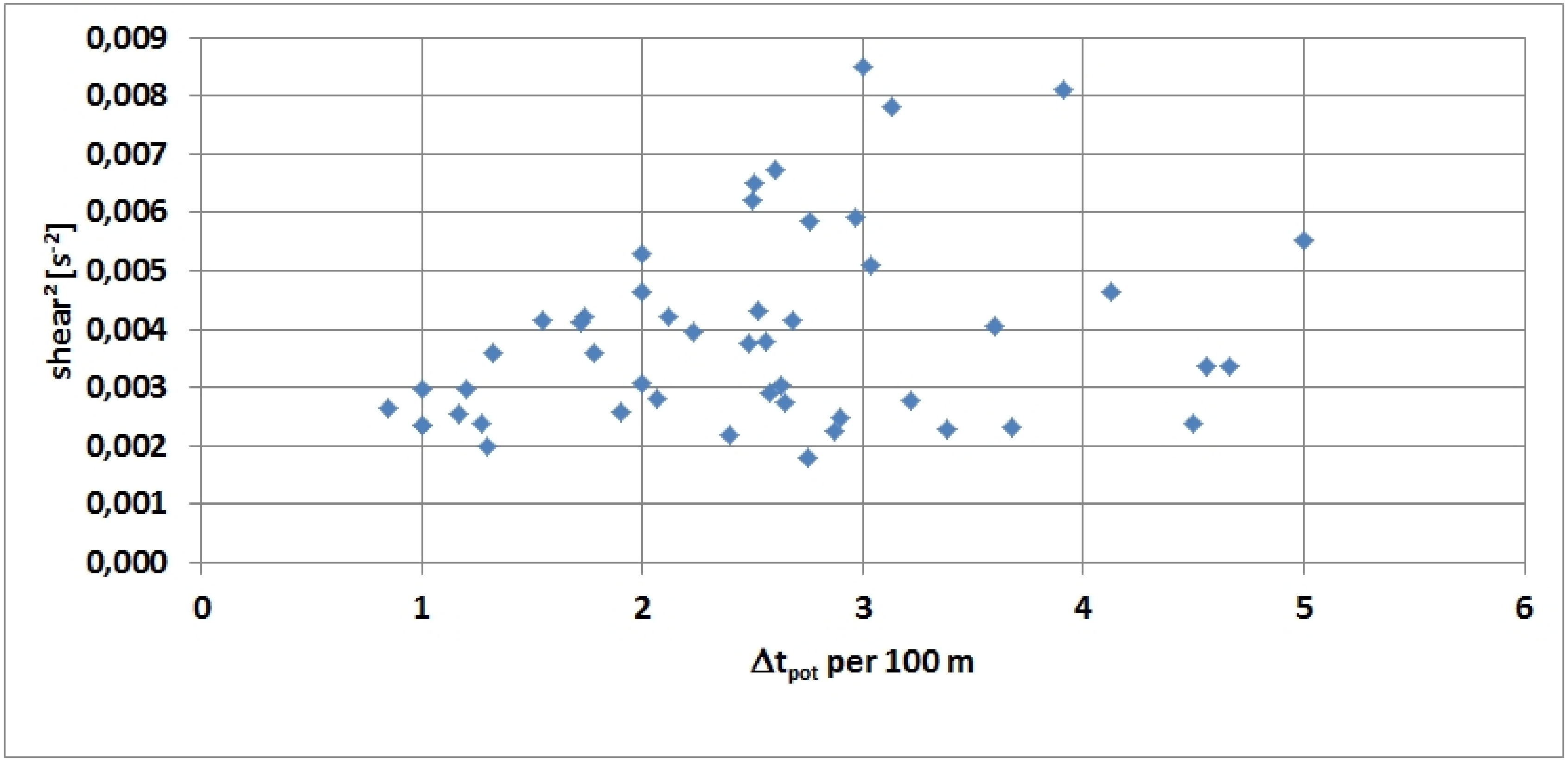
(mechanical turbulence is generated if Ri falls below Ri_{krit})

