BOUNDARY-LAYER HEIGHT ESTIMATED BY CEILOMETER

Noora Eresmaa, Jari Härkönen and Ari Karppinen
Finnish Meteorological Institute, Helsinki, Finland

Abstract

Boundary-layer height, being one of the most important parameters in air-quality modeling, can be evaluated by several different device and methods. However, none of these methods alone can be used as an operative regime. The idealized 3-step method partly fulfills the gap. The method fits the backscattering profile of ceilometer measurements into a weighted profile of three error functions, thus it has potential for determining three vertical aerosol layer heights including boundary-layer height, residual layer and surface layer. The method has been tested by ceilometer and radiosounding monitoring data of the Helsinki Testbed Campaign. The results show a strong correlation between the 3-step method and soundings (correlation coefficient r = 0.89, N = 89).

Keywords: Mixing height, ceilometer

1. INTRODUCTION

The planetary boundary layer is the lowest part of the troposphere directly influenced by the ground. Since substances emitted into this layer disperse gradually horizontally and vertically through the action of turbulence, this layer is also called the mixing layer.

The height of the mixing layer, mixing height (MH), determines not only the volume available for pollutants to disperse (Seibert et al., 2000) but also the structure of turbulence in boundary layer (Hashmonay et al., 1991). Despite of the importance of mixing layer there is no unambiguous way to measure its height. The most common methods for estimation of MH are use of radiosoundings, remote sensing systems and parameterization methods. All these methods have advantages and disadvantages and consider different related or assumed properties of the boundary layer.

During the last decades the focus on MH estimation studies has been on remote sensing systems. As stated in Beyrich (1997) and Asimakopoulos et al. (2004, a proper MH determination from measurements must satisfy the following criteria:

- vertical profiles of atmospheric parameters cover layer between ground and 2 kilometers
- vertical resolution high (10-30 meters) to avoid uncertainties
- time resolution of 1 hour or less to describe the evolution of the boundary layer

One of the remote sensing instruments meeting these conditions is a ceilometer, which measures the atmospheric backscattering profile. The measured backscatter intensity depends mainly on particulate concentration in the air. Since in general aerosol concentrations in free atmosphere are lower than in boundary layer where most of the sources of aerosols are located, the boundary layer height can be distinguished by a strong gradient in the vertical back-scattering profile.

In this work we have developed and evaluated a novel method for estimating the MH from ceilometer observations in clear sky situations. The applied ceilometer-method requires that vertical distribution of aerosols in the atmosphere includes one or more normally distributed aerosol layers. The intensity of backscattered laser beams is illustrated by a series of cumulative normal distributions (figure 1), which is also the basis of the applied fitting function. Fitted ceilometer data determines the heights of the aerosol layers including MH. The reference MH is evaluated using radiosounding data. The detailed treatment of the methods is presented in section 2.

Noora Eresmaa, Finnish Meteorological Institute, P.O.Box 503, FI-00101 Helsinki, Finland
e-mail noora.eresmaa@fmi.fi

2. MEASUREMENTS AND METHODS

The data used in this study has been obtained in Helsinki Testbed project (2005-2007; http://testbed.fmi.fi) in Vantaa, Finland. The observations used in this study have been limited into conditions when the cloud base is above 2000 meters.

The instrument used in this study, Vaisala ceilometer CL31, measures the optical backscatter intensity of the air at a wavelength of 910 nm. The main technical properties of CL31 are listed in Table 1. For this study, the raw data of ceilometer profiles were obtained every 16 seconds. Furthermore, the original ceilometer data were averaged over the period of 15 minutes.

