Turbulence Measurements With Lidar

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1) COPS science goals

The Convective and Orographically-induced Precipitation Study (COPS) was endorsed as Research and Development Project (RDP) of the World Weather Research Program (WWRP). The overarching goal of COPS is to

advance the quality of forecasts of orographically-induced convective precipitation by 4D observations and modeling of its life cycle.

Overviews of COPS are given in Wulfmeyer et al. BAMS 2008, QJRMS 2011.

Within this work, the IPM water-vapor differential absorption lidar (DIAL) is explored for studying transport processes in complex terrain leading to shallow and organized convection in dependence of local forcing conditions (see Fig.1).

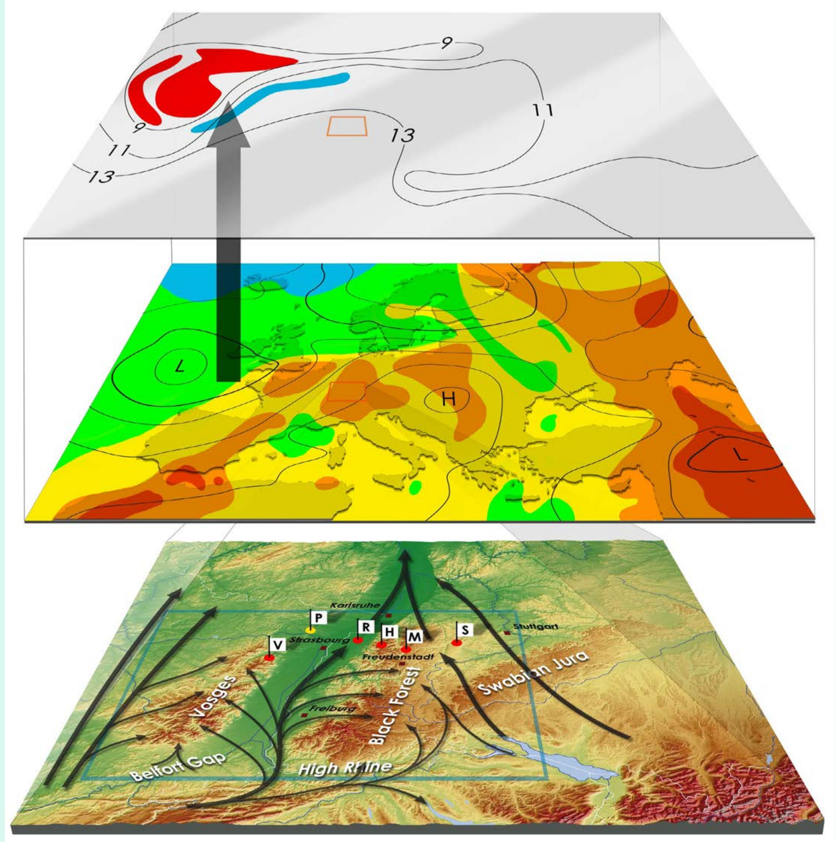


Fig.1. *Forcing concept for mid-latitude precipitation in the COPS domain (southwestern Germany / eastern France). The red bullets indicate the location of the supersites. Middle panel: θe at 850 hPa (color), geopotential height (black contours). Upper panel: Potential vorticity on the 315 K surface. Red values > 2 PVU, blue values < 0.5 PVU. The contours indicate the tropopause height (km).*