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

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

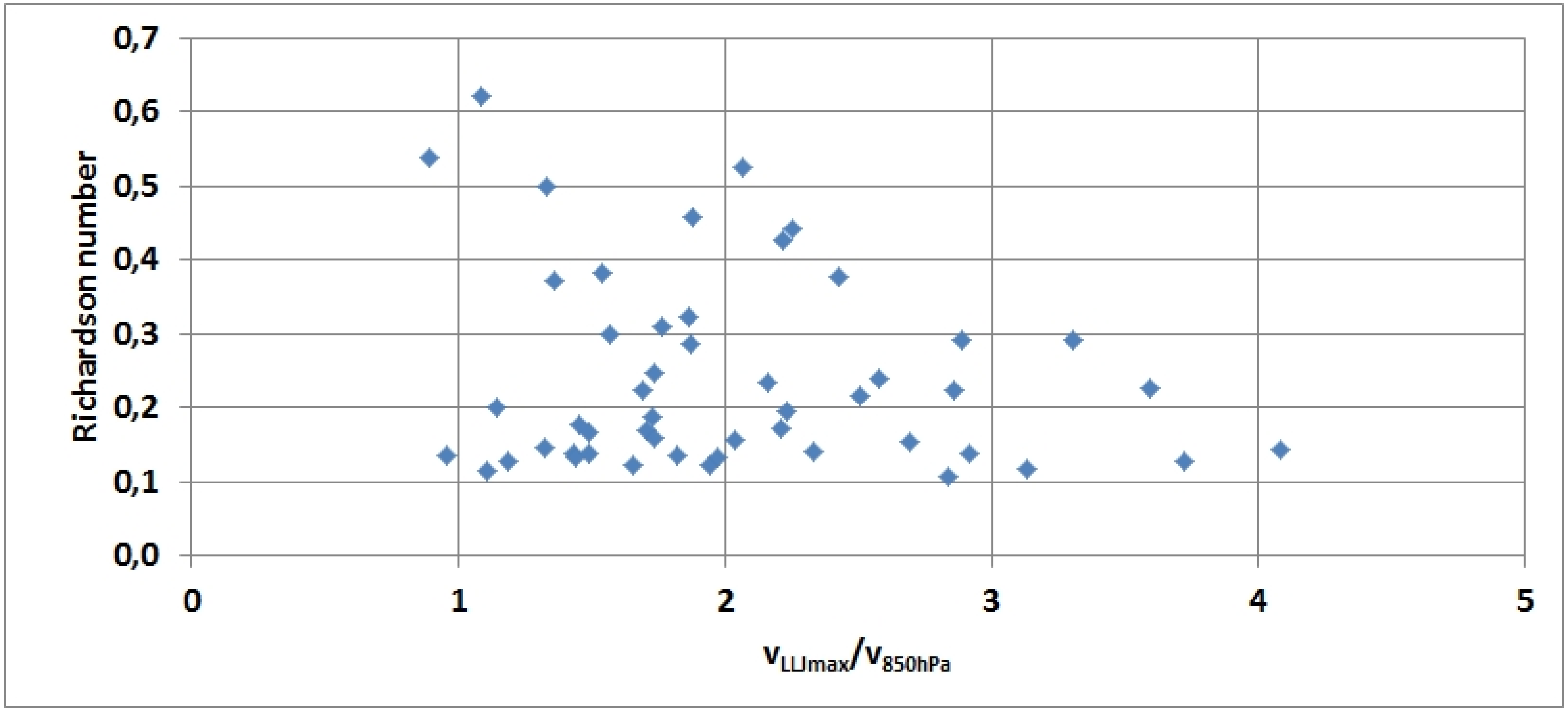
RASS observations Augsburg

correlation between shear and temperature gradient



RASS observations Augsburg

Richardson number during LLJ events



