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Observation of the structure of the urban boundary layer with different ceilometers and validation by RASS data

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Abstract

Urban air quality assessment requires the knowledge of the temporal and spatial structure of the mixing layer, because this structure controls the vertical dilution of near-surface pollutants. The behaviour of the mixing layer is a consequence of vertical temperature and moisture profiles in the lower atmosphere so that remote sensing can be a suitable tool to monitor it. Three ceilometers, a Vaisala LD40 and two Vaisala CL31, have been operated for many months in the German city of Augsburg in order to observe the vertical aerosol distribution. Wind and temperature profile information have been obtained for a part of the period from radio-acoustic sounding system (RASS) observations. This paper investigates the abilities of the instruments and compares the information received by the ceilometers among each other and with temperature profiles from the RASS data.

Zusammenfassung

Die Bewertung der Luftqualität in städtischen Gebieten erfordert die Kenntnis der zeitlichen und räumlichen Struktur der Mischungsschicht, da die Eigenschaften dieser Schicht die vertikale Verdünnung von in Bodennähe freigesetzten Schadstoffen bestimmt. Das Verhalten der Mischungsschicht ist eine Folge der vertikalen Temperatur- und Feuchteverteilung, so dass Fernerkundung eine brauchbare Methode zu ihrer Erfassung sein kann. Drei Ceilometer, ein Vaisala LD40 und zwei Vaisala CL31, wurden für viele Monate in Augsburg zur Beobachtung der vertikalen Aerosolverteilung eingesetzt. Informationen zu Wind- und Temperaturprofilen wurden für einen teil des Beobachtungszeitraums mit einem radio-akustischen Sondierungssystem (RASS) erhalten. Diese Studie untersucht die Möglichkeiten der verwendeten Instrumente und vergleicht die beiden Ceilometer-Typen untereinander und mit den Temperaturprofilen vom RASS.

1 Introduction

There are a variety of interactions between the atmosphere and electro-magnetic and acoustic radiation including absorption, fluorescence, elastic (Mie and Rayleigh) and inelastic (Raman) scattering, reflection, and diffraction. These interactions offer several opportunities to detect features and properties of the atmosphere within specific frequency bands and has led to the development of several different remote sensing techniques in the last 70 years (DERR and LITTLE, 1970). Specific atmospheric boundary layer (ABL) research with these measurement techniques has been performed in the last about 30 to 40 years (WILZAK et al., 1996). Thus, remote sensing has become a powerful tool to get meteorological data like wind (EMEIS et al., 2007a) and flux (ENGELBART et al., 2007) profiles, information on the layering of the atmospheric boundary layer, and on the mixing-layer height (BEYRICH 1995, 1997; EMEIS et al., 2008b).

We will concentrate here on active remote sensing methods which comprise devices that emit a well defined signal and then receive the backscatter from the atmosphere. Especially we will deal with optical instruments (ceilometers) and a radio-acoustic device called RASS (radio-acoustic sounding system, MARSHALL et al., 1972). A ceilometer is a small LIDAR which records the vertical profile of the optical backscatter intensity in the near infrared due to the aerosol distribution in the lower atmosphere (up to three to four kilometres, MÜNKEL et al., 2003; WEITKAMP, 2005, MÜNKEL et al., 2007). The information is qualitative and cannot be calibrated unless the size distribution and the extinction properties of the aerosol particles are known for the whole profile. Two types of a RASS are available: a wind profiler (or Bragg or RADAR)-RASS and a Doppler- or SODAR-RASS (ENGELBART and BANGE, 2002). The RASS used in this study is a Doppler-RASS where a pair of electro-magnetic antennas complements a SODAR. This sounding system records the speed of acoustic shock fronts propagating vertically into the atmosphere. This information can be converted into a temperature profile up to several hundreds of metres above ground. Both instruments are operated continuously and

