Atmos. Meas. Tech. Discuss., 8, 353–373, 2015
www.atmos-meas-tech-discuss.net/8/353/2015/
doi:10.5194/amtd-8-353-2015

Atmospheric Measurement Techniques Discussions
Open Access

Combined vertical-velocity observations with Doppler lidar, cloud radar and wind profiler

J. Bühl[1], R. Leinweber[2], U. Görsdorf[2], M. Radenz[1], A. Ansmann[1], and V. Lehmann[2]

[1]Institute for Tropospheric Research (TROPOS), Permoserstr. 15, 04318 Leipzig, Germany
[2]Deutscher Wetterdienst, Meteorologisches Observatorium Lindenberg (MOL), Am Observatorium 12, 15848 Tauche, Germany

Received: 9 December 2014 – Accepted: 9 December 2014 – Published: 12 January 2015

Correspondence to: J. Bühl (buehl@tropos.de)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Case studies of combined vertical-velocity measurements of Doppler lidar, cloud radar and wind profiler are presented. The measurements were taken at the Meteorological Observatory Lindenberg, Germany. Synergistic products are presented that are derived from the vertical-velocity measurements of the three instruments: A comprehensive classification mask of vertically moving atmospheric targets and the terminal fall velocity of water droplets and ice crystals corrected for vertical air motion. It is shown that the measurements of the Doppler lidar can extent the view of the cloud radar and the wind profiler, especially when observing clouds.

1 Introduction

Mixed-phase layered clouds are a critical component of the global weather and climate system. The occurrence of these clouds is difficult to predict, because the interaction between aerosols, cloud droplets and atmospheric dynamics is not understood. Errors in the prediction of layered clouds strongly affect the accuracy of global climate projections, because of their extended global appearance (Zhang et al., 2010).

Vertical motions of different scales are important for the development and the life-cycle of layered clouds. These clouds can can be created by large-scale wave motions like gravity waves. On the other hand, it was shown by Korolev and Field (2008) and recently by Simmel et al. (2014) that turbulent motion within the cloud layer can maintain its mixed-phase state, even if ice particles have formed that draw water vapor from the liquid droplets due to the Bergeron-Findeisen process.

This large variety of scales and processes cannot be covered by a single instrument. Different efforts have been done to combine remote-sensing instruments in order to get a detailed picture of the processes involved in such mixed-phase layered clouds on small (Wandinger, 2012; Bühl et al., 2012, 2013) and large scales (Böhme et al., 2004).

At the Meteorological Observatory Lindenberg (MOL) of the German Weather Service (DWD), a combination of lidars and a MIRA-35 cloud radar have been run for several years, also in the context of Cloudnet (Illingworth et al., 2007). Additionally an ultra-high-frequency (UHF) wind profiler is being run operationally to retrieve the height-dependent advection speed of the air. Recently, a Streamline Doppler lidar of HALO Photonics company has been added to this measurement suite. With the Doppler lidar, the cloud radar and the wind profiler, three instruments are combined that can study the movement of the air at different scales and a variety of conditions. The systems are collocated within a radius of 30 m and pointed vertical so that their observation volumes overlap.

All three velocity-measuring instruments are most sensitive to particles or structures which are similar in size to the operating wavelength λ of the instrument. The Doppler lidar ($\lambda = 1.5\,\mu m$) is most sensitive to aerosol particles (100 nm to 10 µm). The cloud radar ($\lambda = 8.5$ mm) mainly senses large cloud droplets (30 to 100 µm) and falling particles like drizzle droplets, rain droplets or ice crystals (100 µm to 10 mm). The wind profiler detects echoes from refractive index fluctuations originating from turbulent eddies in the atmosphere with sizes in the range of its wavelength $\lambda = 0.62$ m and Rayleigh scattering from particles. In this work, the combined operation of this unique set of instruments is demonstrated in order to study the vertical motions in and around layered clouds. The combination of wind profiler and cloud radar has been done before (Böhme et al., 2004; Protat and Williams, 2011). It is shown in this paper, that an additional Doppler lidar can deliver critical information about the vertical velocity of small cloud droplets and their fast-changing turbulent motion. For that purpose, first results of the MOL/TROPOS measurement campaign COLRAWI (Combined Observations with Lidar, Radar and Wind Profiler) are presented. It is shown that turbulent air motion, large scale waves and the vertical movement of falling ice and water particles can be measured at once. In this way a coherent picture of different kinds of vertical motions in the atmosphere can be drawn and the unbiased fall velocity of particles can be measured.

This paper deals with first promising examples how to combine Doppler lidar, cloud radar and wind profiler. In Sect. 2 and overview is given about the three instruments and their simultaneous operation. In Sect. 3, case studies are presented and links between the data from the different instruments are established. A summary is given in Sect. 4.