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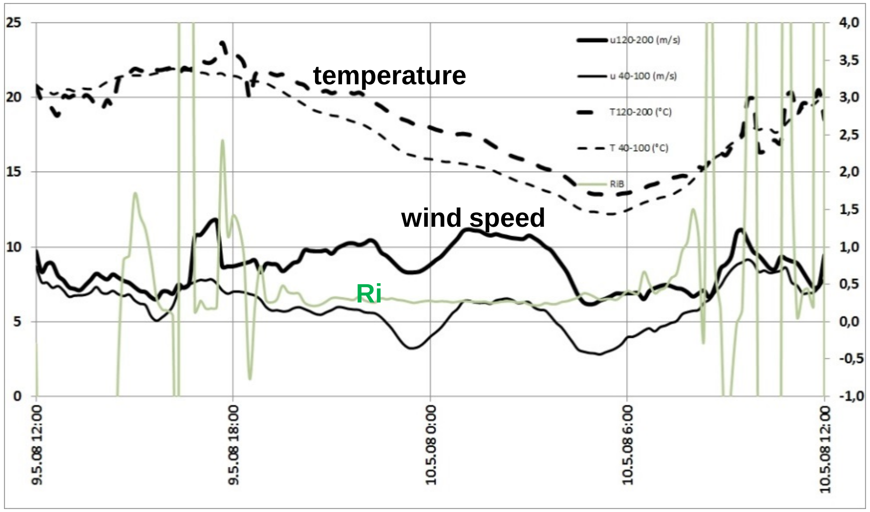
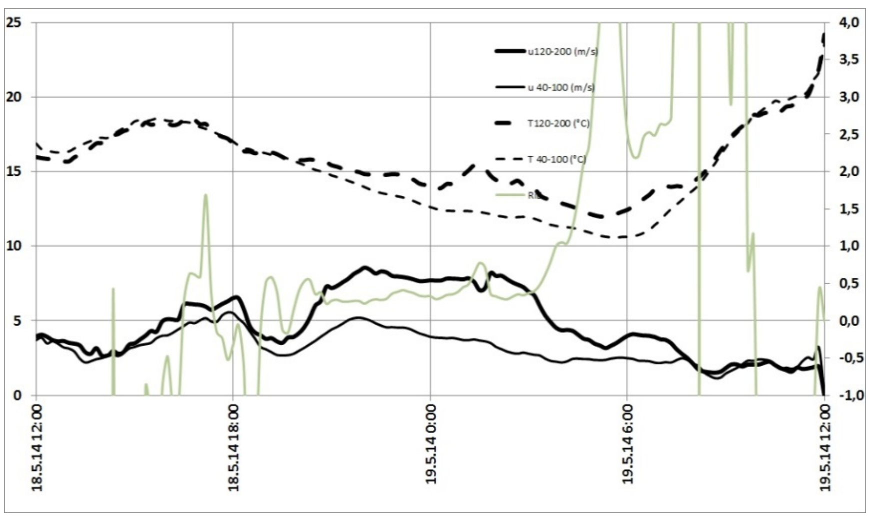
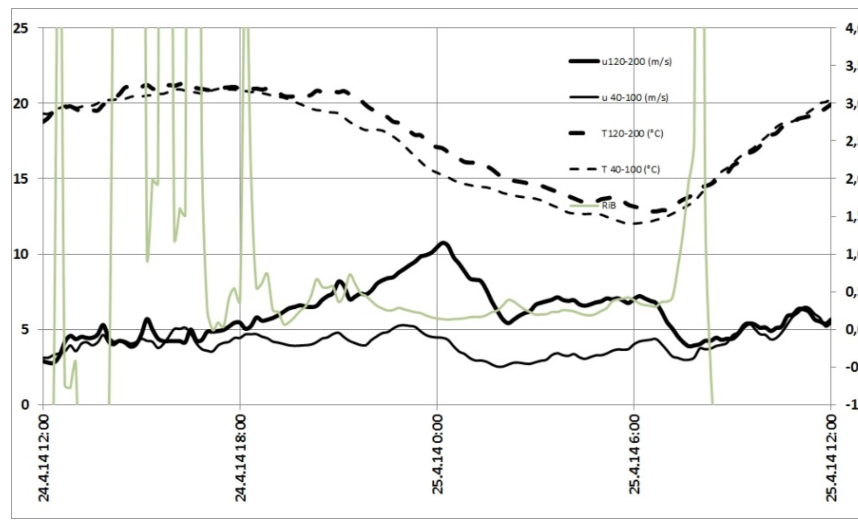
RASS observations Augsburg

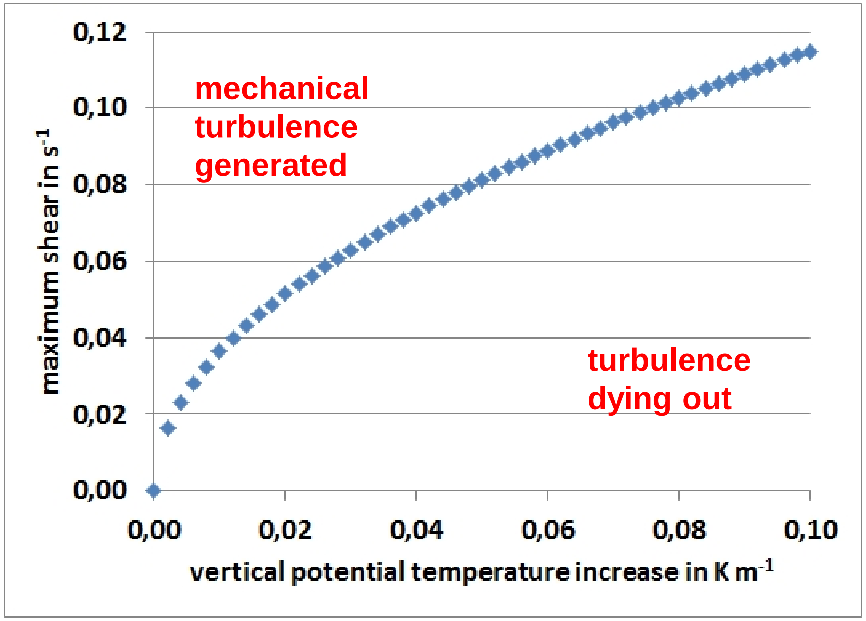
critical Richardson Number between 40 and 200 m above ground as limiting value for nocturnal LLJ







