What determines the nocturnal vertical wind gradient?

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or, more generally:

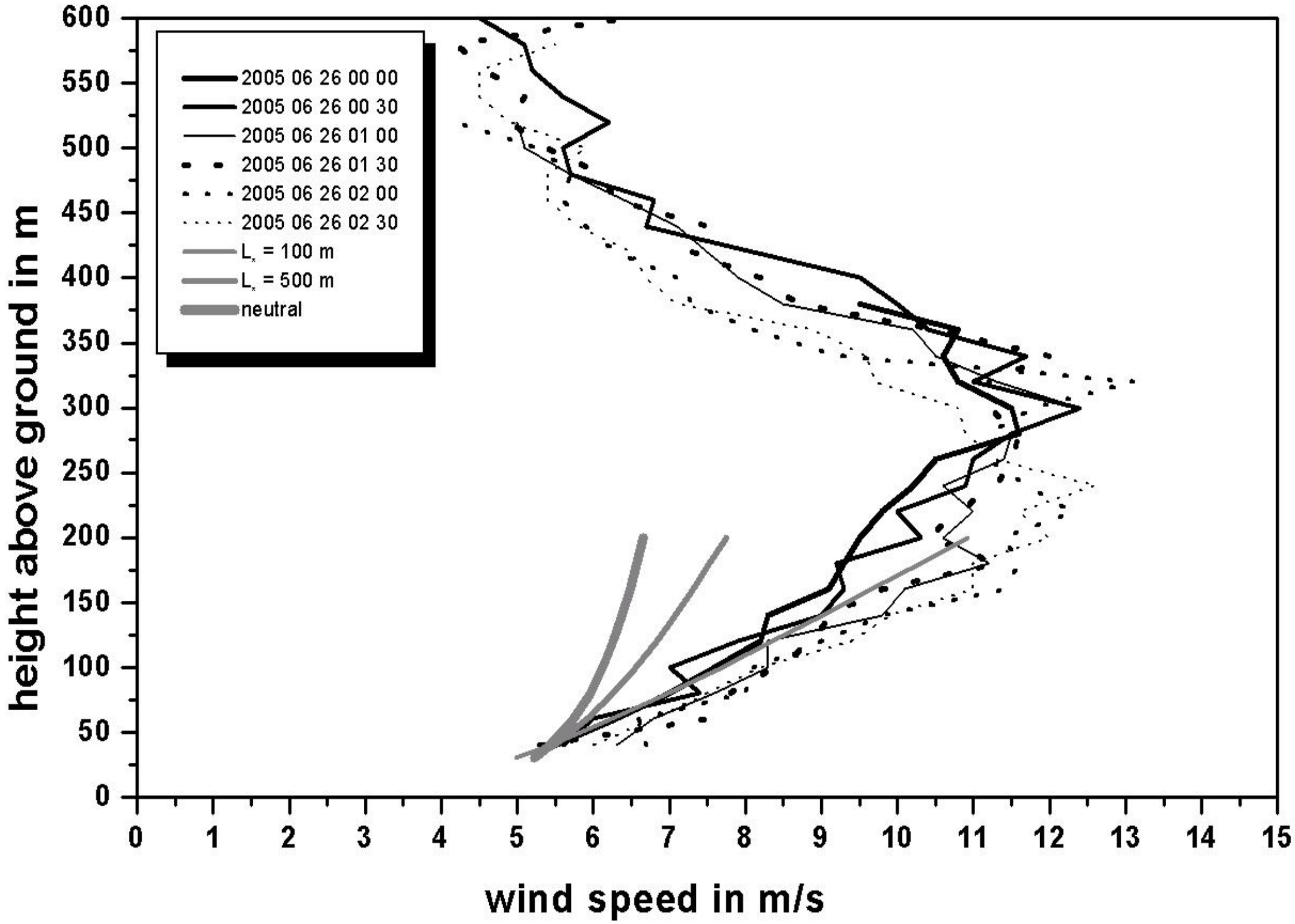
What determines the maximum shear in stably stratified boundary layers?