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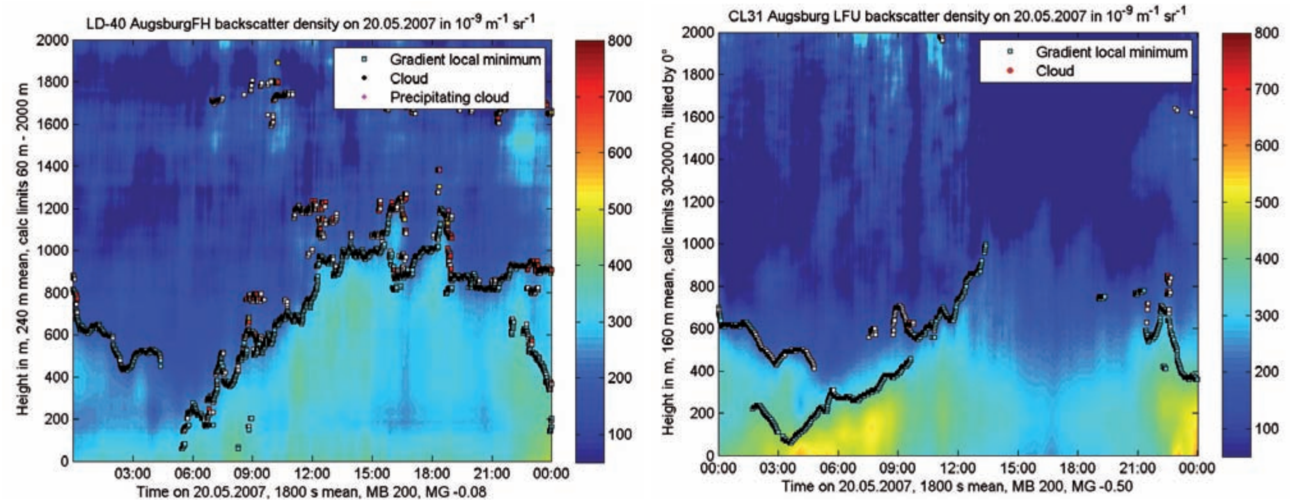

Figure 1: Comparison of 24 hours of optical backscatter intensity for heights up to 2000 m above ground from the Vaisala LD40 (left) and from the Vaisala CL31 (right) during the intercomparison exercise on 20 May 2007 in Augsburg, Germany. The dots indicate the results from the mixing-layer height determination algorithm described in EMEIS et al. (2007b).

give the diurnal variation of the boundary-layer structure.

The purpose of this paper is to present some results from the different ceilometers and to compare them to the RASS data. This can be done for the lower 540 m above ground because this height was the maximum range for the temperature profile detection from the RASS. Both instruments have a comparable height resolution within this range. When performing this comparison one has to keep in mind that the RASS data contains direct information on a state variable of the atmosphere – the temperature – whereas the ceilometer data contains only information on the aerosol distribution. It has to be assumed that this aerosol distribution follows the vertical thermal structure of the atmosphere. Therefore the influence of horizontal advection of aerosol layers should be negligible for a meaningful comparison to RASS profiles. It will be shown further that such a comparison provides a new understanding of the mixing of the near-surface atmosphere and their layering as well as an evaluation of the findings by each instrument.

2 Measurement site and instrumentation

In 2007 the remote sensing instruments have been placed in the centre and at the northern outskirts of Augsburg, a town with about 265 000 inhabitants that is situated about 60 km to the Northwest of Munich, Germany.

Two different types of ceilometers (MÜNKEL and RÄSÄNEN, 2004) have been used. One is a double-lens Vaisala LD40 with two parallel optical axes (one for the emitted light beam and one for the receiving telescope) using infrared light with a wavelength of 855 nm, a height resolution of 7.5 m, and a maximum range of 13000 m. The overlap of the two optical axes of this instrument is insufficient (less than 50 %) below a height of about 200 m. There is no overlap at all below 60 m above the instrument. The other ceilometer is the one-lens CL31 using infrared light of 910 nm, a height resolution of 10 m, and a maximum range of 7500 m. This instrument has a complete overlap in all range gates because the light is emitted through a drilled hole in the mirror of the receiving telescope. A sketch on the optical configuration of both instruments can be found in EMEIS et al. (2008a). The slightly different wavelengths and the unequal optical construction of both instruments lead to some differences in the recorded optical backscatter intensities. Both ceilometers were sounding at zero zenith angles. For both of them averaging over 2 min and 60 m is not sufficient to suppress the detection of some noise generated artefacts; 4 min and 120 m averaging works well for convective layers below 800 m but more reliable results are achieved with a time averaging interval of at least 10 min. The two CL31 were operated since September 2006 in the city centre and since October 2007 at the northern edge of the city. The second CL31 at the northern edge of the city replaced a LD40 which was operated from December 2006 to September 2007. The ceilometers have been brought together for two shorter intercomparison periods. The ceilometers output range corrected optical backscatter intensities. These backscatter intensities are then postprocessed by an automated MLH detection algorithm described in detail in EMEIS et al. (2007b).