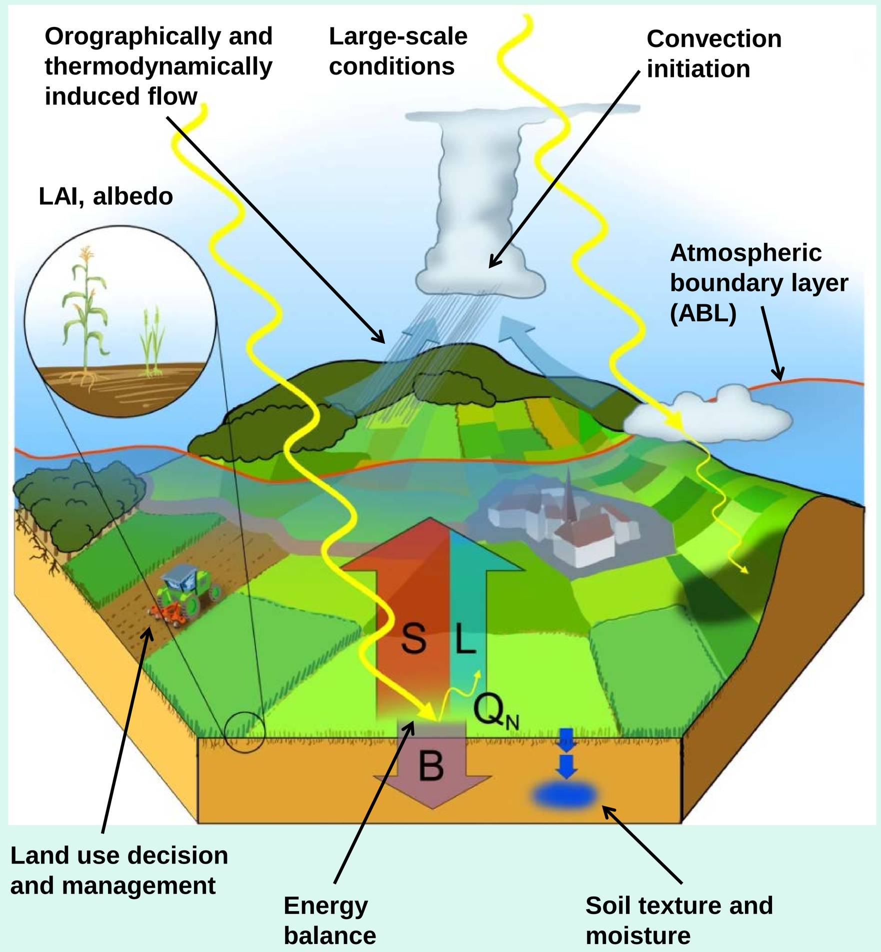


Fig.2. *The land system and its feedback processes.*

2) COPS IOP 11b

Meteorological conditions

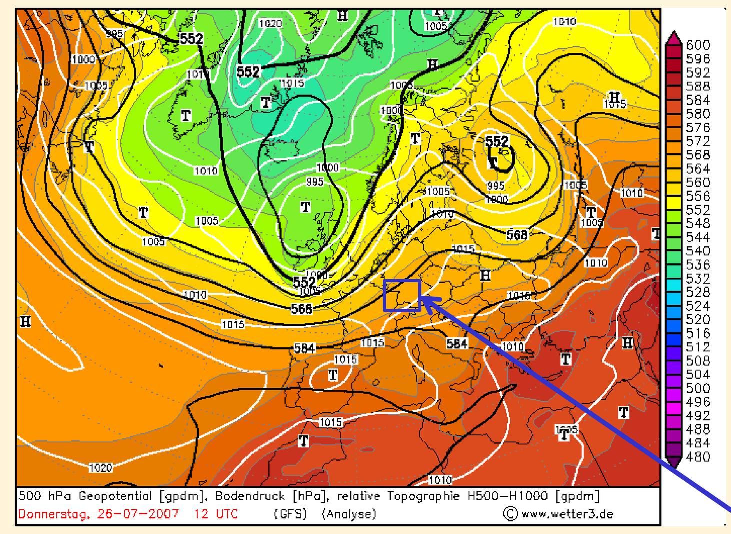


Fig.3. *500-hPa geopotential, surface pressure, and thickness of H500-H1000 layer.*