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

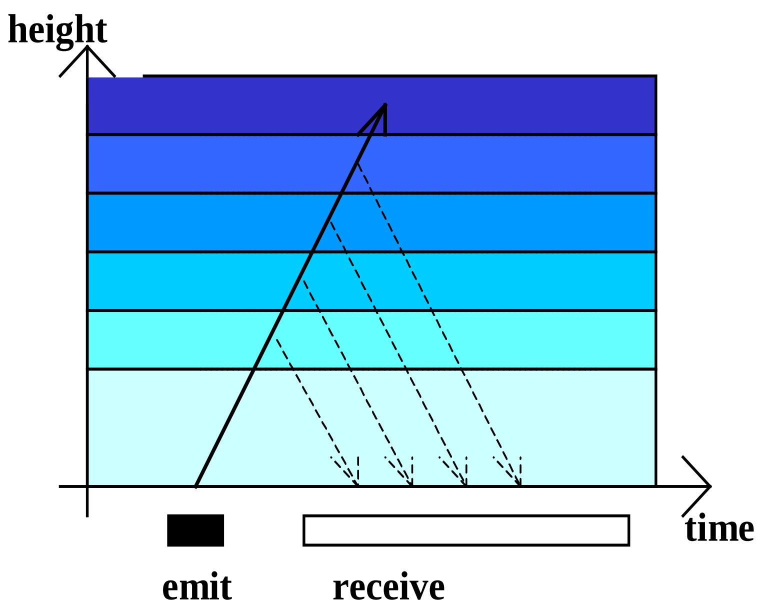


$$Ri_{krit} = \frac{g \partial \Theta / \partial z}{\Theta (\partial u / \partial z)^2} \approx 0.25$$

