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## 1. INTRODUCTION

The main purpose of eye-safe lidar ceilometers is regular reporting of cloud base height, vertical visibility, and cloud cover. These instruments operate unattended in harsh weather conditions. The application of state-of-the-art electronics increases the quality of backscatter profiles and thus qualifies modern ceilometers for the automated characterization of the boundary layer structure, like determination of the height of the mixing layer.

## 2. INSTRUMENT

This paper concentrates on the Vaisala Ceilometer CL31 (Figure 1, Ravila and Räsänen, 2004). Its single lens optics that uses the inner part of the lens for transmitting and its outer part for receiving light provides sufficient overlap of the transmitter and the receiver field-of-view over the whole measuring range. This results in an improved near-range performance compared to two lens systems and allows reliable detection of also the very low nocturnal stable layers below 200 m not seen by other instrument types.

The main performance characteristics of the ceilometer are listed in Table 1.



**Figure 1:** Vaisala Ceilometer CL31 and its single lens optical concept.

Minimum range resolution	5 m
Typical range resolution for boundary layer scans	10 m
Minimum report interval	2 s
Typical report interval for boundary layer scans	16 s
Measuring range for cloud base detection	0 ... 7500 m
Backscatter profile range	0 ... 7700 m
Range for boundary layer fine structure profiling	0 ... 3000 m
Eye-safety class	1M
Total height	1190 mm
Total weight	31 kg

**Table 1:** Main performance characteristics of the ceilometer CL31.

## 3. METHOD

In a reasonably transparent atmosphere the lidar backscatter profiles can be expected to track the aerosol concentration. This concentration, in turn, can be expected to reveal details about the vertical structure of the atmospheric boundary layer, such as mixing layer height.

The known methods to assess this quantity from backscatter profiles are generally based on the assumption that the mixed layer has a somewhat constant aerosol concentration that is distinctly higher than that of the air above (Steyn et al., 1999).

For detailed discussions of these methods see for example Eresmaa et al. (2006), Martucci et al. (2004), and Sicard et al. (2006).

A widely applied method is the gradient method that looks for the steepest decrease within the backscatter profile. Layer heights given in this paper are derived from local gradient minima. In most cases the lowest of these gradient minima marks the top of the mixed layer (Figure 2).

Additional local gradient minima are plotted in some of the examples given below. These reveal more information on the boundary layer structure like a residual layer in Figure 3 and elevated aerosol layers far above the mixed layer in Figure 7.

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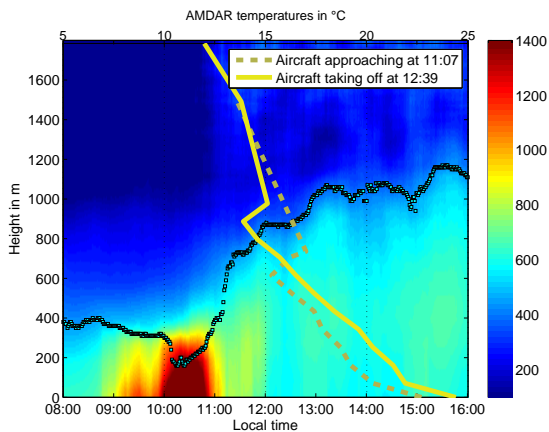
## 4. RESULTS

Routine boundary layer scans with the CL31 ceilometer are performed by research institutes and environmental agencies in numerous places. Examples from three of these sites and from two temporary measuring campaigns have been picked for detailed discussion within this section.

### 4.1 Convective boundary layer in Perth

The Western Australian Department of Environment and Conservation is using a CL31 ceilometer to test its usability for air quality applications. The installation site is the air monitoring station at Caversham close to Perth International Airport.

Figure 2 shows how mixing layer heights determined by the ceilometer can be verified by temperature profiles reported from aircraft participating in the AMDAR program.



**Figure 2:** Density plot of overlap and range corrected ceilometer backscatter profiles recorded in Caversham near Perth, Western Australia on May 9, 2007. Data are averaged over 30 min and 360 m. AMDAR temperature profiles indicate a depth of the convective boundary layer of about 600 m at 11:07 and 900 m at 12:39. These values are correlated well with the mixing layer heights reported by the ceilometer (black squares).