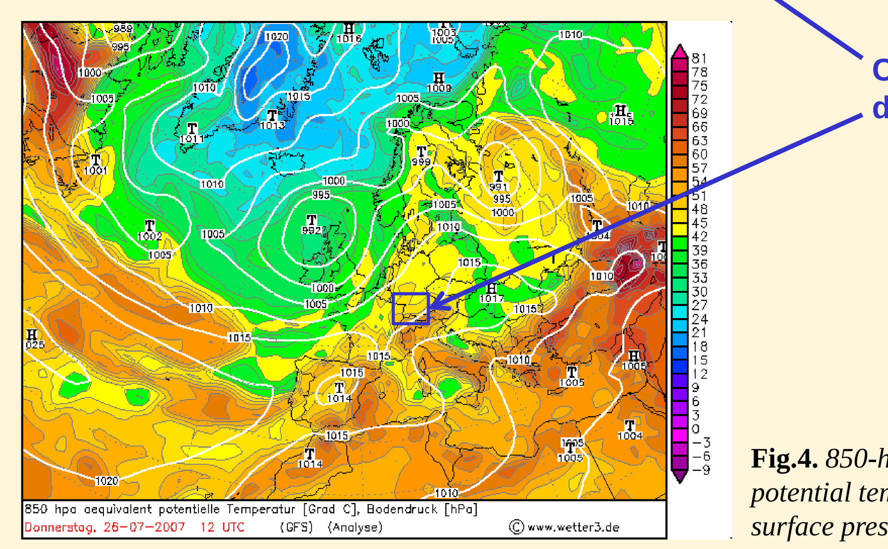


Fig.4. *850-hPa equivalent potential temperature and surface pressure.*

A long-wave trough approached the COPS region from the west and pushed a high-pressure ridge to the east. This resulted in an increasing southwesterly flow during the day. Large-scale forcing remained weak. The day was supposed to stay fair and dry apart from some cumulus clouds (Cu hum to Cu con) mainly over the mountains. Some CAPE developed at the end of the day associated with a weak crossing vorticity maximum so that a slight probability of convection was forecasted in the late afternoon.

3) DIAL setup and system performance in comparison with Raman lidar

The new water-vapor DIAL is based on a 6-W laser transmitter operating at 820 nm. The receiver has a diameter of 80 cm and 3D scanning capability. Raw data were collected with resolutions of 15 m and 4 ms, respectively. The DIAL system was operated mainly in the vertically pointing mode. Due to its high accuracy and resolution, we focused on studies of the vertical structure of humidity, atmospheric stability, and mesoscale transport processes including turbulence in the convective boundary layer.

Fig.5. *Supersite H with unique combination of remote sensing systems.*

Comparisons with soundings

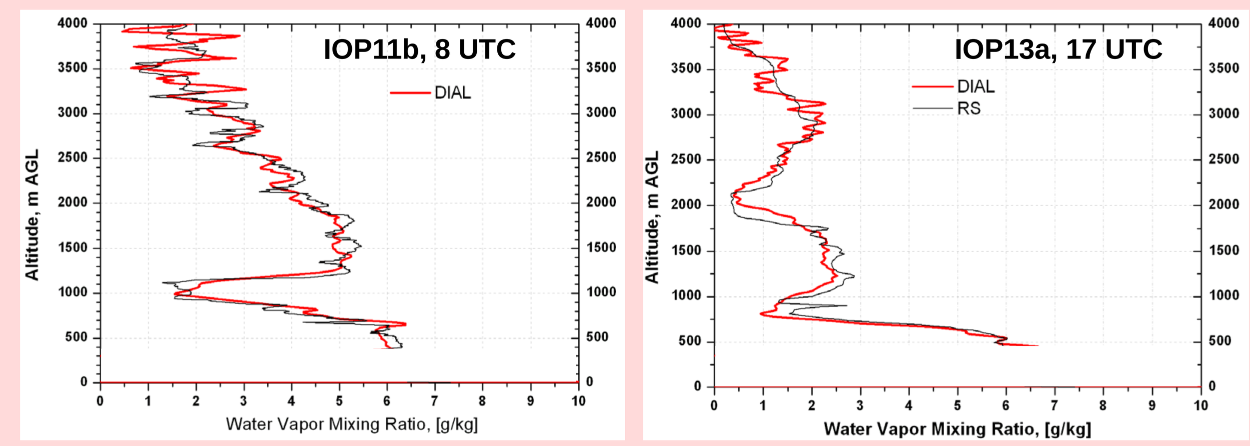


Fig.7. *Two arbitrary comparisons between radio soundings (RS 92) and DIAL measurements with 10s, 150m resolutions, respectively.*

Fig.6. *IPM water-vapor DIAL system mounted in mobile trailer. The transmitter is operating at 820 nm and delivers an average power of 6 W. The receiver consists of a 3D 80-cm scanner with an APD photodetector unit.*