Doppler windlidar

wind, turbulence, aerosol detection, mixing-layer height, low-level jet

Doppler windlidar measuring principle

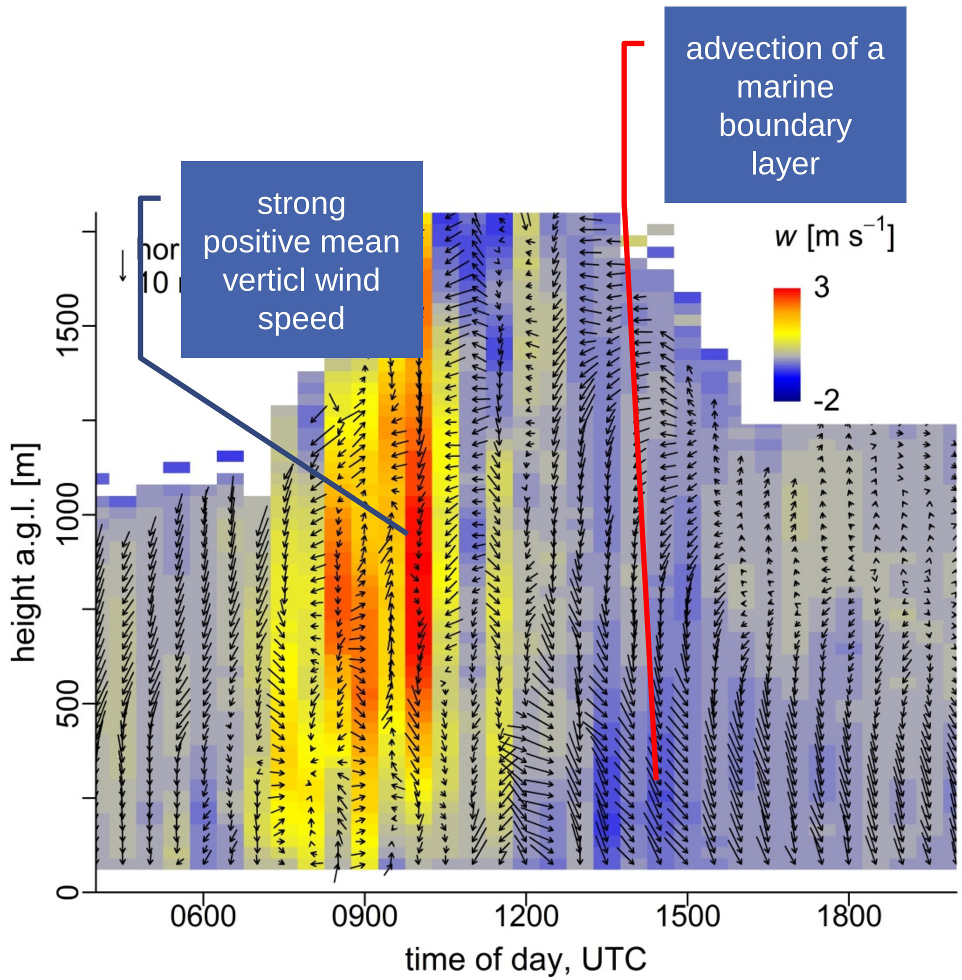


detection:

travel time of signal = height
backscatter intensity = particle size and number distribution
depolarisation = particle shape
Doppler-shift = wind speed in the line of sight

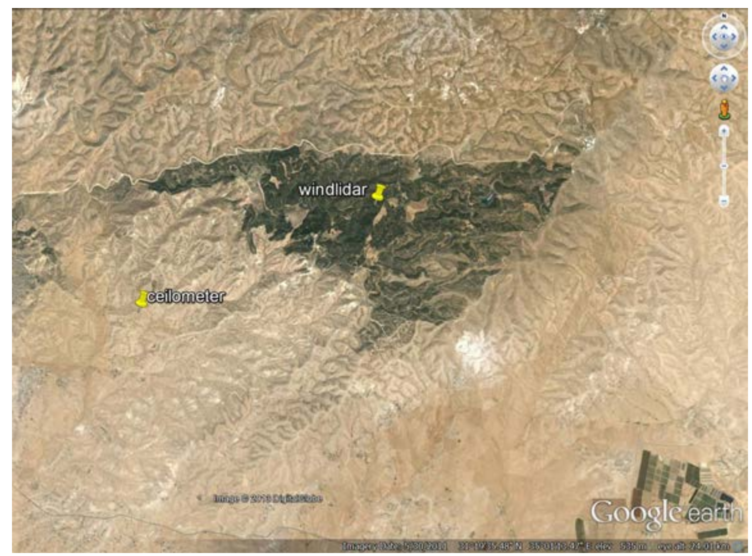
mobile Doppler windlidar from Halo Photonics

Yatir Forest, Israel



(Eder and Mauder, IMK-IFU (KIT), personal communication)