### 4.2 Convective and residual layer in Augsburg

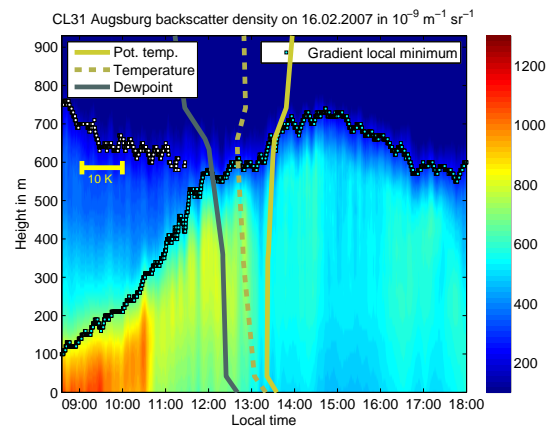
A CL31 ceilometer is installed at the Augsburg aerosol monitoring station in Augsburg, Germany. The example given in Figure 3 shows that the Bavarian continental climate favors the formation of convective boundary layers even in wintertime.

### 4.3 Mixing layer height below clouds in Seattle

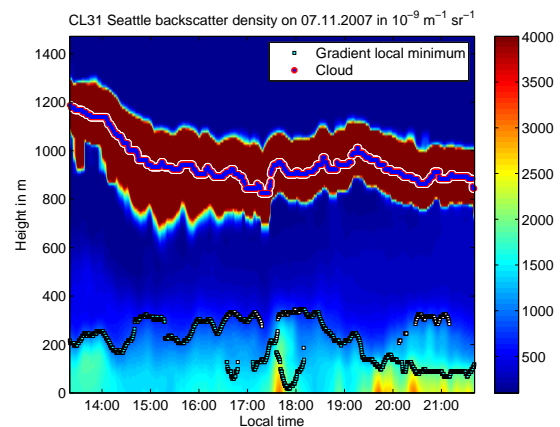
The Puget Sound Clean Air Agency in Seattle, WA is currently running a measuring campaign aimed at judging the ability of ceilometers to report stable boundary layers in autumn and winter.

Figure 5 gives an example where such layers are detected even in the presence of clouds. Up to two local

gradient minima are plotted to illustrate structures within the boundary layer aerosol concentration.



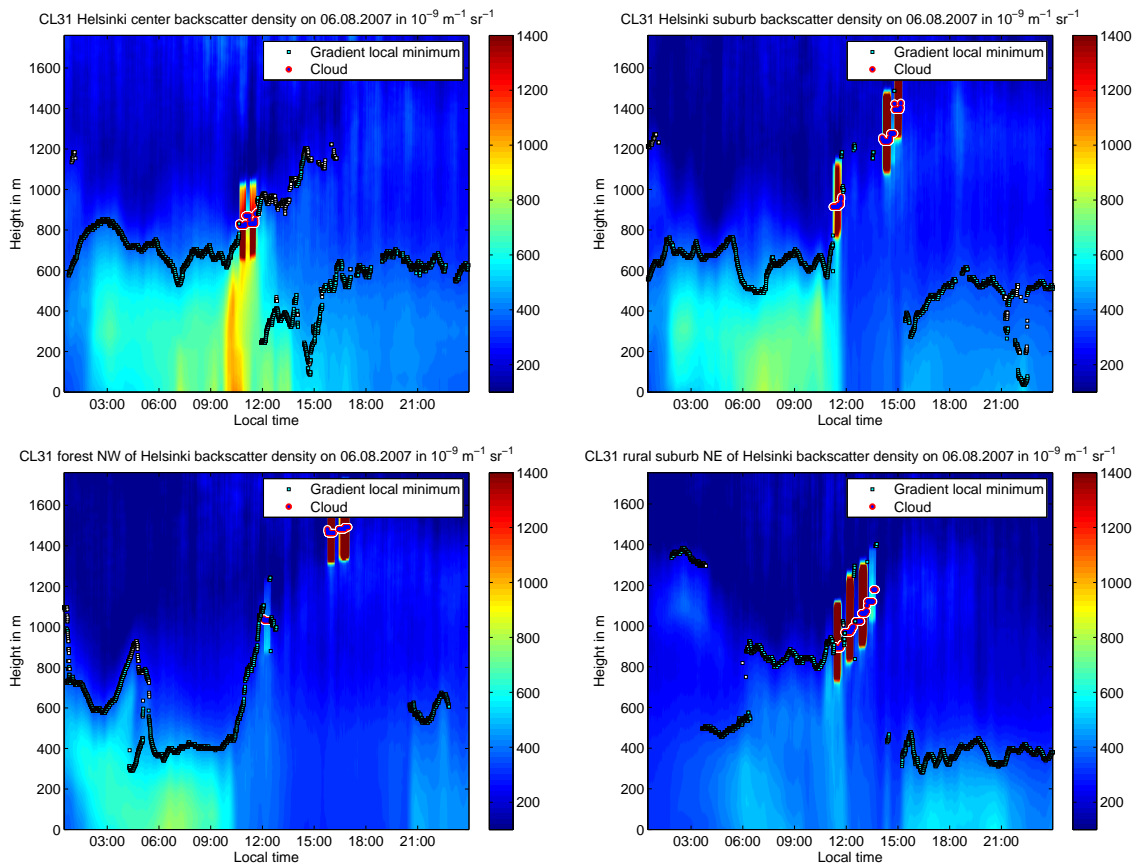
**Figure 3:** Ceilometer backscatter density plot showing the evolution of a convective boundary layer in Augsburg, Germany on February 16, 2007. At 12:00 this layer reaches the height of a residual layer originating from the preceding day. The 13:00 radiosounding indicates a mixing layer height of 650 m. Averaging parameters are 7 min and 180 m. Aerosol density is gradually decreasing with increasing mixing layer height.