The Metek RASS used in this study consists of a three-antenna SODAR using an acoustic frequency of 1600 Hz, a height resolution of 20 m, and a maximum range of about 1000 m. Two antennas were tilted at 16 degrees zenith angle, the third antenna was pointing vertical. The

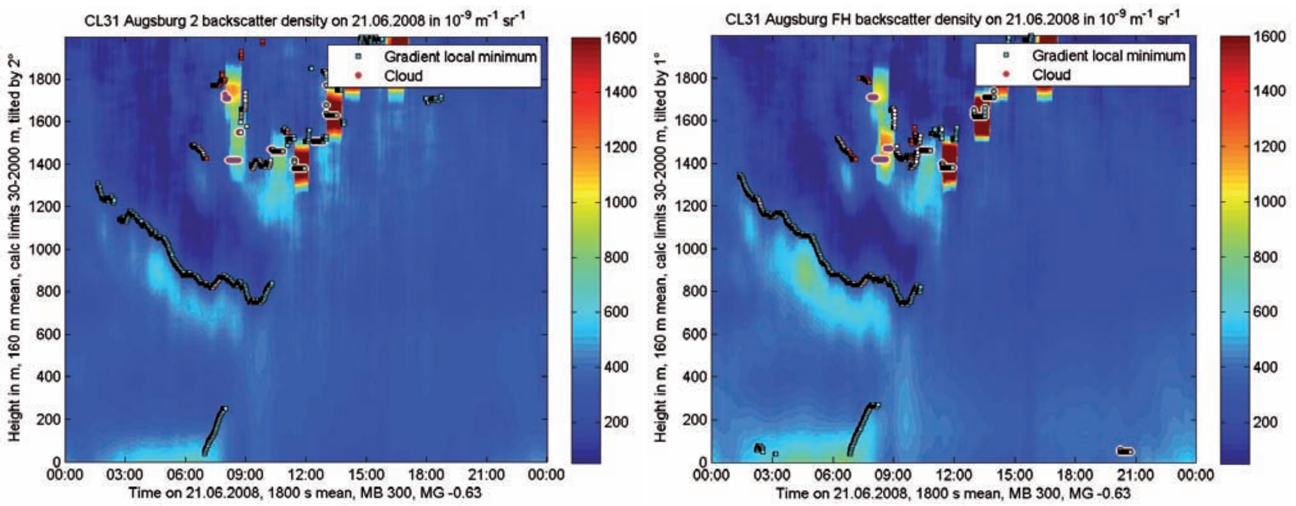

Figure 2: Comparison of 24 hours of backscatter data from two CL31 ceilometers for a height range up to 2000 m above ground during an intercomparison exercise on 21 June 2008. The dots indicate the results from the mixing-layer height determination algorithm described in EMEIS et al. (2007b).

acoustic signal propagation is observed by a two antenna radar system (3.8 m diameter each) working continuously at 474 MHz with a power of 20 W. The emitting antenna is placed 2.5 m upstream of the SODAR, the receiving antenna 2.5 m downstream. Data analysis provides the temperature profile up to 540 m and 20 m height resolution with an accuracy of 0.3 K. Additionally, a Doppler-RASS delivers all the data which a normal SODAR would also deliver: vertical profiles of the wind vector, and the acoustic backscatter intensity. The RASS is operated at the northern edge of the city since April 2008.

3 Results

First a result from the intercomparison period in May 2007 will be displayed here to illustrate the abilities of the two different ceilometers CL31 and LD40. Fig. 1 presents a comparison of the optical backscatter intensities from the two instruments on 20 May 2007. The dominating feature of this day is the development of a convective boundary layer which reaches its greatest height with about 1000 m above ground in the afternoon. An enhanced aerosol concentration can be seen close to the ground until 0900 hours indicating the presence of a stable surface layer. The largest differences between the CL31 and LD40 data are found in the lower 200 m close to the ground due to the different optical paths in the two instruments (one optical axis in the CL31 versus two optical axes in the LD40). Thus, the stable surface layer in the morning can only be detected from the CL31 data.