2 Overview about measurement instruments and strategy

Wind-profiler radars have been designed to measure the wind speed in both the cloudy and clear atmosphere. While the radar technique itself is nearly 70 years old, the wind profiler technique has been developed not before the late 1970s (Strauch et al., 1984; Weber and Wuertz, 1990). A wind profiler exploits Bragg scattering at atmospheric density fluctuations to produce a backscatter signal even under clear-air conditions. Rayleigh scattering from particles also adds to the signal, but as the efficiency of Rayleigh and Bragg scattering is proportional to λ^{-4} and $\lambda^{-\frac{1}{3}}$, respectively, Bragg scattering dominates more and more for longer wavelengths.

The distribution of powerful wind profilers is limited, but they can actually deliver the desperately needed information about the velocity of clear air. They can only be operated by a limited number of institutions, due to their high operational costs. The DWD operates an ultra-high frequency (UHF) wind profiler at MOL (see Fig. 1). It works at 482 MHz and can deliver wind information from 0.5 km to a maximum of 16 km height with a range resolution of 150 m, a measurement interval of about 10 s and a velocity resolution of about 0.1 m s^{-1} (Böhme et al., 2004). The distance between two neighboring range gates is 100 m, due to range interpolation.

Lidars and cloud radars can measure vertical velocity, if a sufficient number of aerosol particles, cloud droplets or ice crystals are present in the target volume. Under clear-air conditions, no velocity information at all can be derived, but the movement of clear air is actually an important measurement quantity. Large-scale atmospheric motion (e.g., gravity waves) can influence a cloud decisively, and falling droplets or ice crystals are slowed down or accelerated by vertical air movements. In the context of

AMTD
8, 353–373, 2015

this work, the Doppler lidar is operated with a measurement interval of 2 s, cloud radar and wind profiler both with 10 s.

Table 1 shows the operational parameters of the main instruments for combined measurements of vertical velocity at MOL. All systems were co-located within a 30 m radius (see Fig. 1) and had therefore overlapping observation volumes. In normal operation the phased-array antenna of the wind profiler is used to derive the height-resolved horizontal wind with a Doppler beam-swinging technique. For the duration of the combined measurements, Doppler lidar, cloud radar and wind profiler were used in a vertical-stare mode. No scanning at all was involved in this project. A schematic representation of the observation volumes is given in Fig. 2 illustrating the big technical differences between the three systems.

In the following, different case studies are presented to demonstrated the manifold of possibilities enabled by this new combination of instruments.

3 Case studies

A combined vertical-velocity measurement with Doppler lidar, cloud radar and wind profiler from 30 July 2013 is shown in Fig. 3. In the following Section different parts of this scene will be analyzed with respect to different aspects of vertical motions in the atmosphere.

3.1 Observations of air motion, aerosols and insects in the boundary layer

It is visible in Fig. 3 that the Doppler lidar, the cloud radar and the wind profiler all see movements in the planetary boundary layer (PBL). The movements of the air are sensed directly by the wind profiler (Fig. 3c). The Doppler lidar can measure those movements indirectly where aerosol particles are present to produce a backscatter signal (Fig. 3a). In the PBL the cloud radar also shows vertical movements, which originate from insects, pollen and other big particles floating in the air. These measured

AMTD
8, 353–373, 2015

Combined observations with Doppler lidar, cloud radar and wind profiler

J. Bühl et al.

velocity values are therefore more ambiguous than those of the Doppler lidar and the wind profiler. For observation of the boundary layer it is most notable that the Doppler lidar is the only system that can measure the vertical values down to about 100 m above the ground. Close to the ground, the signal of the wind profiler is often disturbed (e.g., 10:51 UTC), probably due to the uptake of large scatterers.

The vertical-velocity signal of the three instruments is analyzed in Fig. 4. One can see from this figure that the frequency response of all three instruments is very similar, despite the great technical differences and the different tracer targets involved.

3.2 Wave cloud

A magnified portion of the updraft structure between 11:00 and 11:15 UTC from Fig. 3 is shown in Fig. 5. The Doppler lidar (Fig. 5a) shows a liquid cloud at 2900 m, forming within the updraft structure visible in the wind profiler measurements (Fig. 5c). Where large cloud droplets are present, the imprint of the updraft structure can also be partly seen in the cloud radar measurements (see Fig. 5b). The wind profiler also indicates subsidence regions at the edges of the layered cloud. From the wind profiler measurements also a connection between the gravity wave and the thermal updrafts occurring between 10:05 and 10:10 UTC appears probable.

3.3 Classification of vertical velocity features in a complex atmospheric scene

The combination of Doppler lidar, cloud radar and wind profiler allows the characterization of different features in the vertical velocity patterns at once. Thin layered clouds are detected most easily with the Doppler lidar, big falling particles are most easily detected by the cloud radar and the motion of clear air can be sensed with the wind profiler. When comparing Fig. 3a and d, it is obvious that the wind profiler signal is broadened by small-scale turbulence (visible, e.g., at cloud tops) and by Rayleigh scattering at large particles (e.g., at 12:05 UTC).