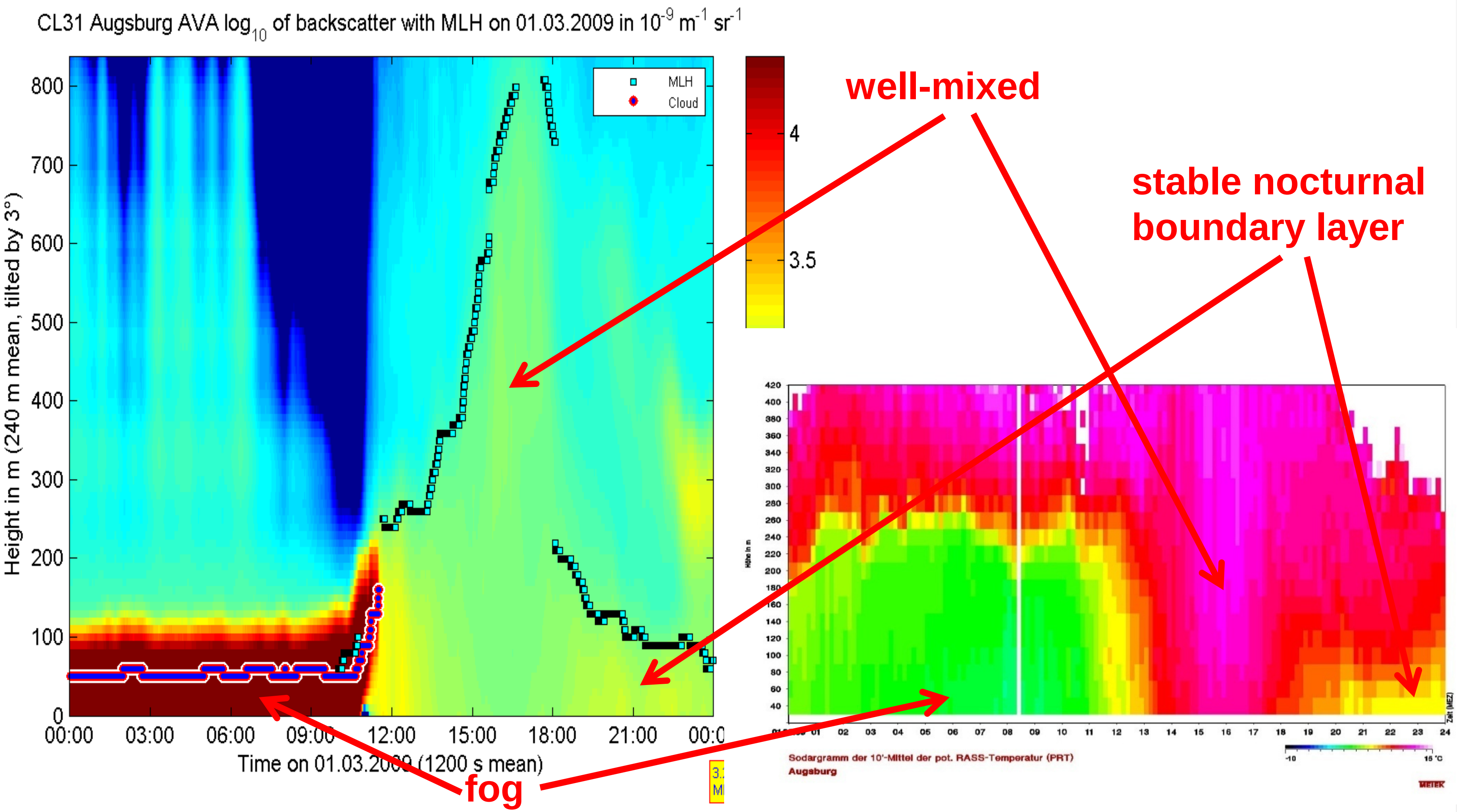
The 3-d wind field above the Yatir forest on 10 Sept 2013.
The colour indicates the vertical wind component.
The white arrows indicate the horizontal wind component:
the direction of the arrow shows the wind direction,
the length of the arrow shows the wind speed.
During the afternoon hours,