Noise error comparison with Raman lidar

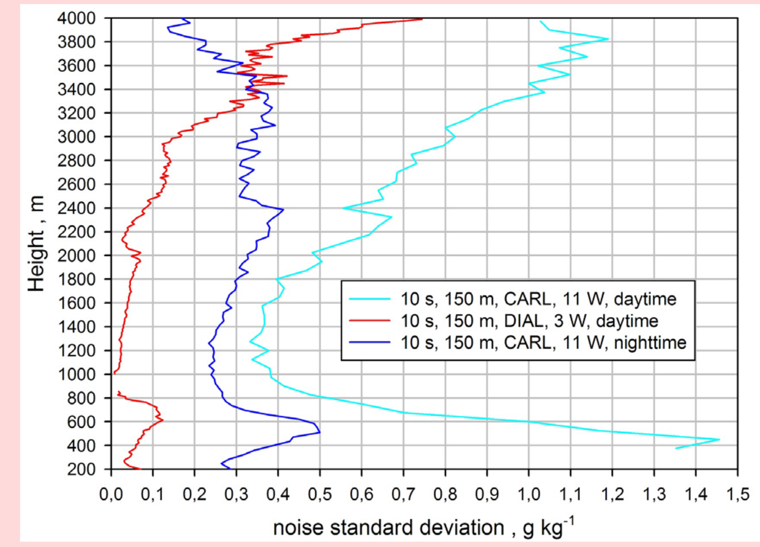
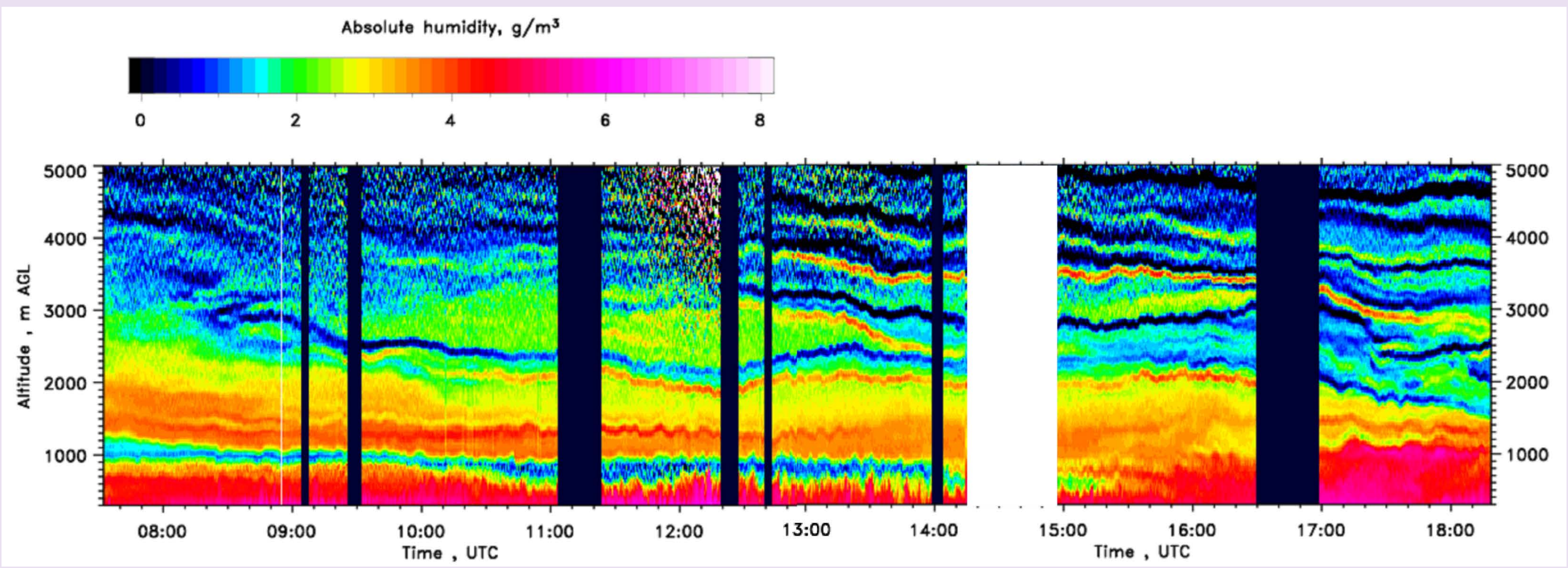
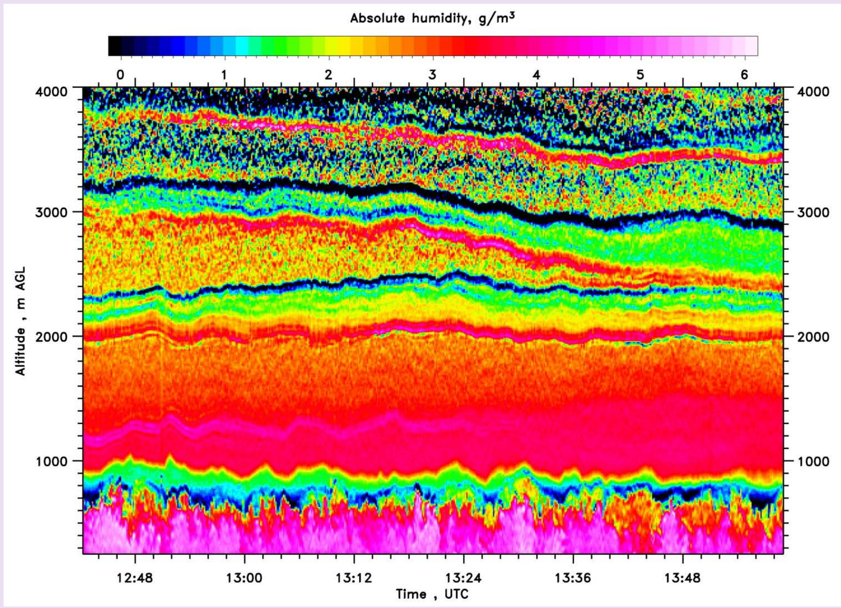