It turns out, as expected from the overlap characteristics described in the previous section, that the one-lens system (the CL31) is much better suited to investigate the aerosol distribution in the lower layers close to the ground. But also at greater heights some differences can be found, which probably have to be credited to the slightly different wavelengths of the two instruments.

But also two instruments of the same kind (here the two CL31) show some differences when bringing them together for an intercomparison. Fig. 2, taking data from 21 June 2008 as an example, demonstrates that both instruments essentially show the same features but some smaller details are slightly different. This is also a day with the development of a convective boundary layer (CBL) from 0800 hours onwards, which has low aerosol content. This developing CBL destroys a pre-existing stable surface layer. The top height of this CBL is around 1200 to 1400 m in the afternoon. In the evening the formation of a new shallow surface layer is starting and can be seen from the gradually increasing optical backscatter intensity near the ground. But the gradient of the optical backscatter intensity at the top of this newly formed layer is still not sufficient to be detected by the automated detection algorithm (EMEIS et al., 2007b).

For the lowest 540 m above ground the ceilometer data in Fig. 2 can be compared to the RASS temperature data in Fig. 3 (left). This temperature data shows a near-surface inversion with radiatively cooled air underneath in the morning hours until about 0800 hours CET and in the late evening after about 1900 hours. In both cases the height of the cold air mass is increasing with time. During daytime between 0900 and 1800 hours the air is more or less perfectly mixed (convective boundary layer) and no major vertical gradients in the potential temperature profiles are visible. The white areas in Fig. 3 indicate missing data. Here the horizontal wind speed is so large that the acoustic shock fronts from the SODAR part of the RASS are blown too far downstream and are no longer in the focus of the radar antennas.

By comparing the temperature profiles in Fig. 3 (left) with the aerosol backscatter profiles in Fig. 2 we see that

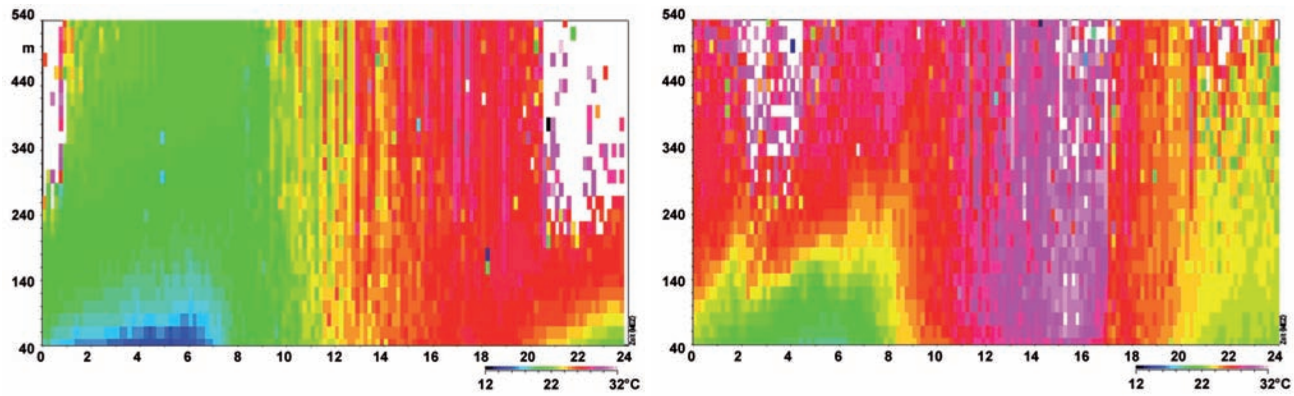

Figure 3: Potential temperature on 21 June 2008 (left) and 25 June 2008 (right) from 0000 to 2400 hours CET from RASS data for a height range between 40 and 540 m above ground. The colour scale ranges from 12°C (dark blue) to 32°C (purple). White pixels indicate missing and erroneous data (see text for an explanation).