AMTD
8, 353–373, 2015

A collection of different vertical-velocity features, detected in this combined measurement, is shown in Fig. 6. The figure shows that the combination of the three instruments is a unique way to coherently resolve and identify the different types of vertical motion in the troposphere. Such a collection of vertical velocity features can be useful as input for the detailed modeling of clouds.

3.4 Quantification of terminal fall velocities in a warm precipitating cloud

The fall velocity of a particle yields important information about its size and shape (Mitchell, 1996; Heymsfield and Westbrook, 2010). The apparent fall velocity of particles can, however, be offset by vertical air motion and conceal or bias this information. The combination of Doppler lidar, cloud radar and wind profiler allows to retrieve the true terminal fall velocity of a particle relative to the surrounding air. In Fig. 7 the vertical velocities measured by Doppler lidar and cloud radar are shown (top). Particles in the cloud are found to move up and downwards. When the vertical air velocity which has been measured by the wind profiler the true terminal fall velocity of the particles becomes visible. This fall velocity can then be used, e.g., to derive the particles maximum diameter with methods like presented by Heymsfield and Westbrook (2010).

At the top of the cloud layer, where the velocity is strongly increasing with height, the subtraction of the wind profiler measurements is therefore not complete, because of the lower vertical resolution of the wind profiler. The Doppler lidar does not show this effect, because it only shows measurements which are from a very restricted height level at cloud base. The Doppler lidar, however, operates with a smaller measurement interval (2 s), which explains why several smaller updraft events are still visible after subtraction of the wind profiler data. This emphasizes the need for a Doppler lidar in order to record the fast-changing vertical motions at cloud base, where the vertical and temporal resolution of both wind profiler and cloud radar are not sufficient.

AMTD
8, 353–373, 2015

3.5 Quantification of terminal fall velocities in a mixed-phase cloud layer

In Fig. 8 a combined vertical-velocity measurement from 25 September 2013 is shown. It is visible from Fig. 8 that Doppler lidar, cloud radar and wind profiler show completely disjunct measurements in this cloud layer. Figure 9 shows the vertical-velocity values and the corresponding turbulent spectra for the line indicated in Fig. 8. It is visible that only the Doppler lidar can resolve the turbulent motions at this cloud base. The properties of the falling particles (Fig. 8b) and the air motion (Fig. 8c) are sensed by cloud radar and wind profiler.

After subtraction of the vertical velocities measured by the wind profiler at the corresponding time and height interval, the true fall speed of the particles relative to the air becomes visible (see Fig. 10 and compare with Fig. 8). After this correction, fall streaks in the virga are more coherent. The wind-profiler vertical velocities itself are corrected by spectral division of the wind-profiler and the cloud-radar spectra in order to remove the particle influence from the wind profiler measurements and get the pure vertical-wind information. A detailed description of this method will be given elsewhere (paper in preparation). In the highly turbulent regions of the liquid cloud layers the mutual correction between Doppler lidar, cloud radar and wind profiler fails, because the temporal and spacial resolution of the cloud radar and wind profiler are not sufficient to resolve the small-scale turbulence.

4 Summary

The combined observation of vertical velocity patterns with a Doppler lidar, a 35 GHz cloud radar and a UHF wind profiler has been demonstrated. For the first time, these three instruments were used to measure within the same measurement volume. It was shown that it is possible to characterize different kinds of vertical motions occurring at different scales, including gravity waves, thermal updrafts, turbulence at cloud base and falling particles. The terminal fall velocity of particles relative to the surrounding air

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

AMTD

8, 353–373, 2015

Combined observations with Doppler lidar, cloud radar and wind profiler

J. Bühl et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

could be retrieved by subtraction of the vertical velocity of clear-air from the apparent particle fall velocity.

5 Conclusion and discussion

The combined vertical-velocity measurements yield unique information about the movements of small and big particles together with the true movement of the air. The use of a wind profiler can fill the white spaces left on the vertical-velocity picture drawn by Doppler lidars and cloud radars. On the other hand, a Doppler lidar can detect cloud and aerosol particles, where cloud radar and wind profiler are not sensitive enough. Large-scale atmospheric motion becomes visible together with clouds and the extent and strengths of vertical-velocity fields can be studied independent of the presence of tracers, like aerosol particles or cloud droplets. If all vertical-velocity measurements can be connected properly, it may be possible to derive size and shape information directly from this true particle fall velocity.

Acknowledgements. The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 262254.