onshore nocturnal low-level jet

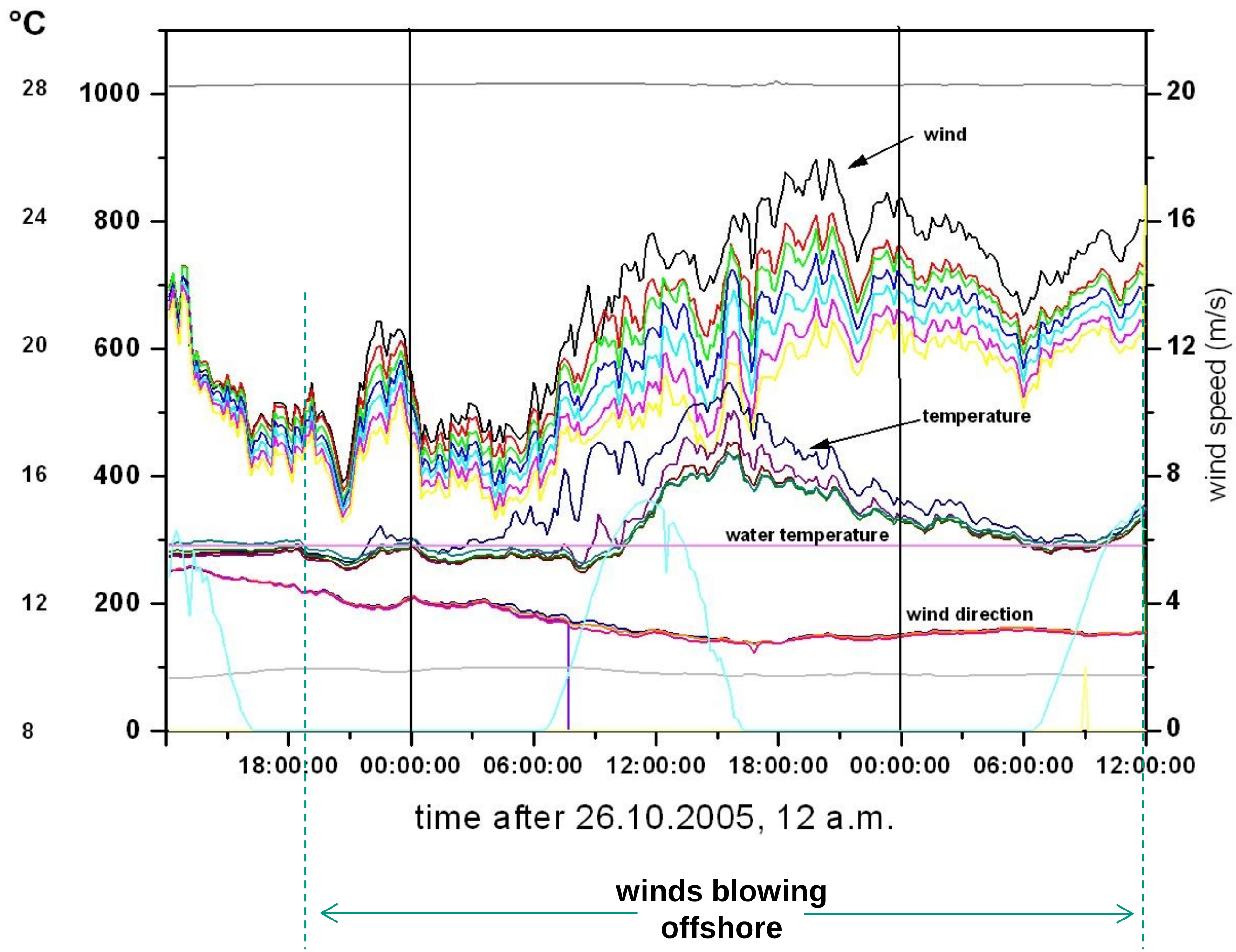
vertical wind profiles

26 June 2005

AdP Ch d G

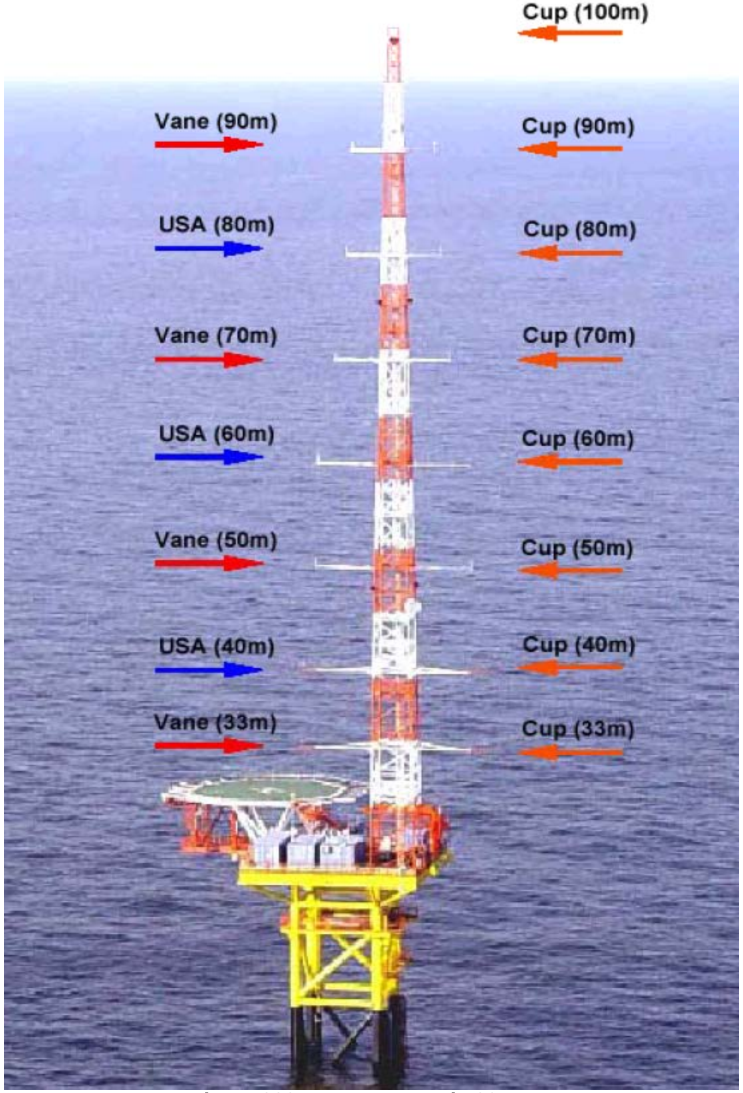


offshore wind shear depending on difference ‘SST – air temperature’



RASS

SODAR plus electro-magnetic antennas



FINO 1

offshore met mast off the German North Sea coast

Neumann, T., K. Nolopp, 2007: DEWI-Magazin 30,
http://www.dewi.de/dewi_res/fileadmin/pdf/publications/Magazin_30/08.pdf

inland
low-level jets

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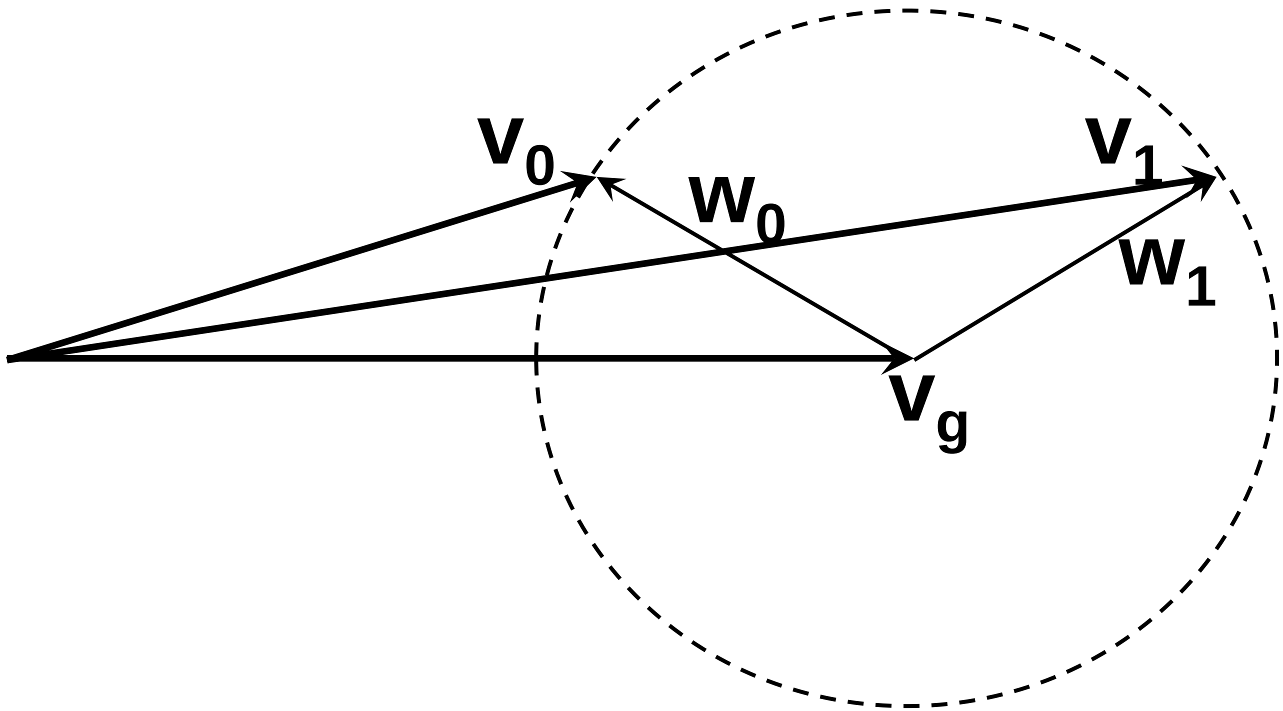
low-level jet as inertial oscillation (Blackadar 1957)



$$w = v_g - v$$

low-level jet as inertial oscillation (Blackadar 1957)

the consequences were:

maximum wind speed within LLJ between 1 v_g and 2 v_g

turning of wind direction during night

is this observed?