An idealized 3-step method has been used to obtain the mixing height from ceilometer observations. This method is a revision of the idealized backscattering profile method for one layer described by Steyn et al. (1999). In this 3-step method an idealized profile *B(z)* is fitted to the measured profile by formula

$$B(z) = \underbrace{\Delta B_{12} - \Delta B_{12} erf\left(\frac{z - H_{step1}}{\Delta h_1}\right)}_{STEP1} + \underbrace{\Delta B_{23} - \Delta B_{23} erf\left(\frac{z - H_{step2}}{\Delta h_2}\right)}_{STEP2} + \underbrace{\frac{B_3 + B_4}{2} - \Delta B_{34} erf\left(\frac{z - H_{step3}}{\Delta h_3}\right)}_{STEP3} \tag{1}$$

where $\Delta B_{12} = \frac{B_1 - B_2}{2}$, $\Delta B_{23} = \frac{B_2 - B_3}{2}$ and $\Delta B_{34} = \frac{B_3 - B_4}{2}$. B_1 is the backscatter on the ground, B_4 the mean backscatters in free atmosphere above the boundary layer and B_2 and B_3 the mean backscatters between steps. Location parameter H_{stepi} and scale parameter Δh_i are related to the altitude of step *i* and thickness of the entrainment layer (ELT) capping the step, respectively. The depth of ELT is typically defined by the mixing ratio of boundary layer and overlying air: the bottom of ELT is defined as a layer in which the mixing ratio is 4-10 %, while the top is defined by ratio of 90-98 %. Ordinates of the error function thus determine the ELT to be $2.77\Delta h_i$ for mixing ratio of 5 – 95 %. An illustration of the idealized profile is shown in figure 1.

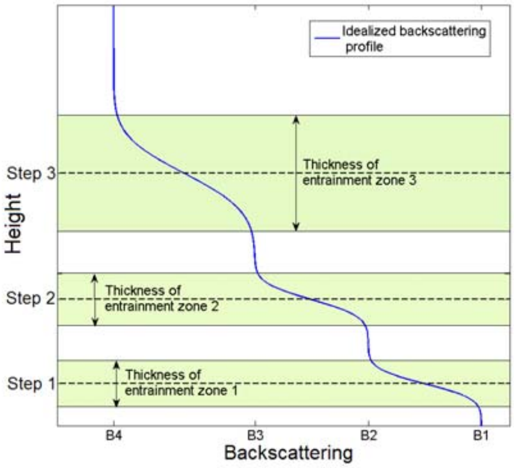

Figure 1. An illustration of the idealized backscattering profile.

The idealized 3-step method produces three estimates for the mixing layer height. We chose the strongest – i.e. at which the backscatter *B(z)* faces the biggest decrease – of these steps to mark the MH. However, some exceptions apply to this: the maximum estimate for the MH was set to 2200 meters and the MH may not exceed the height of the cloud.

To estimate the MH based on soundings we divided the soundings into convective and stable cases. This division was based on the temperature profile: if $\partial\theta/\partial z$ between ground and 50 meters above ground is negative, the case was considered convective (13% of investigated cases); otherwise stable (87% of cases). In convective situations, the MH was estimated from radiosoundings by following the dry adiabate starting at the surface up to its intersection with the actual temperature profile (Holzworth 1964, 1967). Thus, this so called "Holzworth-method" estimates the maximum mixing height.

The Richardson number method is traditionally used for MH estimation in stably stratified atmosphere. In this work we followed the Richardson number profile determined by formula of Joffre et al. (2001) with a critical number of 1. This formula aims at smoothing out some of the inherent fluctuations, especially of wind, between adjacent layers:

$$Ri(z_{i+1}) = \frac{g}{T_s}\frac{(\theta_{i+2}-\theta_i)(z_{i+2}-z_i)}{(V_{i+2}-V_i)^2} \tag{2}$$

T_s is the near-surface air temperature, θ_i the potential temperature and V_i the wind speed at corresponding level z_i. The sub-index i refers to the number of the layer of the profile.

3. RESULTS

We present here the results of comparison of ceilometer derived MH values with radiosounding estimates. The comparison between MH values estimated by the ceilometer and those from radiosoundings is shown in figure 2. The red stars represent the MHs based on step 1, blue circles MHs based on step 2 and black squares MHs based on step 3.

A total of 99 clear sky cases were analyzed. 10 observations were tagged and rejected from the statistical analysis because representing low backscattering signal conditions near the surface (rejected cases not shown in figure 2). A regression line was fitted to the remaining 89 cases yielding

$$MH_{ceilometer} = (0.83 \pm 0.09) MH_{sounding} + (46 \pm 47) \tag{3}$$

The error margins of Eq. (3) correspond to 95 % confidence level of the regression coefficients.