References

Böhme, T., Hauf, T., and Lehmann, V.: Investigation of short-period gravity waves with the Lindenberg 482 MHz tropospheric wind profiler, Q. J. Roy. Meteor. Soc., 130, 2933–2952, doi:10.1256/qj.03.179, 2004. 354, 355, 356

Bühl, J., Engelmann, R., and Ansmann, A.: Removing the laser-chirp influence from coherent doppler lidar datasets by two-dimensional deconvolution, J. Atmos. Ocean. Tech., 29, 1042–1051, doi:10.1175/JTECH-D-11-00144.1, 2012. 354

Bühl, J., Ansmann, A., Seifert, P., Baars, H., and Engelmann, R.: Towards a quantitative characterization of heterogeneous ice formation with lidar/radar: comparison of

AMTD

8, 353–373, 2015

CALIPSO/CloudSat with ground-based observations, Geophys. Res. Lett., 40, 4404–4408, doi:10.1002/grl.50792, 2013. 354

Heymsfield, A. J. and Westbrook, C. D.: Advances in the Estimation of Ice Particle Fall Speeds Using Laboratory and Field Measurements, J. Atmos. Sci., 67, 2469–2482, doi:10.1175/2010JAS3379.1, 2010. 359

Illingworth, A. J., Hogan, R. J., O'Connor, E. J., Bouniol, D., Delanoë, J., Pelon, J., Protat, A., Brooks, M. E., Gaussiat, N., Wilson, D. R., Donovan, D. P., Baltink, H. K., van Zadelhoff, G.-J., Eastment, J. D., Goddard, J. W. F., Wrench, C. L., Haeffelin, M., Krasnov, O. A., Russchenberg, H. W. J., Piriou, J.-M., Vinit, F., Seifert, A., Tompkins, A. M., and Willén, U.: Cloudnet, B. Am. Meteorol. Soc., 88, 883–898, doi:10.1175/BAMS-88-6-883, 2007. 355

Korolev, A. and Field, P. R.: The effect of dynamics on mixed-phase clouds: theoretical considerations, J. Atmos. Sci., 65, 66, doi:10.1175/2007JAS2355.1, 2008. 354

Mitchell, D. L.: Use of mass- and area-dimensional power laws for determining precipitation particle terminal velocities, J. Atmos. Sci., 53, 1710–1723, doi:10.1175/1520-0469(1996)053<1710:UOMAAD>2.0.CO;2, 1996. 359

Protat, A. and Williams, C. R.: The accuracy of radar estimates of ice terminal fall speed from vertically pointing Doppler radar measurements, J. Appl. Meteorol. Clim., 50, 2120–2138, doi:10.1175/JAMC-D-10-05031.1, 2011. 355

Simmel, M., Bühl, J., Ansmann, A., and Tegen, I.: Ice formation in altocumulus clouds over Leipzig: Remote sensing measurements and detailed model simulations, Geophys. Res. Abstr., EGU2014-6500, EGU General Assembly 2014, Vienna, Austria, 2014. 354

Strauch, R. G., Merritt, D. A., Moran, K. P., Earnshaw, K. B., and De Kamp, D. V.: The Colorado wind-profiling network, J. Atmos. Ocean. Tech., 1, 37–49, doi:10.1175/1520-0426(1984)001<0037:TCWPN>2.0.CO;2, 1984. 356

Wandinger, U.: Observation of Aerosol-Cloud-Turbulence Interaction with Integrated Remote-Sensing Instrumentation, in: Proceedings 26th ILRC, 2012. 354

Weber, B. L. and Wuertz, D. B.: Comparison of rawinsonde and wind profiler radar measurements, J. Atmos. Ocean. Tech., 7, 157–174, doi:10.1175/1520-0426(1990)007<0157:CORAWP>2.0.CO;2, 1990. 356

Zhang, Y., Klein, S. A., Boyle, J., and Mace, G. G.: Evaluation of tropical cloud and precipitation statistics of community atmosphere Model version 3 using CloudSat and CALIPSO data, J. Geophys. Res.-Atmos., 115, D12205, doi:10.1029/2009JD012006, 2010. 354

AMTD
8, 353–373, 2015

Combined observations with Doppler lidar, cloud radar and wind profiler

J. Bühl et al.

Table 1. Technical properties of the three main instruments involved in the combined measurements.

Designation	Doppler lidar	Wind profiler	Cloud radar
System type	HALO Streamline Doppler lidar	UHF wind profiler	MIRA-35 cloud radar
Wavelength	1.5 µm	0.62 m	8.5 mm
Pulse width	160 ns	1000 ns	200 ns
Range gate length	48 m	94 m	30 m
Integration time	2 s	10 s	10 s
Beam width	0.05 mrad	50 mrad	10 mrad
Pulse repetition rate	15 kHz	12.2 kHz	5 kHz
Average emitted power	200 mW	200 W	30 W