there is a 180°-shift in wind direction between surface
and boundary-layer top which indicates a stationary circulation.
Please note that this picture is not shown in local time,
but in UTC (i.e. 12:00 means 14:00 Israel winter time)



Comparisons between different instruments

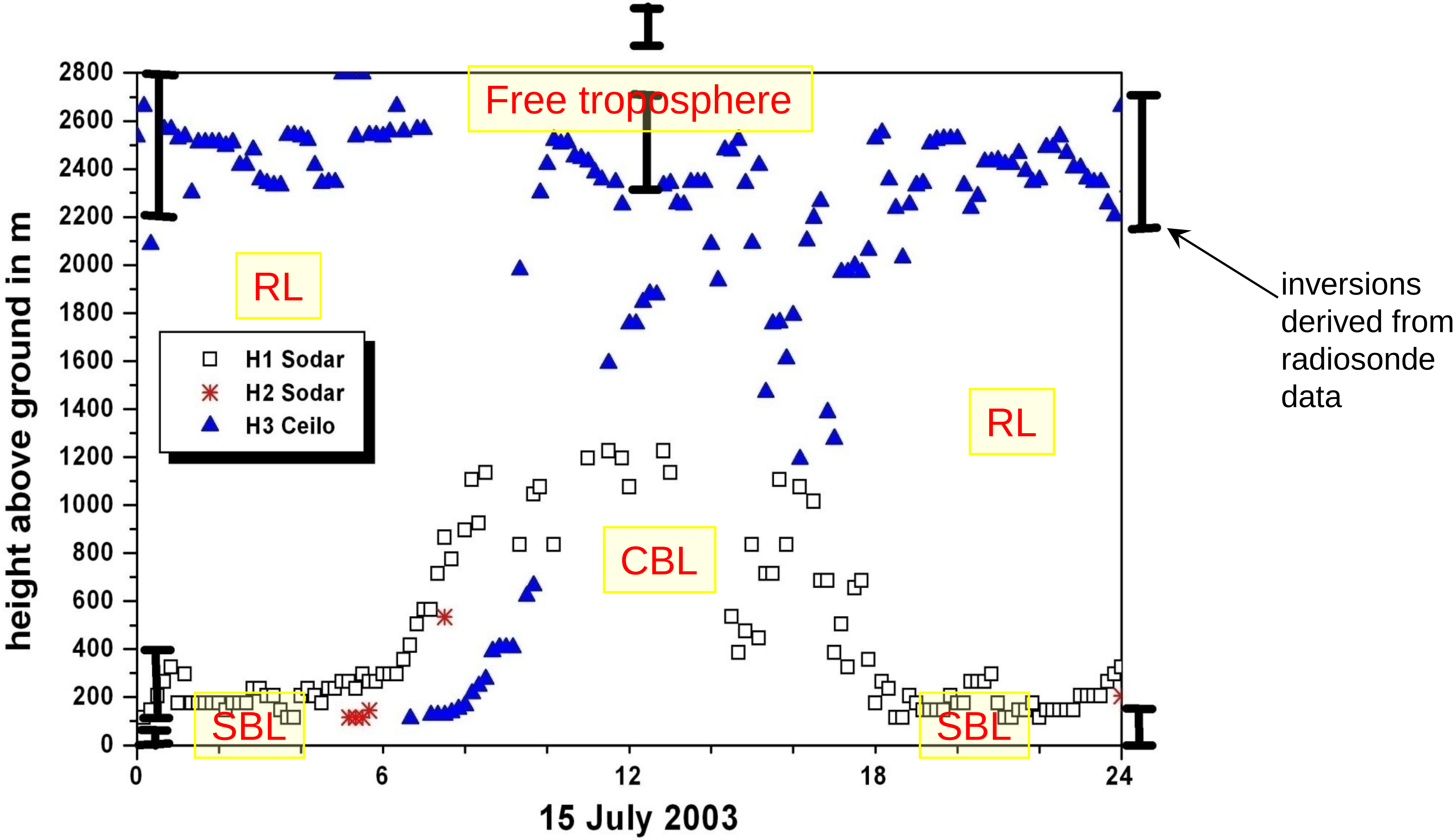
temperature profile and aerosol backscatter