SODAR (RASS) readings from Hannover and Augsburg (Germany)

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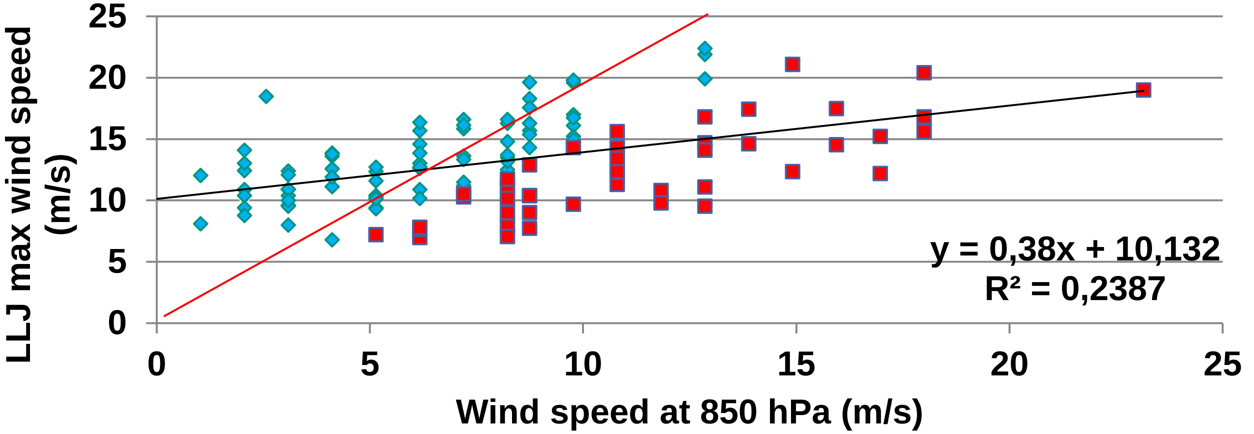
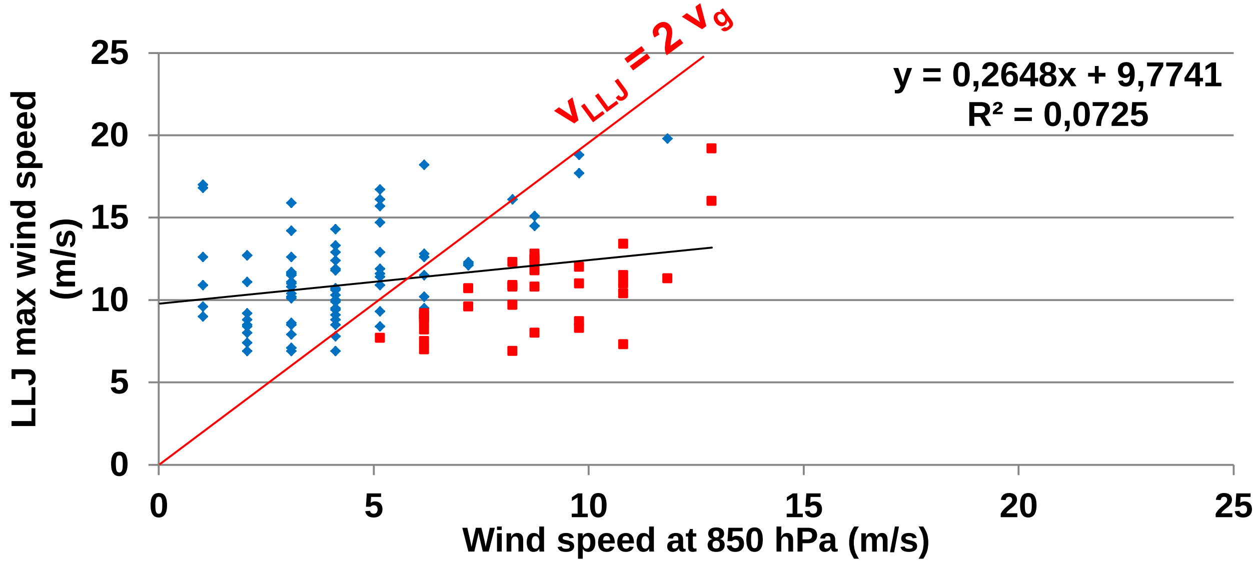
maximum LLJ wind speed and driving pressure gradient (blue symbols: LLJ wind speed more than 1.5 times 850 hPa wind speed)



Hannover, Germany (North)



Augsburg, Germany (South)

gradient Richardson number

$$Ri = \frac{g \partial \Theta / \partial z}{\Theta (\partial u / \partial z)^2}$$

Θ (z)	potential temperature
g	gravity
u (z)	wind speed
z	vertical co-ordinate

critical Richardson numbers

turbulent ➔ laminar: turbulence is suppressed for $Ri > Ri_{krit\_1}$ (about 0.25)