Fig.8. *Typical day- and nighttime noise error profiles of state-of-the-art using DIAL and Raman lidar systems.*

DIAL provides considerable higher resolution in the ABL so that DIAL is much better suited for daytime turbulence measurements. DIAL is very flexible to reduce system noise, as the reduction factor reads for time $\sqrt{\frac{\Delta T_1}{\Delta T_2}}$**, and for range even** $\left(\sqrt{\frac{\Delta R_1}{\Delta R_2}}\right)^3$.

4) High-resolution water-vapor remote sensing





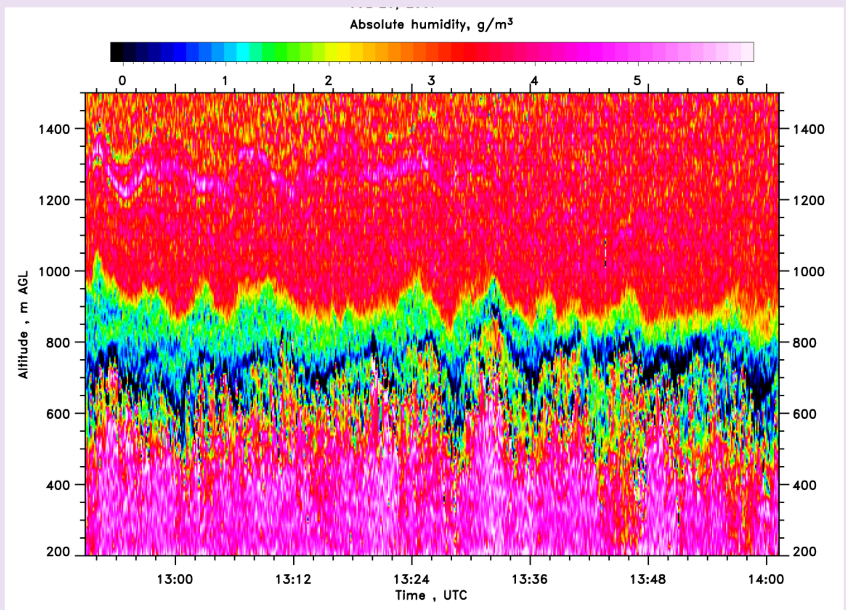


Fig.9. *Upper panel: Time-height cross section of absolute humidity measured with resolutions of 10s and 150m, respectively. The data show a tremendous vertical variability. A shallow convective boundary layer was detected between 10:30-15:30 UTC.*
Bottom, left panel: Zoom in the data with resolutions of 10 s and 60 m, respectively.
Bottom, right panel: Humidity measurement with extraordinary resolutions of 1s and 15m, respectively. This is likely the highest resolution that has been achieved yet with respect to water-vapor remote sensing. Clearly turbulent eddies are resolved causing vertical water vapor transport.