**Figure 5:** Ceilometer backscatter density plots recorded at Lake Washington, 10 km NW of Seattle city center on November 7, 2007. There is a clear indication of a boundary layer below the cloud base. The evening hours show an increased aerosol density close to the ground with the formation of a low stable nocturnal layer. Averaging parameters are 10 min and 150 m.

### 4.4 Summer day evolution in and around Helsinki

The Finnish Meteorological Institute (FMI) and other Finnish industry and research institutes have established a research project of mesoscale meteorology, an observational network in Southern Finland. This network is called Helsinki Testbed and is expected to provide new information on observing systems and strategies, mesoscale weather phenomena and applications in a coastal high-latitude environment.



**Figure 4:** Ceilometer backscatter density plots recorded in and around Helsinki, Finland on August 6, 2007. The forest and rural installation sites are in a distance of about 50 km from the city center. There is a similar diurnal development at all sites with distinct local differences that illustrate the advantages of a mesoscale network for boundary layer investigation. The city center ceilometer shows enlarged aerosol concentration caused by the morning traffic. The formation of a convective layer is most distinct at the forest site that is most distant from the sea. Averaging parameters are 20 min and 350 m.

Data from Helsinki Testbed are available from <http://testbed.fmi.fi>.

Figure 4 shows the diurnal development of the boundary layer at four different ceilometer sites on a summer day. Regional distinctions reflect the different environmental conditions, the increased backscatter values in the morning hours at the city center site can be explained by traffic emissions. More examples from Helsinki Testbed are discussed in M $\ddot{u}$ nk $\ddot{e}$ l (2007).

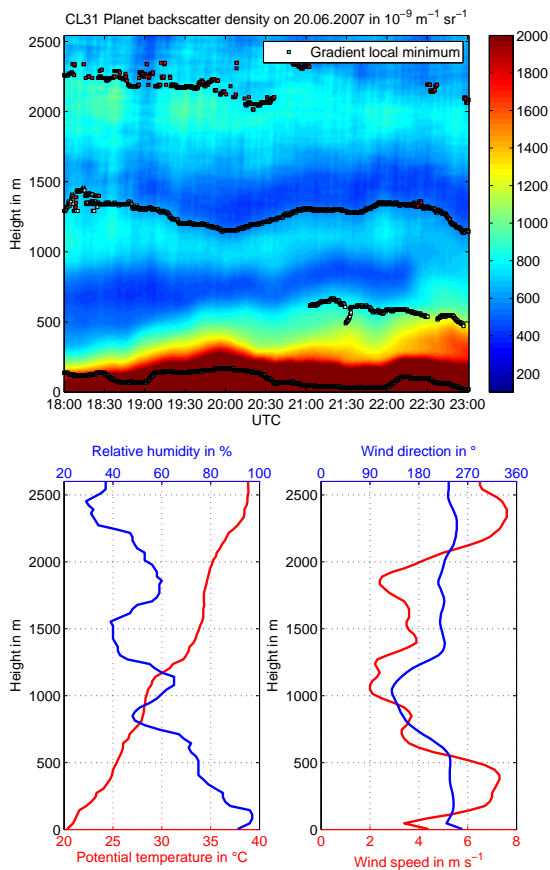
#### 4.5 Marine measurements in the Mediterranean