laminar ➔ turbulent: mechanical turbulence is produced, if $Ri < Ri_{krit\_2}$

usually $Ri_{krit\_2} < Ri_{krit\_1}$ hysteresis

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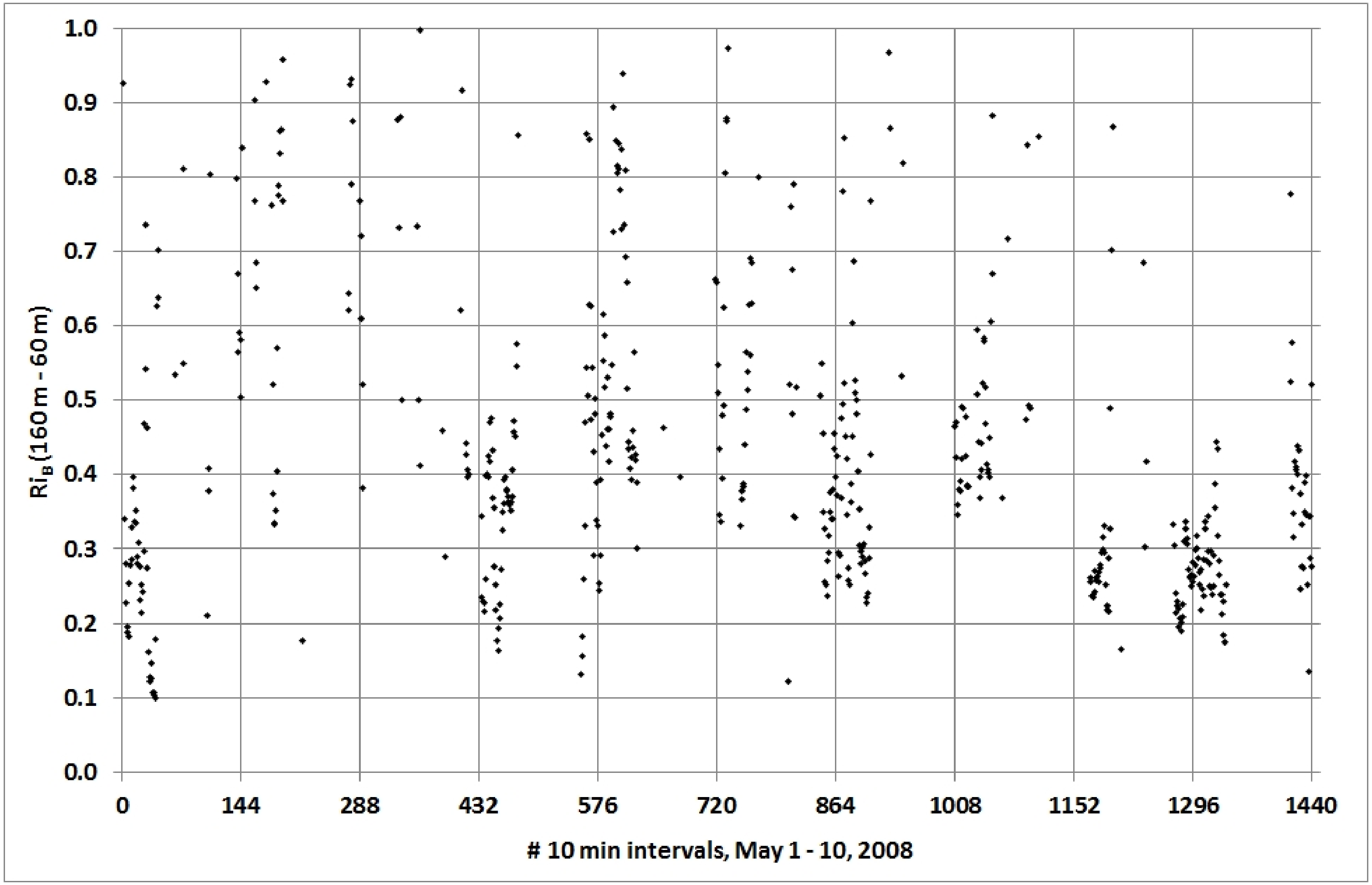
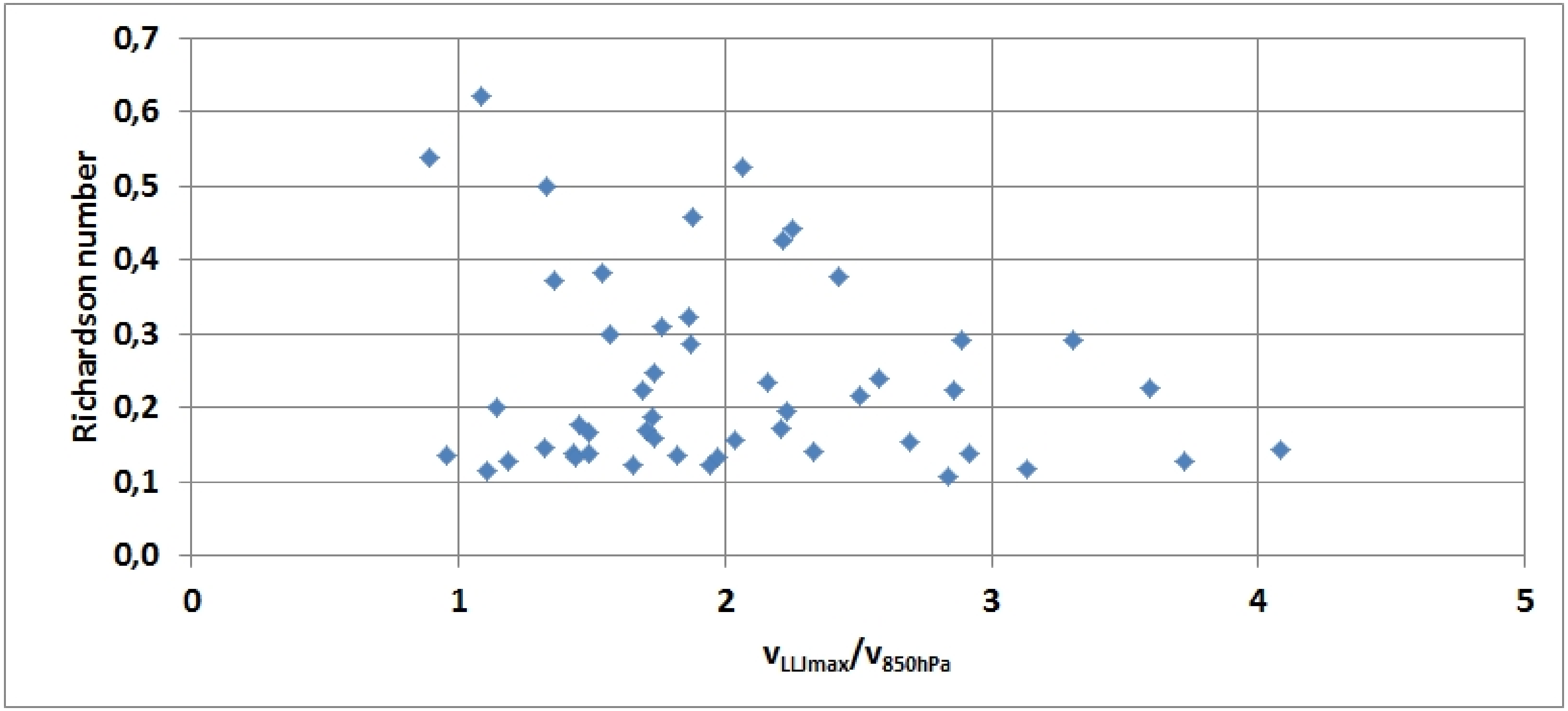
RASS readings at Augsburg (Germany)

gradient Richardson number (60 to 160 m) for ten days



RASS readings at Augsburg (Germany)