comparison of RASS data (potential temperature, right) with aerosol backscatter from a ceilometer (left)



Institute for Meteorology and Climate Research – Atmospheric Environmental Research

Differences in MLH detection from SODAR and Ceilometer data taken in Budapest



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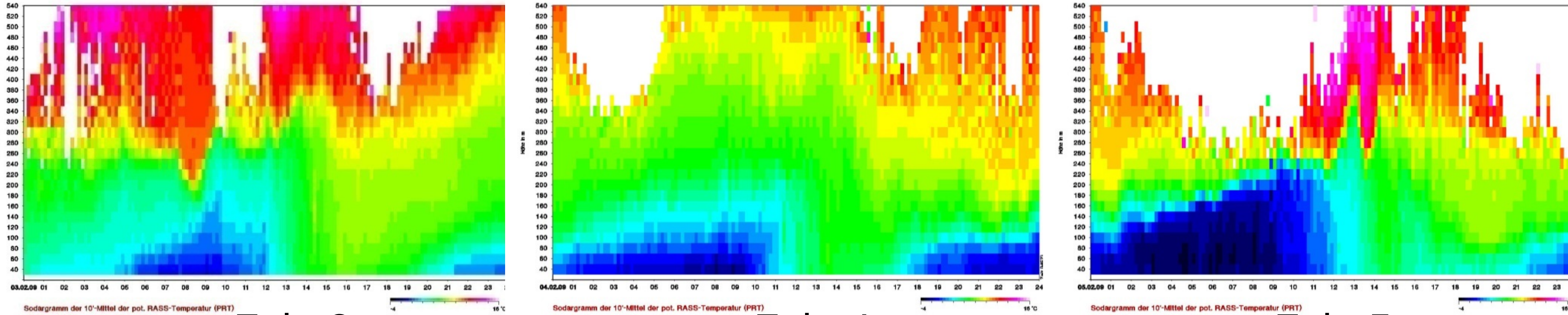
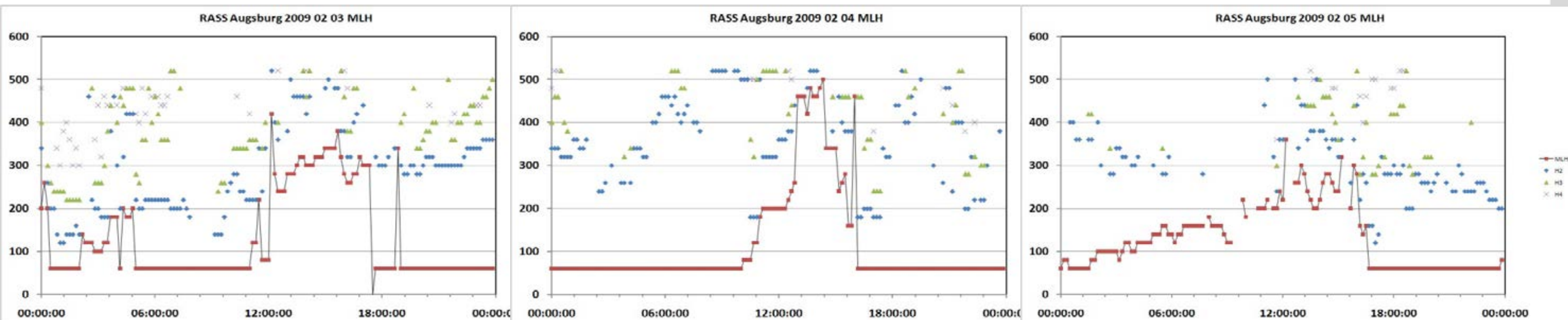
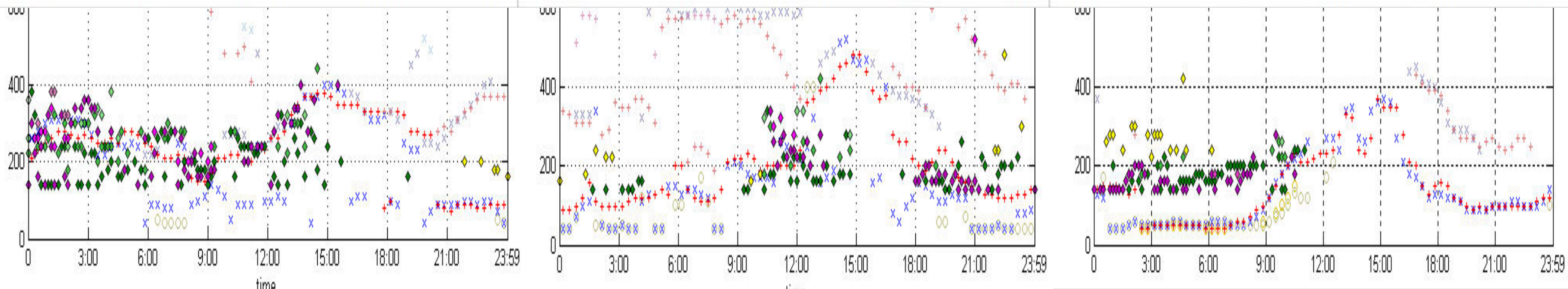
RASS data Augsburg February 2009

potential temperature (top), MLH RASS (middle), MHL SODAR/Ceilo (bottom)



Feb. 3 | Feb. 4 | Feb. 5





Summary

Clicker question:

Which instrument is best?

A sodar

B ceilometer

C wind lidar

D RASS

E don’t know

quality criteria:

data availability

vertical range

direct/indirect detection

Doppler analysis

☺☺☺💣 **RASS delivers temperature profiles, wind profiles are additionally available.**
MLH directly from temperature profiles. LLJ from wind profiles.
Does not work properly under high wind speeds. Restricted range.

☺☺☺💣 **wind lidar detects wind profiles, aerosol distribution and water droplets. It has to be assumed that the aerosol follows the thermal structure of the atmosphere and the wind.**
MLH from aerosol backscatter, wind speed variance, LLJ from wind profiles.
Does not work properly in extreme clear (aerosol-free) air and during precipitation events and fog.

☺☺💣💣 **Ceilometer detects aerosol distribution and water droplets. It has to be assumed that the aerosol follows the thermal structure of the atmosphere.**
MLH indirectly from aerosol backscatter using a MLH algorithm.
Does not work properly in extreme clear (aerosol-free) air and during precipitation events and fog.

☺💣💣💣 **SODAR detects wind profiles, temperature fluctuations and gradients, but no absolute temperature.**
MLH indirectly from acoustic backscatter (MLH algorithm). LLJ from wind profiles.
Does not work properly under perfectly neutral stratification, with very high wind speeds, and during stronger precipitation events. Restricted range.

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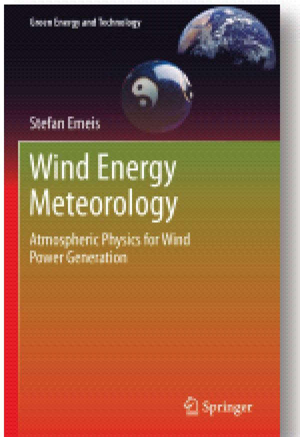
Thank you very much for your attention



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

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

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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.