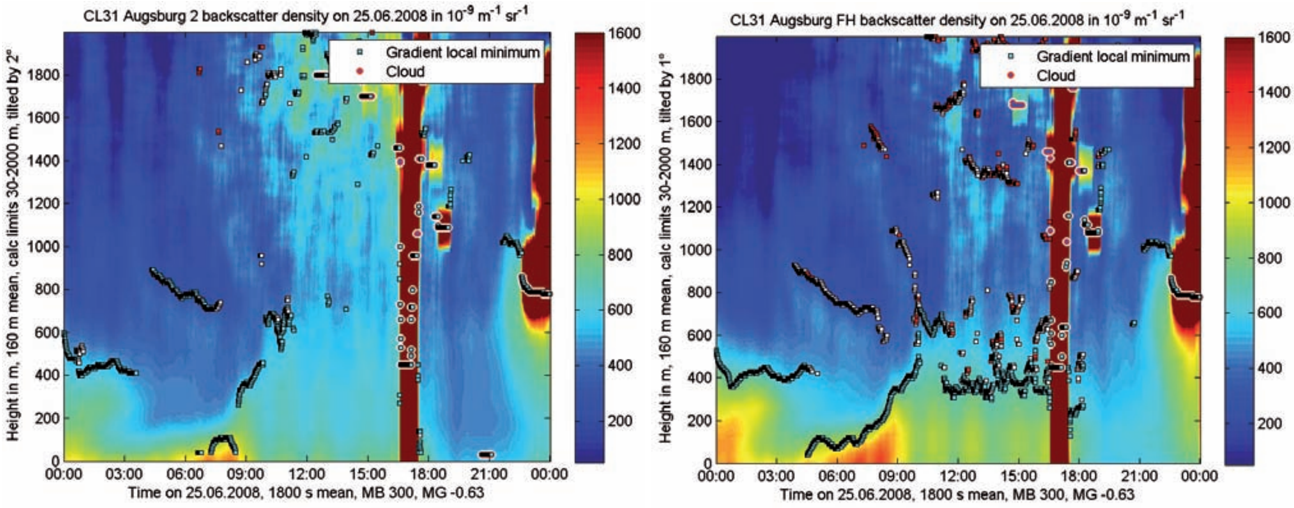

Figure 4: As Fig. 2, but for 25 June 2008.

the high optical backscatter intensity in the lowest 150 to 200 m between 0200 and 0800 hours CET in Fig. 2 corresponds well with the stable stratification seen there in Fig. 3 (left). Also the height of the aerosol-laden layer corresponds quite well to the height of the cool air layer with about 200 m from 0600 to 0800 hours and about 100 m in the later evening. The steady increase in time of the depth of the cool layer, however, is not depicted so well in the aerosol backscatter.

Fig. 4 and the right-hand frame in Fig. 3 show a second example for the comparison of ceilometer and RASS data. On this day the night-time stable layer has been deeper. In Fig. 3 (right) this cooler layer can be seen before 0900 hours CET and after 1900 hours. The depth is between 300 and 400 m in the early morning and 400 to 500 m in the late evening. Interesting is a double feature in the early morning hours. The top of the cool air rises rapidly from midnight until about 200 hours. Then, by advection (the wind direction is turning from southeast to southwest and the wind speed increases intermittently) the temperature structure is disturbed and a new more slowly deepening cool air layer forms. This feature is mirrored also in the optical backscatter by the aerosol in Fig. 4. An existing aerosol layer with a top around 400 m vanishes at about 0200 hours and starts to rebuild after the wind speed has returned to the low values before the disturbance at about 0300 hours. At about 1000 hours the onset of the CBL leads to a rapid vertical mixing. This can be seen from the vertically constant potential temperature and from the uniformly enhanced optical backscatter intensity for heights up to about 700 m. The dots at about 400 m around noon and in the early afternoon in the right-hand frame of Fig. 4 seem to be spurious. They are artefacts which have been generated internally by the ceilometer software. Fig. 3 (right) gives no indication that there is some layering at about 400 m in the early afternoon.

A second meteorological feature can be seen from Fig. 4 and the right-hand frame in Fig. 3. At about 1640 hours a rain shower moved over the station and the temperature decreased by about 5 degrees (Fig. 3, right). This rain shower is visible in Fig.4 as a brownish vertical band of very high optical backscatter intensity. After the shower the backscatter intensity in the CBL is reduced. From the vertically constant potential temperature it is obvious that this layer is still well-mixed, even after the shower. This well-mixed layer is preserved further as a residual layer above the newly forming stable surface layer in the later evening.