gradient Richardson number (40 to 200 m) during LLJ events



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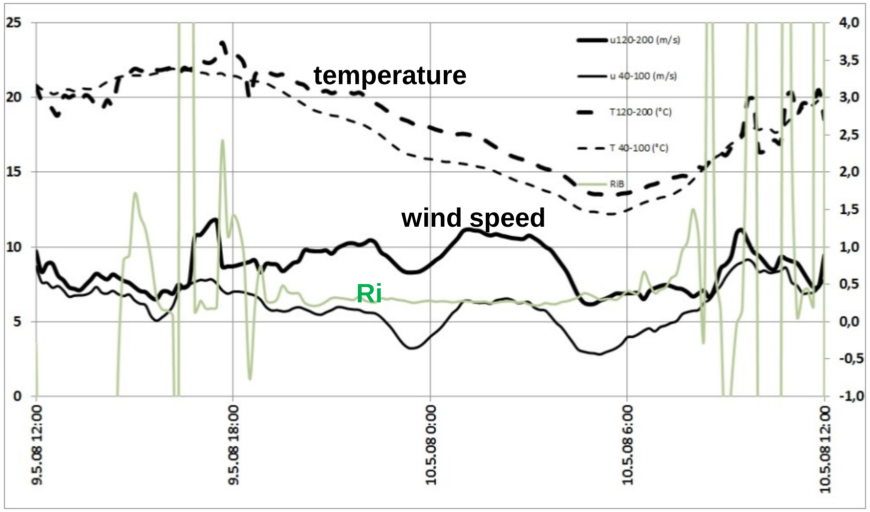
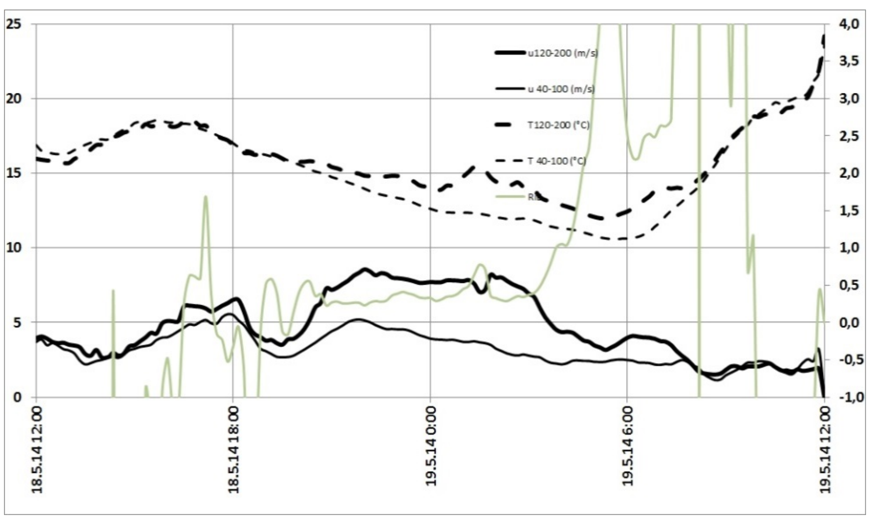
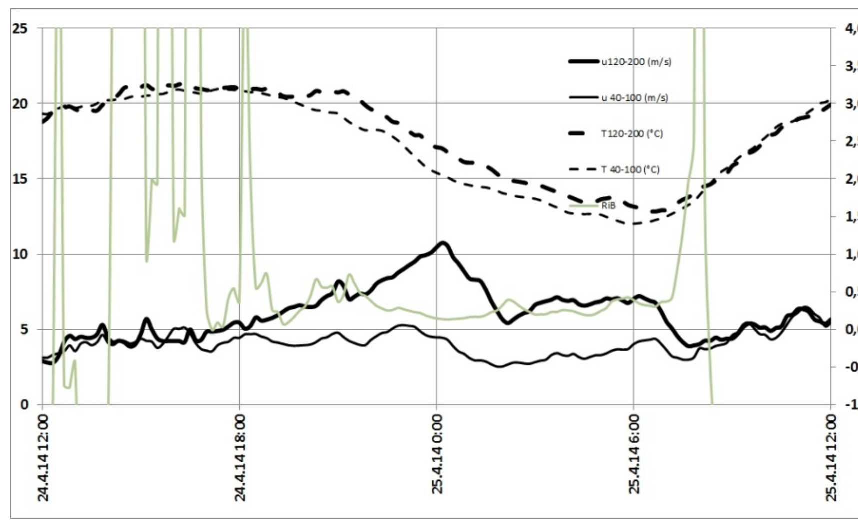


RASS readings at Augsburg

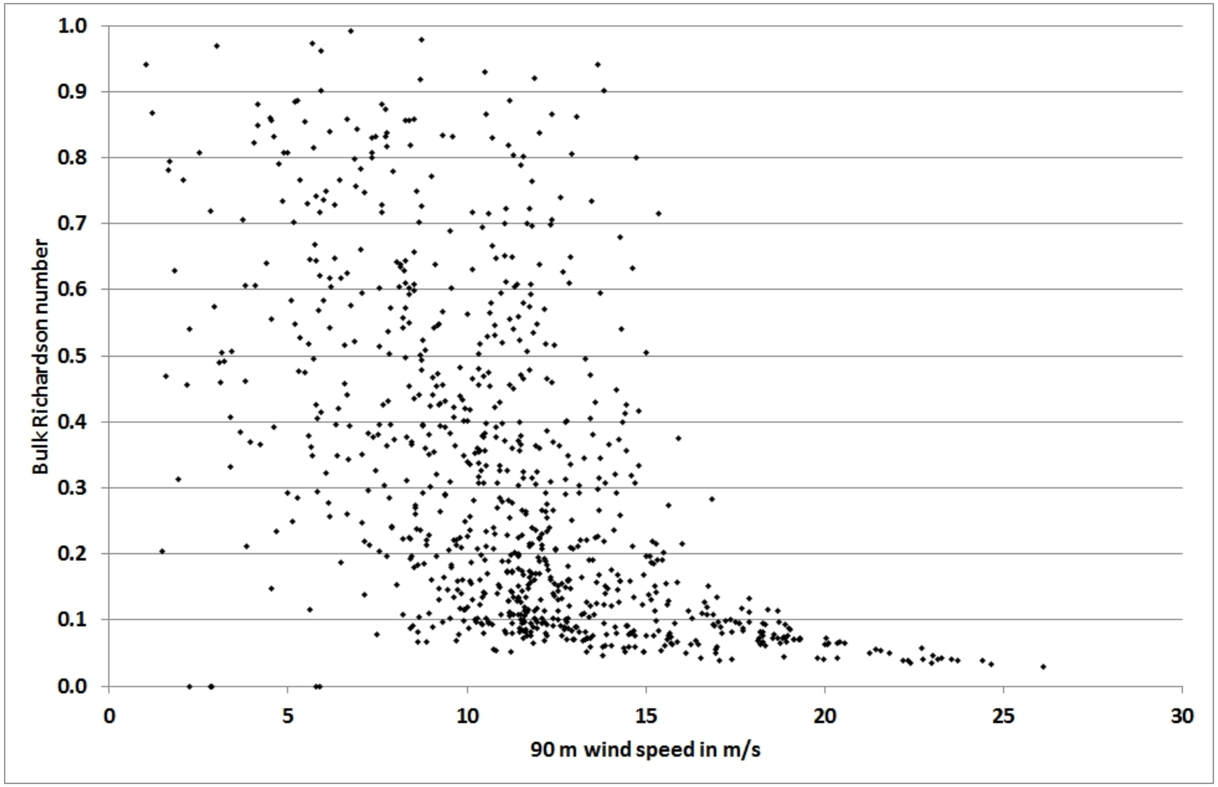
critical Richardson number between 40 and 200 m above ground as limiting parameter for nocturnal LLJ wind speed





offshore wind profiles

observations at FINO 1, stable stratification only: 90 m wind versus Richardson number 10 min mean data, 2005 (entire year)