AMTD
8, 353–373, 2015

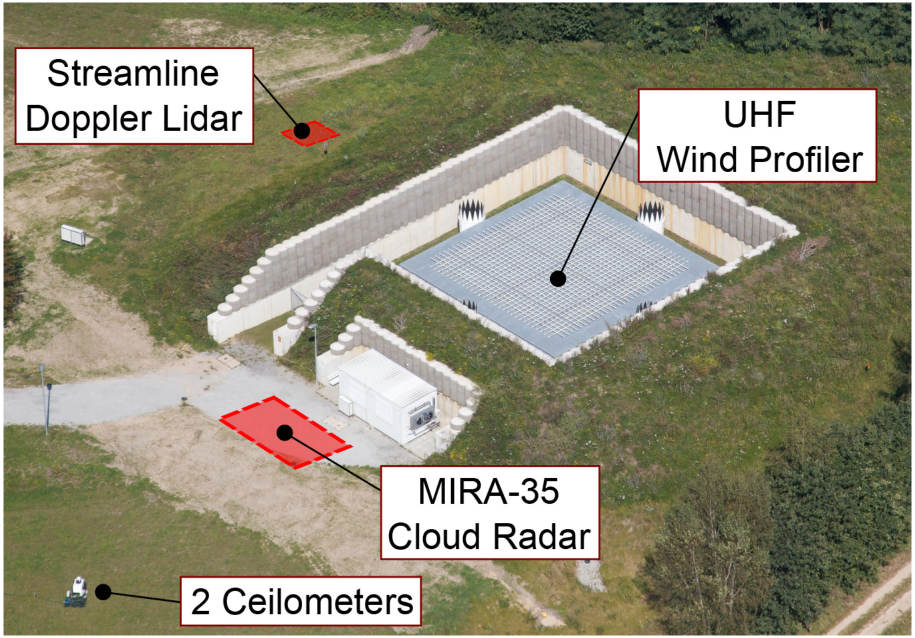

Figure 1. Aerial view of the wind profiler site at MOL. The photograph was taken in September 2011. In the meantime a Streamline Doppler lidar and a MIRA-35 cloud radar were deployed next to the wind profiler. (During the measurements presented here, all instruments were pointing vertical at all times. Operational parameters of the systems measuring vertical-velocity can be found in Table 1.)

AMTD
8, 353–373, 2015

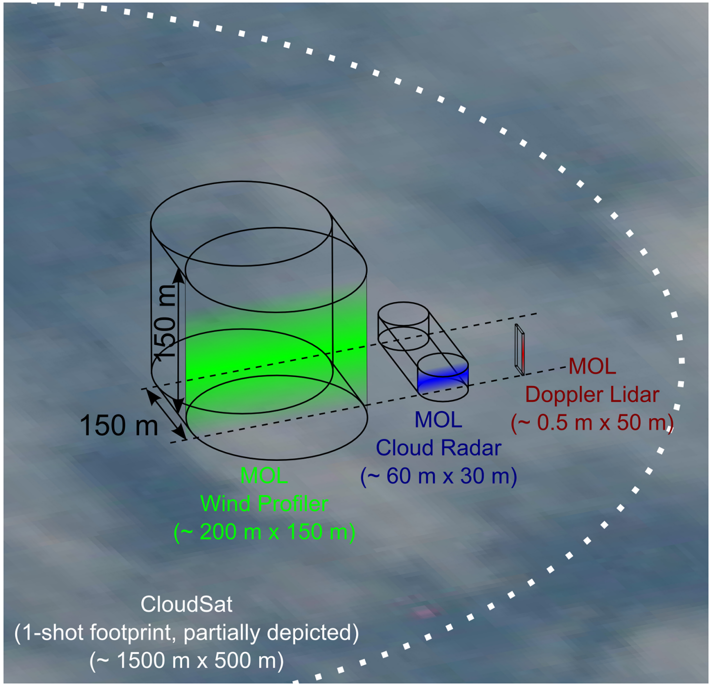

Figure 2. Comparison of observation volumina of Doppler lidar (red), cloud radar (blue) and wind profiler (green). Beam diameter times folded pulse length is given in brackets below the system names. The length interval of 150 m, indicated by two dashed lines, is the displacement of the cloud during an integration time of 10 s, when moving with an advection speed of $15\,\mathrm{m\,s^{-1}}$. In the background, a representation to scale of the altocumulus at 4000 m height is shown. In this figure, only the sizes of the observation volumina are shown. In reality, the observation volumina of cloud radar and Doppler lidar would overlap from about 1000 m height upwards. One pulse of the wind profiler fills a factor of $10^4 \ldots 10^5$ more space than the Doppler lidar.