5) Profiling of turbulent moments

Moisture budget:

$$\frac{\partial \bar{q}}{\partial t} + \bar{U}_j \frac{\partial \bar{q}}{\partial x_j} = \nu_q \frac{\partial^2 \bar{q}}{\partial x_j^2} + \frac{S_q}{\rho_{air}} - \frac{\partial \left(\overline{u_j' q'}\right)}{\partial x_j}$$

Flux profile:

$$\frac{\overline{w'q'}}{\left(\overline{w'q'}\right)_s} = 1 - \frac{z}{z_i} + \frac{\left(\overline{w'q'}\right)_E}{\left(\overline{w'q'}\right)_s} \frac{z}{z_i}$$

Entrainment flux:

$$F_E \cong r \sqrt{\overline{q'^2}}_E \sqrt{\overline{w'^2}}_E$$

$$F_E \cong C \overline{q'^2}_E \frac{N_E}{\left(\frac{\partial \bar{q}}{\partial z}\right)_E}$$

(see Wulfmeyer et al. BLM 2010; Sorbjan JAS 1996, BLM 2001, BLM 2005)

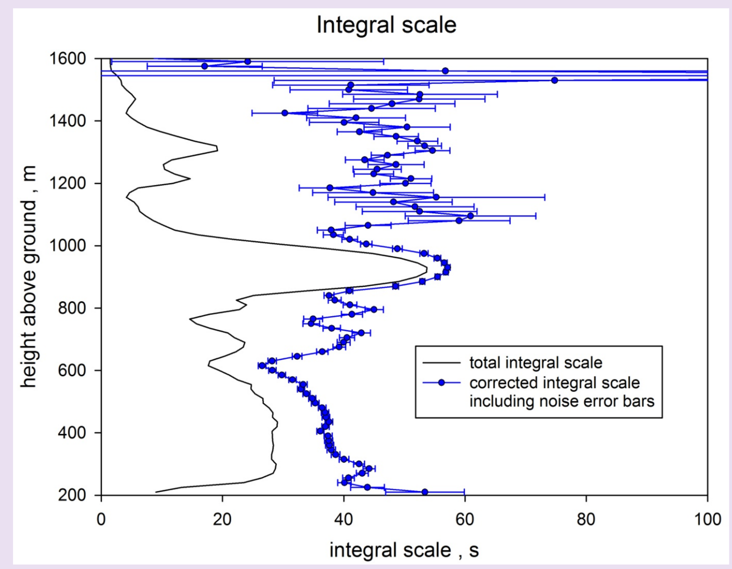


Fig.10. *Integrale scale profile.*

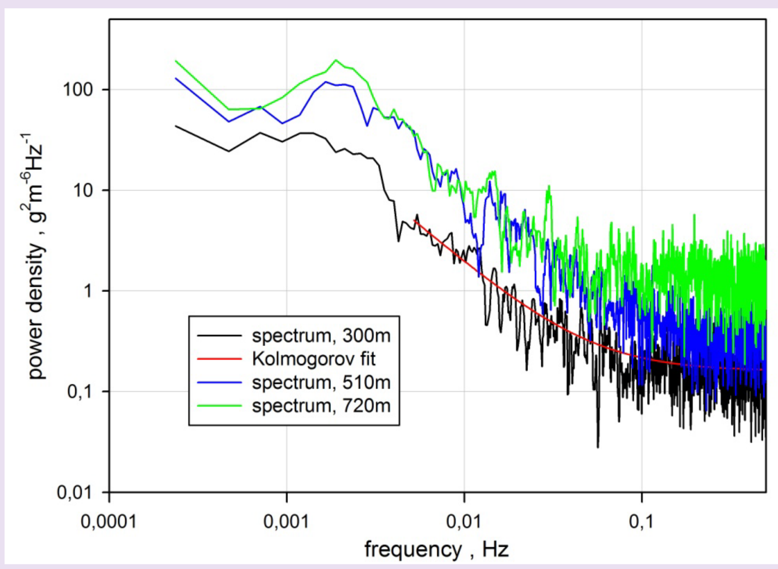


Fig.11. *Water-vapor variance spectra at 3 height levels.*

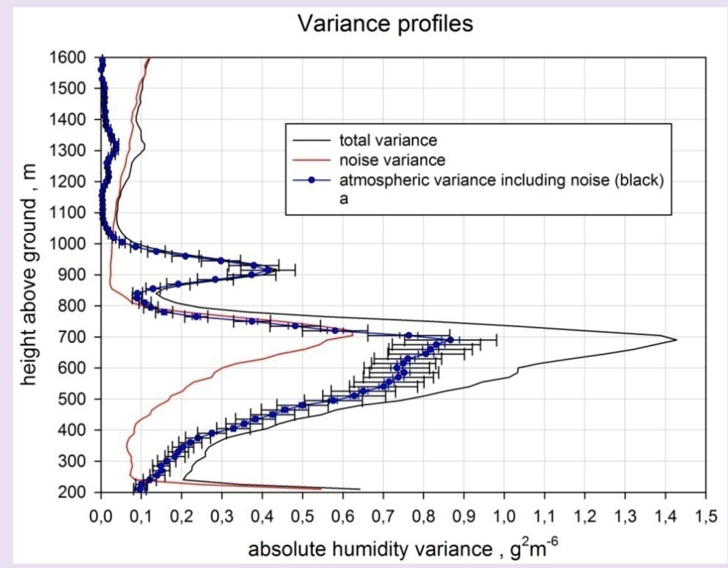


Fig.12. *Total variance (black), system noise variance (red), and atmospheric humidity variance profile including noise and sampling error bars. Two peaks occur due to the presence of the dry layer at ABL top.*

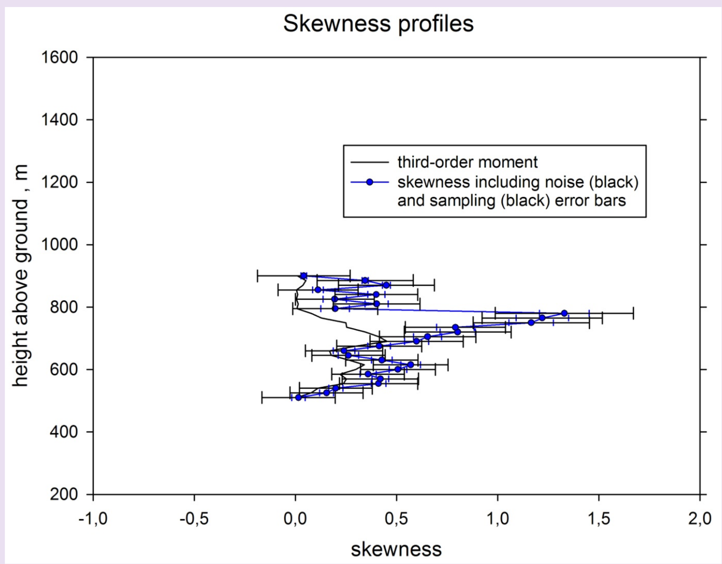


Fig.13. *Third-order moment (black) and atmospheric humidity skewness profile including noise and sampling error bars. The skewness is maximum in the entrainment zone.*

6) Summary

- **DIAL is simply the best for water-vapor turbulence profiling**
- **Superior to Raman lidar in the ABL even at considerable lower power**
- **Excellent daytime performance up to middle troposphere**
- **Integral scale high enough for resolving turbulent transport**
- **Turbulence profiling mainly limited by sampling errors**
- **Variance and skewness maxima in entrainment zone**
- **Combination with Doppler and temperature lidar permits estimation of entrainment flux**
- **Future:**
  - **analyses using lidar synergy**
  - **2D and 3D scans of turbulent properties**
  - **Land-surface exchange studies in heterogeneous terrain**

Important links and references: COPS: ***www.uni-hohenheim.de/cops, www.cops2007.de, cera-www.dkrz.de/WDCC/ui/Index.jsp;*** WWRP: ***http://www.wmo.int/pages/prog/arep/wwrp/new/wwrp_new_en.html***; ***Wulfmeyer et al. BAMS 89, 1477-1486, 2008; Wulfmeyer et al. QJRMS 107, 3-30, 2011; Wulfmeyer et al. BLM 136, 253-284, 2010.***

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