The research vessel Planet of the German Navy took part in a measuring campaign in the Ligurian Sea south of Genoa, Italy. A ceilometer was installed on the upper deck of the vessel. Backscatter profiles were recorded throughout the whole passage including the return voyage to Germany.

Figure 7 shows a consistent aerosol stratification up to a height of 2500 m. Emeis et al. (2007) have reported a similar behavior in an alpine valley in wintertime.



**Figure 6:** Research vessel Planet.



**Figure 7:** Ceilometer backscatter density and 21:00 UTC radiosounding plots recorded on board the vessel Planet in the Ligurian Sea on June 20, 2007. Above the low marine boundary layer there are two increased backscatter layers with local maxima around 1100 m and 2000 m. These layers are well correlated with local maxima in the relative humidity profile. A possible reason for this stratification is the strong wind shear from 600 m to 1300 m height that enables the inflow of dry winds from mountains situated east of the observing site. Averaging parameters are 10 min and 150 m.

## 5. CONCLUSIONS

The Vaisala CL31 lidar ceilometer is an affordable, reliable and essentially maintenance free tool for characterization of the boundary layer structure. Backscatter profiling is done in parallel with and not compromising of the cloud base height measurement.

The main parameter retrieved from the backscatter profile is the mixing height, but the high sensitivity also allows identification of subtle features in the planetary boundary layer. The single lens technology employed enables sensitive detection of even the very low altitude nocturnal boundary layers. The technology has reached the state where automated analysis is possible and the CL31 is already in operational use for this task.

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- Institute of Meteorology and Climate Research, Atmospheric Environmental Research Division, Forschungszentrum Karlsruhe GmbH, Garmisch-Partenkirchen, Germany.
- Puget Sound Clean Air Agency, Seattle, WA.

## 7. REFERENCES

- Emeis, S., C. Jahn, C. Münkel, C. Münsterer, K. Schäfer, 2007: Multiple atmospheric layering and mixing-layer height in the Inn valley observed by remote sensing. - *Meteorol. Z.* **16**, 415-424.
- Eresmaa, N., A. Karppinen, S. M. Joffre, J. Räsänen, H. Talvitie, 2006: Mixing height determination by ceilometer. - *Atmos. Chem. Phys. Discuss.* **6**, 1485–1493.  
<http://www.atmos-chem-phys-discuss.net/5/12697/2005/acpd-5-12697-2005.pdf>
- Martucci, G., M. K. Srivastava, V. Mitev, R. Matthey, M. Frioud, 2004: Comparison of lidar methods to determine the Aerosol Mixed Layer top. - In: Schäfer, K., A. Comeron, M. Carleer, R.H. Picard (Eds.): *Remote Sensing of Clouds and the Atmosphere VIII*, Proc. SPIE, Bellingham, WA, USA, Vol. 5235, 447-456.
- Münkel, C., 2007: Mixing height determination with lidar ceilometers - results from Helsinki Testbed. - *Meteorol. Z.* **16**, 451-459.
- Ravila, P., J. Räsänen, 2004: New laser ceilometer using enhanced single lens optics. - Eighth Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface at the 84th AMS Annual Meeting (Seattle, WA).  
[http://ams.confex.com/ams/84Annual/techprogram/paper\\_68092.htm](http://ams.confex.com/ams/84Annual/techprogram/paper_68092.htm)
- Sicard, M., C. Pérez, F. Rocadenbosch, J. M. Baldasano, D. García-Vizcaino, 2006: Mixed-Layer Depth Determination in the Barcelona Coastal Area From Regular Lidar Measurements: Methods, Results and Limitations. - *Bound.-Layer Meteor.* **119**, 135-157.
- Steyn, D.G., M. Baldi, R.M. Hoff, 1999: The detection of mixed layer depth and entrainment zone thickness from lidar backscatter profiles. - *J. Atmos. Oceanic Technol.* **16**, 953–959.