AMTD
8, 353–373, 2015

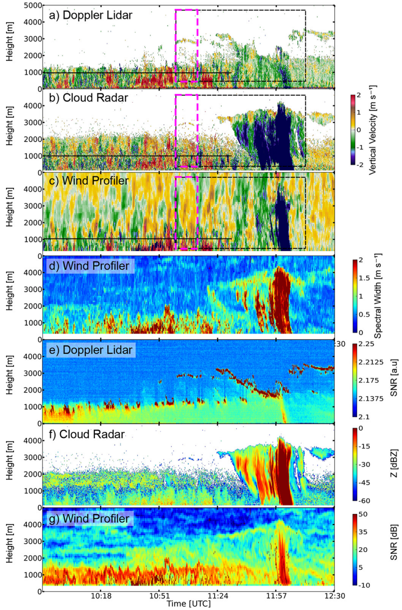

Figure 3. The combined measurements of Doppler lidar **(a** and **e)**, cloud radar (**b** and **f**) and wind profiler **(c**, **d** and **g)** are shown. Vertical velocities **(a–c)** and signal strenght **(e–g)** are shown for all instruments. For the wind profiler, additionally the width of the spectral peak is shown in **(d)**. The measurement shows a developing PBL with cumuli at the PBL top at about 1500 m height **(e)**. These clouds are not visible in the cloud radar, due to their low signal and contamination with pollen and insects. From 11:30 UTC a convective system producing warm rain approaches. It is visible from this overview that the signal strenghts of the different systems are completely disjunct, but their vertical velocity measurements overlap at cloud tops and in the PBL. In **(a)**, **(b)** and **(c)**, the straight black line marks the values from which the spectra in Fig. 4 were calculated, the pink dashed box marks the cloud studied in Fig. 5 and the black dashed box marks the area for which a velocity feature-classification was done in Fig. 6.

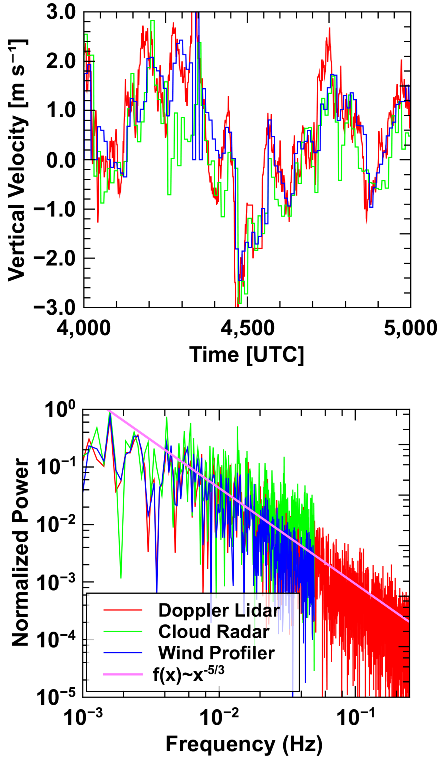

Figure 4. A combined vertical velocity measurement from 30 July 2013, 09:45 to 11:15 UTC at 1000 m height (as indicated in Fig. 3 with a black line) is shown. The Doppler lidar and wind profiler measurements seem to correspond well, outliers are mainly visible in the cloud radar measurements. The reason might be that the cloud radar mainly detects very large objects like pollen and insects, which produce a very strong spectrally very restricted signal, which is difficult to filter and to evaluate correctly. Insects can even be alive and actively counteract the vertical motions induced by the atmosphere. The power spectra of systems are similar with slightly elevated values for the cloud radar, which may be, again, due to noise influence.

AMTD
8, 353–373, 2015

Combined observations with Doppler lidar, cloud radar and wind profiler

J. Bühl et al.

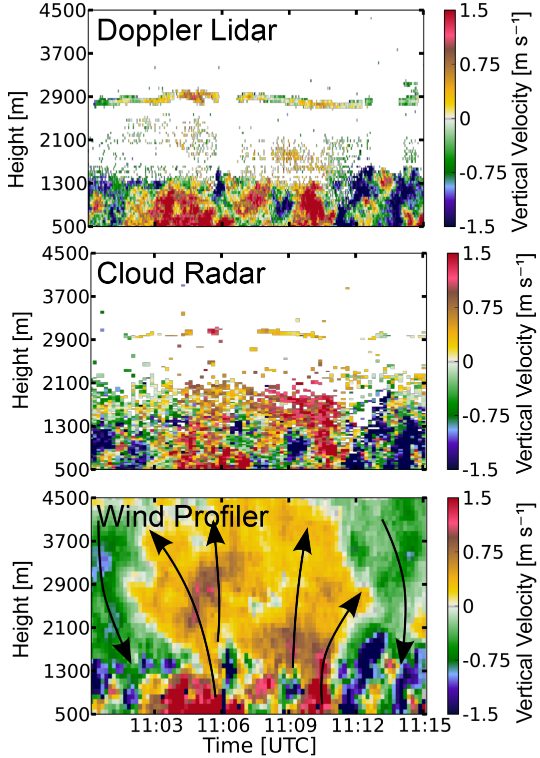

Figure 5. Magnified portion of Fig. 3 (pink dashed box, 11:00–11:15 UTC). The wind profiler gives unambiguous information about the vertical velocity of air in the vicinity of the cloud, which is detected by the Doppler lidar and partly by the cloud radar.