4 Discussion and conclusions

Ceilometers can be used for a long-term monitoring of the vertical structure of the atmosphere underneath the lowest cloud layer over specific surfaces as long as no rain, fog or strong mist obstructs the measurements up to heights of more than 2000 m above ground. Therefore, they are well suited for boundary layer investigations. In cloud-free air, ceilometers record the optical backscatter intensity from aerosols. For the derivation of the vertical structure of the air it has to be assumed that the aerosol distribution is adapted to this structure. Thus, horizontal advection of aerosol layers (especially of heavily polluted layers or smoke plumes) will yield misleading results. High wind speeds with strong turbulent mixing will prevent the formation of a distinct layering of the atmosphere and under these conditions ceilometer data does not yield meaningful results.

SODAR-RASS can be used for a long-term monitoring of the vertical structure of the lower part of the atmosphere which in most situations forms part of the atmospheric boundary layer. Because this measurement system is audible it can only be operated away from housing and recreation areas and administration buildings. The measurements of wind from the SODAR part of the instrument (maximum range: about 1000 m) are obstructed by strong ambient noise, rain, snowfall, and strong winds. The temperature measurements from the RASS part of the system (maximum range: about 550 m) are obstructed by high wind speeds because the sound waves emitted from the instrument are blown to the outside of the focal line of the electro-magnetic antennas. This deficiency is not crucial for air quality aspects because usually an adiabatic temperature profile can be assumed in such cases of strong winds.

The best chance for a combined operation of a ceilometer and a SODAR-RASS can therefore be expected on clear and dry days with low to moderate (up to about 10 to 15 m/s) wind speeds. The coupled operation of such a pair of instrumentation is thus well suited for the analysis of an atmosphere whose vertical structure is mainly determined by radiation processes. The whole depth of shallow stable nocturnal surface layers and the lower part (in the present case up to 540 m above ground) of daytime convective boundary layers can be monitored.

Here, in the present study, some examples from an investigation of an urban boundary layer have been discussed. We analysed three aspects:

- the differences between measurements by two different types of ceilometers
- the differences between measurements with the same type of ceilometer
- the relation between observed aerosol layering and the vertical temperature profile.

The comparison shows that the construction of the optical paths in a ceilometer has a crucial influence on the ability of such an instrument to monitor the surface layer. If the right type of a ceilometer is used (a single-lens system with one optical axis as the CL31) then the lower detection range is at about 30 to 40 m. Double-lens systems are not suited for the monitoring of the lower 200 m. Such instruments will miss regularly shallow and highly polluted stable surface layers.

It further turns out that even two ceilometer of the same type can show some differences. These differences have to be known in advance if such instruments are used e.g. in a network to detect horizontal spatial structures in an urban boundary layer. The output level of the instruments used in this study can be tuned in a certain range. If these instruments are operated to detect horizontal differences in the vertical structure of the atmosphere, this tuning should be done carefully in a comparison experiment prior to the real monitoring campaign.

Even more important is the tuning of the automated mixing-layer height algorithm described in EMEIS et al. (2007b), which has to be applied carefully. Different environmental conditions ranging from heavily polluted mega-cities to areas with low pollution levels (remote rural or polar areas) will require different tuning of this algorithm. Sometimes, if tuned to be too sensitive, such schemes report mixing-layer heights from internally generated artefacts from the instrument's software. Here, a lower sensitivity has been used and only in the right-hand frame of Fig. 4 some artefacts can still be observed.

The main task of this study was to compare the information on the vertical structure of the boundary layer from the ceilometer observations with the temperature profiles from the RASS. The vertical resolutions of both instruments were comparable. Thus, the temperature profiles can then be used to interpret the ceilometer results more closely. They can help e.g. to differentiate between physically meaningful and erroneous mixing-layer heights derived from the ceilometer data (at least for the height range of the RASS). In the shown examples in this study the increased optical backscatter in near-surface layers at night correlated well with the occurrence of cold stable surface layers. Simultaneously, missing vertical structure in the ceilometer results from noon and early-afternoon hours coincided with a vertically constant potential temperature indicating good vertical mixing.

For the potential design of a ceilometer network in a larger city in order to monitor the temporal and spatial variations of the vertical structure of the urban boundary layer probably one RASS is sufficient to assure a safe interpretation of the ceilometer data in the lower layers. These lower layers are the most decisive layers for the assessment of the air quality.

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