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Richardson number

$$Ri = \frac{g \partial \Theta / \partial z}{\Theta (\partial u / \partial z)^2}$$

Θ (z)	potential temperature
g	gravity
u (z)	wind speed
z	vertical co-ordinate

critical Richardson numbers

turbulent ➔ laminar: turbulence is suppressed for $Ri > Ri_{krit\_1}$ (about 0.25)

laminar ➔ turbulent: mechanical turbulence is generated, if $Ri < Ri_{krit\_2}$

inland: Ri_{krit_2} ~ 0.10, offshore: Ri_{krit_2} ~ 0.05

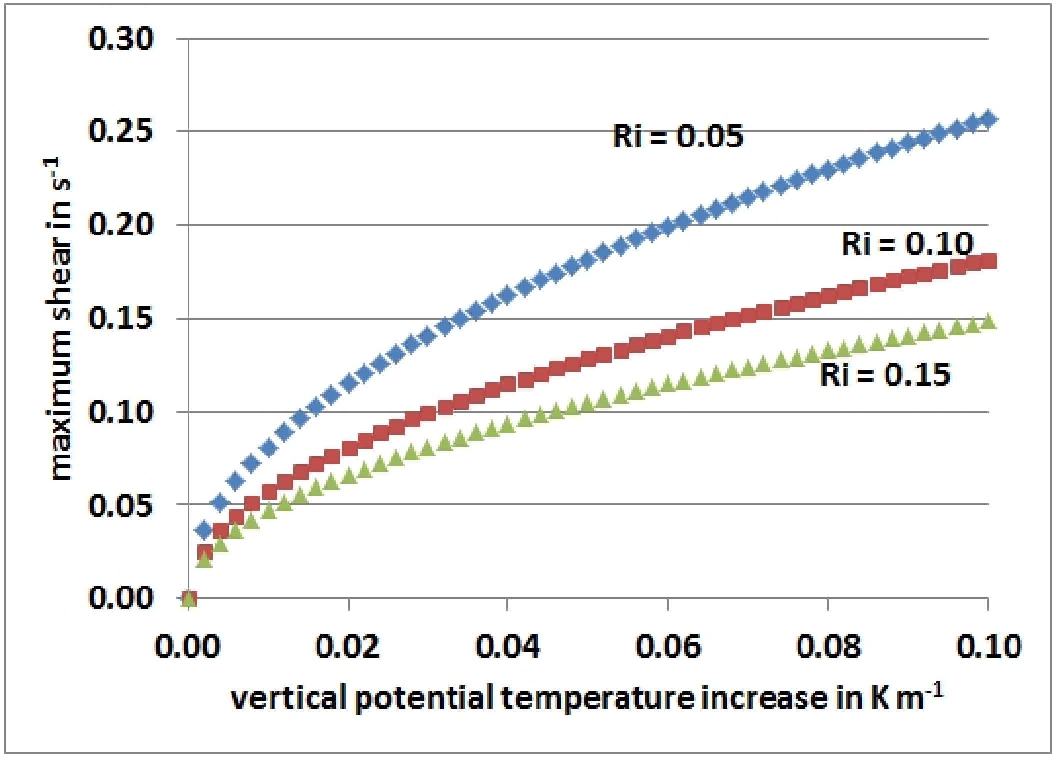
$Ri_{krit\_2} < Ri_{krit\_1}$ hysteresis

wind profile laws

inversion of the definition of Ri:

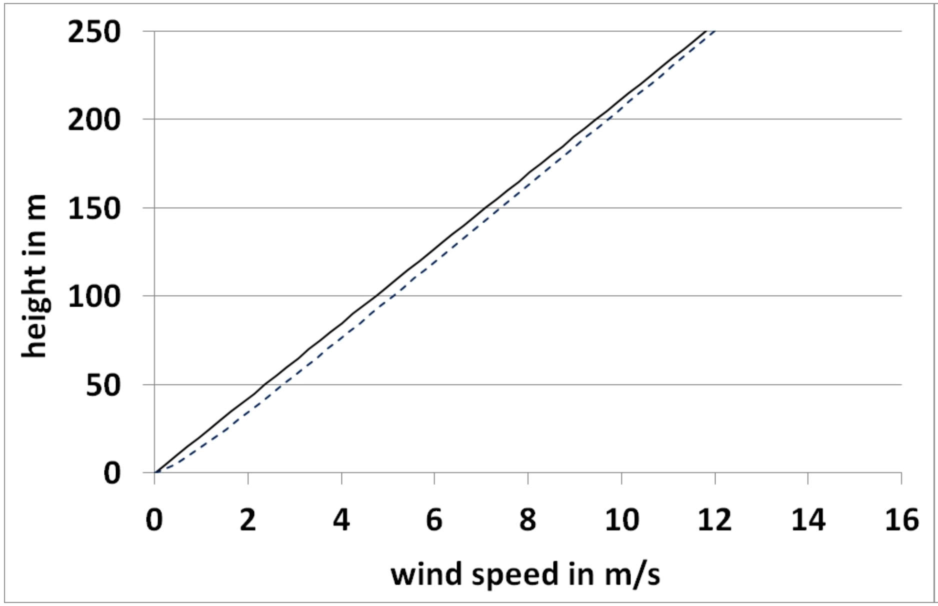
computation of maximum possible shear

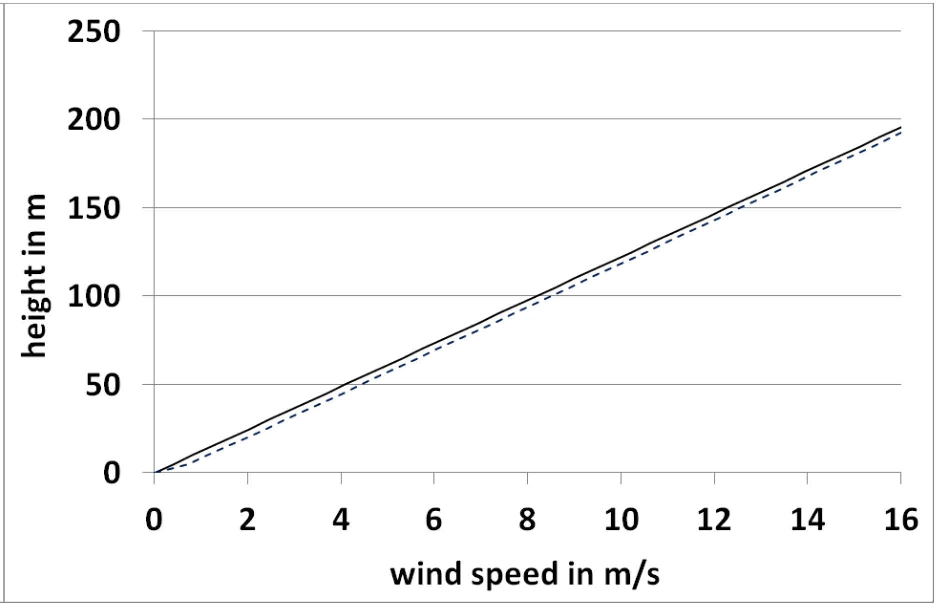
$$\frac{\partial u}{\partial z} = \sqrt{\frac{g\partial\Theta/\partial z}{\Theta Ri_{krit\_2}}}$$



comparison:

full: wind profile from critical Richardson number, dashed: ($u(z) = u_*/k(\ln(z/z_0) + a\, z/L_*)$)





Ri_{krit_2} = 0.15 (inland), $\partial\Theta/\partial z$ = 0.01 K/m

$a = 4.7$, $L_* = 103$ m, $z_0 = 1.0$ m, $u_* = 0.05$ m/s

Ri_{krit_2} = 0.05 (offshore), $\partial\Theta/\partial z$ = 0.01 K/m

$a = 4.7$, $L_* = 58$ m, $z_0 = 0.00001$ m, $u_* = 0.01$ m/s

comparison of wind profile laws

from a Richardson number point of view:

$$u(z) = \sqrt{\frac{g}{\Theta_v Ri_{krit\_2}}} \sqrt{\frac{\Theta(z) - \Theta(0)}{z}} z$$

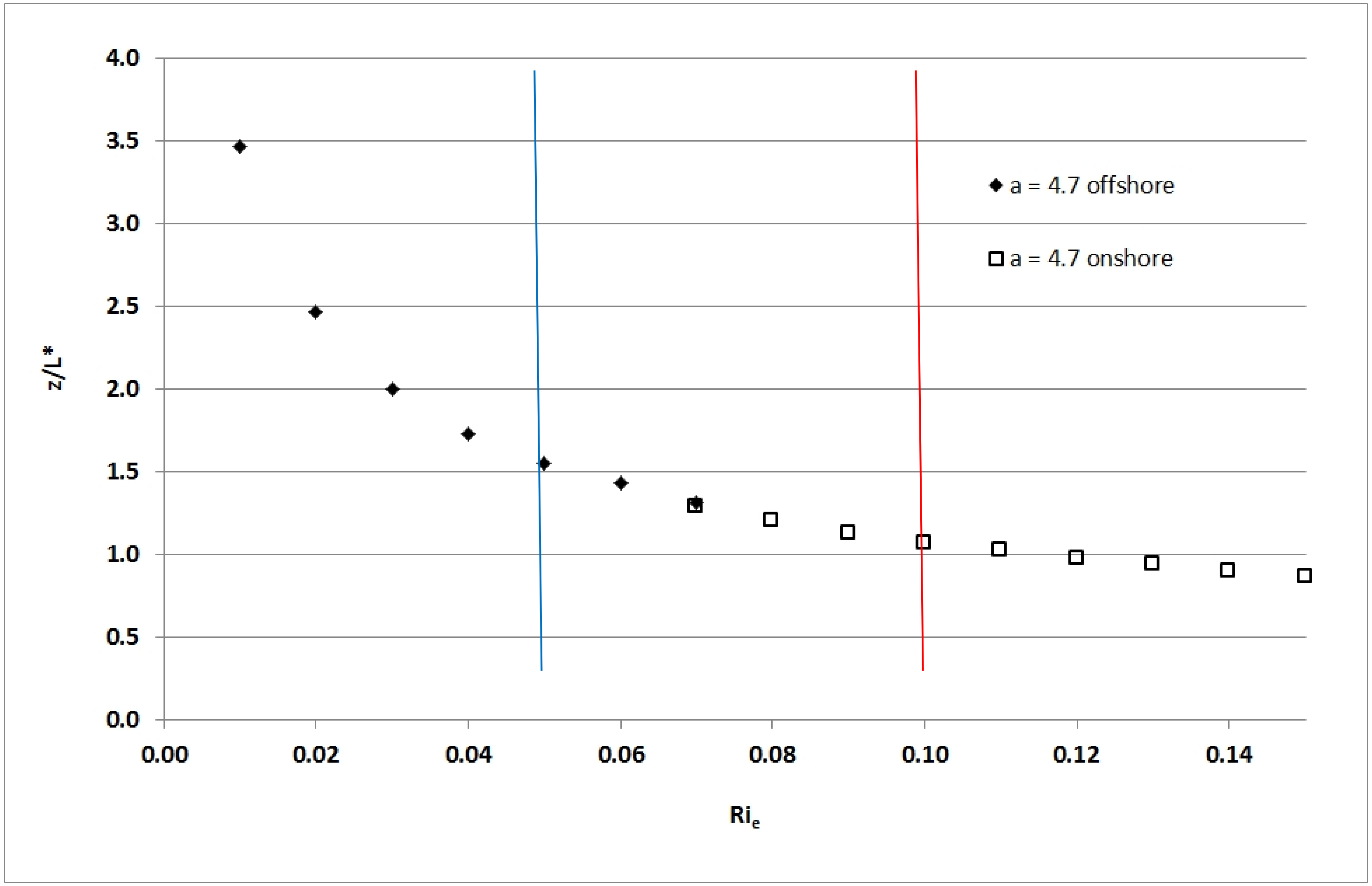
from MOST:

$$u(z) = \frac{u_*}{\kappa} \left(\ln \frac{z}{z_0} + a \frac{z}{L_*} \right)$$

we get a first estimation of Ri_{krit_2}:

$$Ri_{krit\_2} = \frac{L_*}{z} \left(\ln \frac{z}{z_T} \right) \frac{1}{a^2}$$

relation between Ri_{krit_2} and z/L_* for $\partial\Theta/\partial z$ = 0.01 K/m from fitting wind profiles together



Basic questions:

Is MOST suitable for a stable nocturnal boundary layer at all?