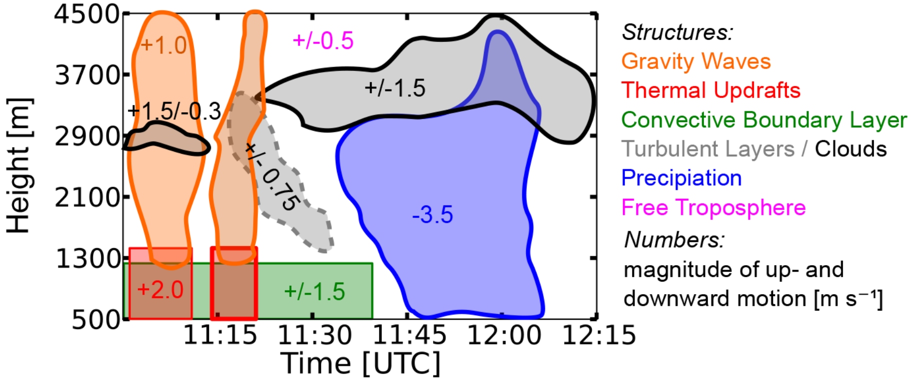

Figure 6. Features of vertical velocity are collected from the area marked in Fig. 3 with a black dashed box. The magnitude of detected vertical velocities is indicated with numbers, the different colors indicate different features described in the legend.

AMTD
8, 353–373, 2015

Combined observations with Doppler lidar, cloud radar and wind profiler

J. Bühl et al.

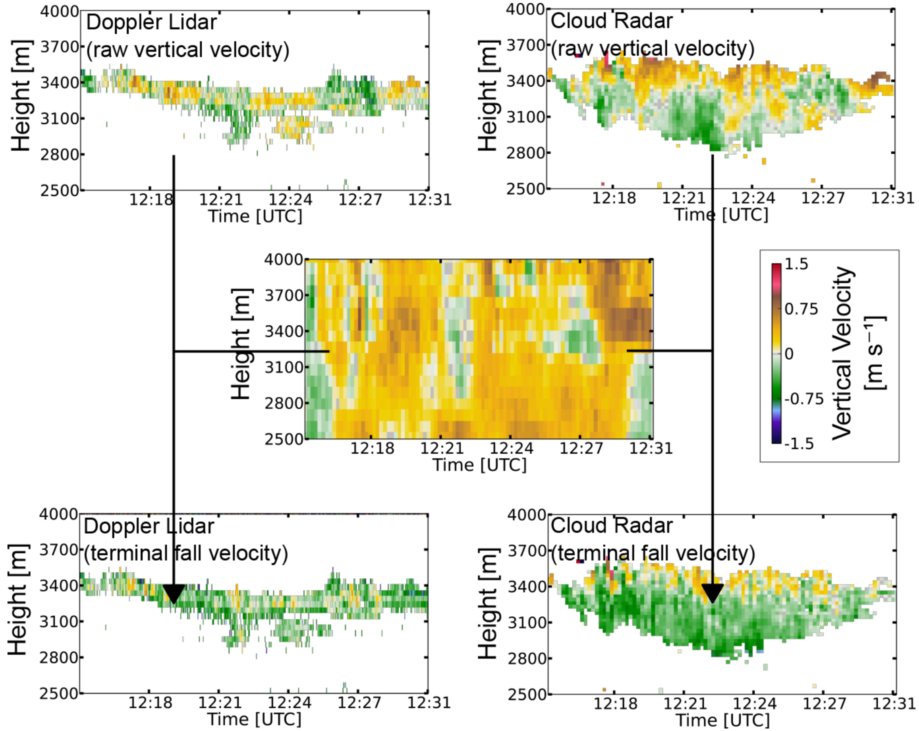

Figure 7. The vertical velocity of air measured by the wind profiler (center) is subtracted from the particle fall-velocities measured by Doppler lidar and cloud radar (top row). The resulting velocities (bottom row) are the terminal fall-velocity of the particles relative to the surrounding air. In the turbulent top layer, the turbulent motion is too fast and happens on too small scales to be correctly resolved by the wind profiler, resulting mostly in unrealistic upward velocities at the cloud top-layer.