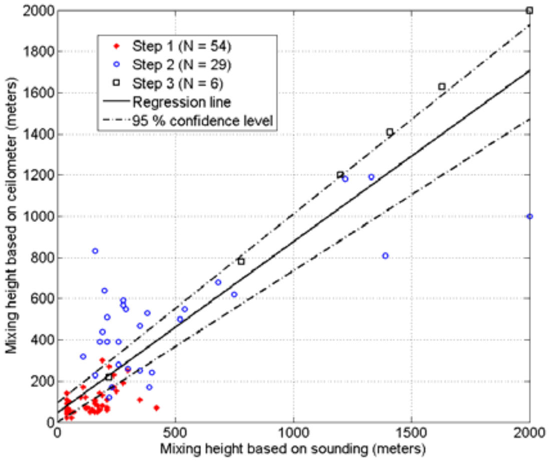

Figure 2. Comparison between mixing heights determined by the ceilometer and radiosoundings.

The correlation between all the MH estimates based on ceilometer and soundings is significant (correlation coefficient r = 0.89; correlation's t-score by Student's t-test t = 25.4; confidence level p > 99.9 %). Thus, on average the mixing heights predicted by the ceilometer agree well with the mixing heights determined by soundings. However, this is true only for the situations when the aerosol concentrations are high enough to provide reliable backscattering profiles.

4. DISCUSSION AND CONCLUSIONS

On average the fitting between MHs derived from soundings and ceilometer observations is good. However, large relative differences occur at low MHs, i.e. MHs estimated by steps 1 and 2. These differences bring out the biggest weakness of the method; the importance of choosing the right step indicating the mixing height. The largest outliers in figure could have been eliminated choosing higher/lower step. However, as the fitting and choosing of the step has been done automated, there are always some outliers not fitting the main group.

Besides the choice of the right step the idealized 3-step method has two other weaknesses: The initial values of the fitting have a strong impact on the result, thus these values have to be selected very carefully. In addition to this, the threshold of aerosol concentration restricts the ceilometer application for determining MH into at least moderately polluted regions. The current method is also sensitive to atmospheric water molecules limiting the use in foggy or cloudy conditions. On the other hand, the described 3-step method provides valuable data from vertical distribution of aerosols in the boundary layer and may be suitable also for observing size distributions of atmospheric aerosols in future.

We emphasize that the distributional terms in equation (1) are not limited to normal distribution as applied in the current work. Actually, observed deviations of the two lowest levels refer to some bounded-type distributions and equation (1) might be a combination of bounded and unbounded distributions. This obviously diminishes the sensitivity of the fitting from the initial values and will be studied in the future.

References

Asimakopoulos, D. N., Helmis, C. G., Michopoulos, J., 2004. Evaluation of SODAR method for the determination of the atmospheric boundary layer mixing height, *Meteorology and Atmospheric Physics*, 85, 85-92

Beyrich, F., 1997. Mixing height estimation from sodar data – a critical discussion, *Atmospheric environment*, 31, 3941-3953

Hashmonay, R., Cohen, A., Dayan, U., 1991. Lidar observations of atmosphere boundary layer in Jerusalem, *Journal of Applied Meteorology*, 30, 1228-1236

Holzworth, C. G., 1964. Estimates of mean maximum wind depths in the contiguous United States, *Monthly Weather Review,* 92, 235-242

Holzworth, C. G., 1967. Mixing depths, wind speeds and air pollution potential for selected locations in United States, *Journal of Applied Meteorology*, 6, 1039-1044

Joffre, S. M., Kangas, M., Heikinheimo, M., Kitaigorodskii, S. A., 2001. Variability of the stable and unstable boundary-layer height and its scales over a boreal forest, *Boundary-Layer Meteorology*, 99, 429-450

Seibert, P., Beyrich, F., Gryning, S. E. Joffre, S., Rasmussen, A., Tercier, P., 2000. Review and intercomparison of the mixing height, *Atmospheric Environment*, 34, 1001-1027

Steyn, D. G., Baldi, M., Hoff, R. M., 1999. The detection of mixed layer depth and entrainment zone thickness from lidar backscatter profiles, *Journal of Atmospheric and Oceanic Technology*, 16, 953-959.