**MOST is based on a mixing length and acting turbulence,
but there is nearly no turbulence at night. Ri-based profiles could be more appropriate.**

Is it justified to describe low-level jets as inertial oscillation?

Data often show an equilibrium flow. Maximum shear occurs just below the onset of mechanical turbulence generation.

If there is sufficient external forcing (large-scale pressure gradient), the height of the LLJ core increases during night (the shear is kept constant).

There is some indication that Ri_{crit} depends on surface characteristics.

Conclusion:

Ri-based wind profile laws could be suitable for stable stratification.

Apart from the critical Richardson number, no other empirical constants are involved (no roughness length, no friction velocity is needed). Vertical temperature gradient is the only parameter.

This would circumvent the contradiction of using a turbulence-based law (i.e., MOST) in situations with nearly no or only intermittend turbulence.

Open question:

Why is the critical Richardson number reached in a few nights only?

Observations lead the way

Observations (or networks) that are needed to benefit your future research, application or product development

highly-resolved vertical profiles of atmospheric humidity
(passive microwave radiometers are not sufficient for boundary-layer research)

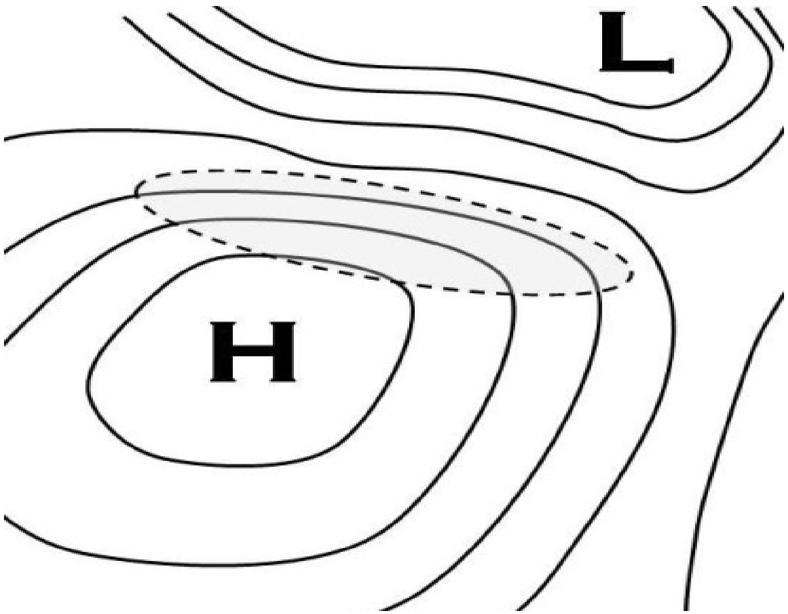
Recommended instruments that are needed to make these observations

small, transportable (Raman) lidars

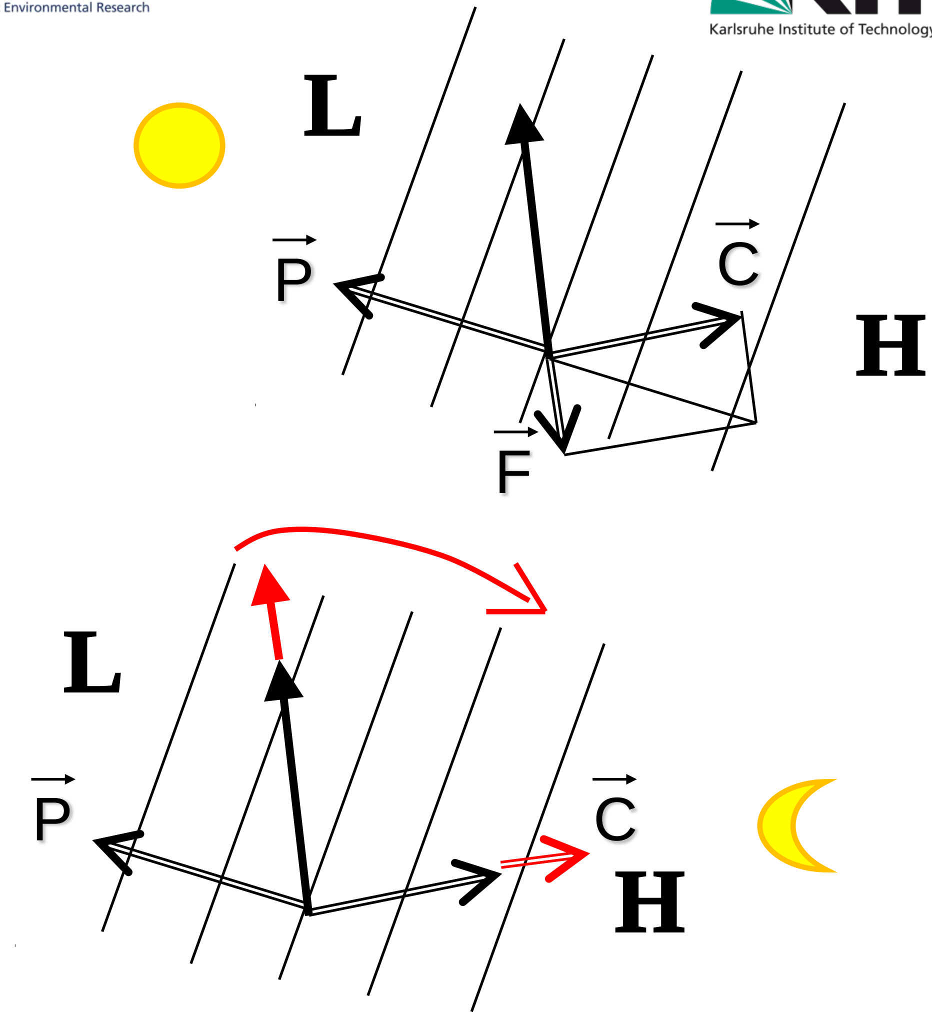
Your view on the greatest observational needs for your discipline in general

observations across all scales in urban and other highly complex environments

Thank you very much for your attention



favourite pressure configuration for low-level jets



balance of forces for low-level jets

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$$\frac{\partial}{\partial t}(u - u_g) = f(v - v_g)$$
$$\frac{\partial}{\partial t}(v - v_g) = -f(u - u_g) \qquad (5)$$

in which u, v, u_g, v_g are components of the wind and geostrophic wind and f the coriolis parameter. The solution and geometric interpretation of these equations are facilitated by introducing the complex number

$$W = (u - u_g) + i(v - v_g) \qquad (6)$$

which, when plotted in the complex plane, gives a vector representing the deviation from the geostrophic wind. The equations (5) then become

$$\frac{\partial W}{\partial t} = -ifW \qquad (7)$$

which may be integrated to give the solution

$$W = W_o e^{-ift} \qquad (8)$$

low-level jet theory by Blackadar 1957