AMTD
8, 353–373, 2015

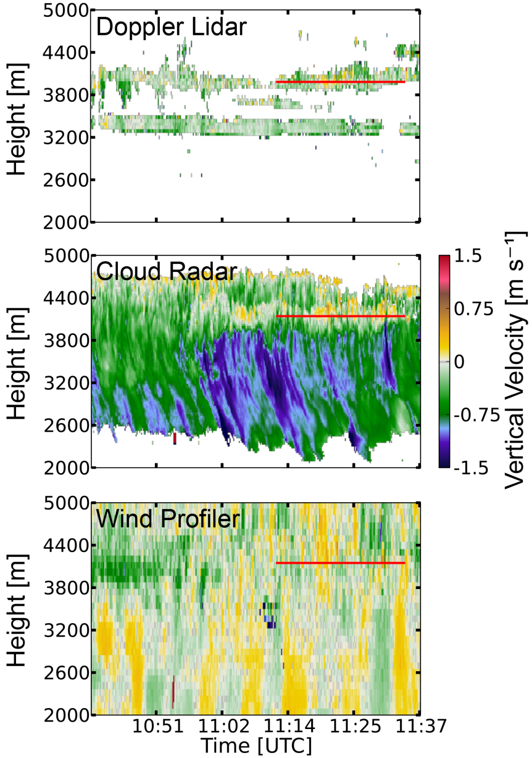

Figure 8. An example of vertical velocities measured in mixed-phase cloud layer recorded on 25 September 2013 at MOL. It is clearly visible that the information of Doppler lidar, cloud radar and wind profiler are mostly disjunct and represent turbulent motion in liquid layers (Doppler lidar), falling particles (Doppler lidar and cloud radar) and vertical air motion (wind profiler). The red line represents the vertical velocity values from which the turbulence spectra in Fig. 9 were computed.

AMTD
8, 353–373, 2015

Combined observations with Doppler lidar, cloud radar and wind profiler

J. Bühl et al.

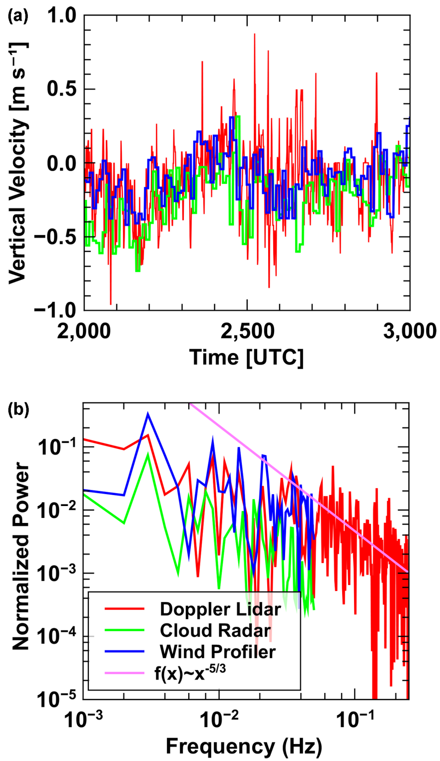

Figure 9. The vertical velocities **(a)** and their power spectra **(b)** are shown, taken at the red lines indicated in Fig. 8. It is clearly visible that only the Doppler lidar is able to sense the inertial subrange, where its power spectrum is close to the $f^{-5/3}$ line. The advantage of the Doppler lidar is also visible in **(a)**, where fast changes of vertical velocity on time scales smaller than 10 s are visible only in the Dopper lidar measurements (red).

AMTD
8, 353–373, 2015

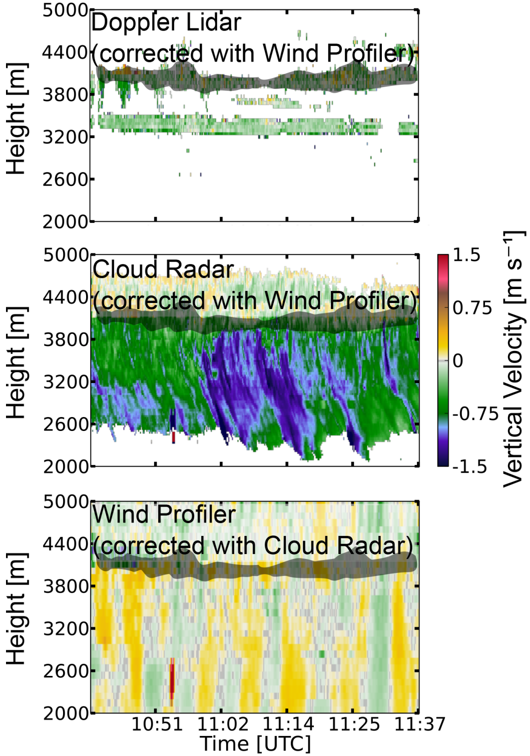

Figure 10. Demonstration of mutual vertical-velocity correction of the measurement shown in Fig. 8. A nearest-neighbor interpolation of the wind-profiler data was subtracted from the cloud-radar and Doppler lidar vertical velocities. The Doppler lidar is used to identify liquid layers (gray area). Inside and above these layers the subtraction procedure might be invalid because of several effects including liquid attenuation and small scale turbulence that cannot be resolved by the wind profiler.

AMTD
8, 353–373, 2015