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Mixing height determination by ceilometer

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Abstract

A novel method for estimating the mixing height based on ceilometer measurements is described and tested against commonly used methods for determining mixing height. In this method an idealised backscatter profile is fitted to the observed backscatter profile. The mixing height is one of the idealised backscatter profile parameters.

An extensive amount of ceilometer data and vertical soundings data from the Helsinki area in 2002 is utilized to test the applicability of the ceilometer for mixing height determination. The results, including 71 convective and 38 stable cases, show that in clear sky conditions the mixing heights determined from ceilometer based aerosol profiles and BL–height estimates based on sounding data are in a good agreement. Rejected outlier cases corresponded to very low aerosol concentrations in the mixed layer leading to a very weak aerosol backscatter signal in the lowest layer.

1 Introduction

The planetary boundary layer (PBL) is the layer where the earth's surface interacts with the large scale atmospheric flow. Since substances emitted into this layer disperse gradually horizontally and vertically through the action of turbulence, and become completely mixed if sufficient time is given and in the absence of sinks or sources, this layer also called the mixing layer (Seibert et al., 1998).

The PBL height or mixing height (MH) is a key parameter in air pollution models determining the volume available for pollutants to dispersion (Seibert et al., 2000) and the structure of turbulence in the boundary layer (Hashmonay et al., 1991). In spite of its importance there is no direct method available to determine the MH. The most common methods for determining the MH are utilisation of radiosoundings, remote sounding systems and parameterization methods. All these methods have advantages and disadvantages and consider different related or assumed properties of the PBL. Thus, it is relevant to develop and evaluate new techniques or methods in order to

lower the inherent uncertainty involved in the determination of the MH.

Among novel remote sensing methods, a promising one is the ceilometer, based on the lidar-technique, which measures the aerosol concentration profile. Since in general aerosol concentrations are lower in the free atmosphere than in the mixing layer where most sources of aerosols are located, it can be expected that MH is associated with a strong gradient in the vertical back-scattering profile.

The objective of this work was to examine the potential of a ceilometer in determining the mixing height in clear sky conditions. The reference mixing height was determined utilizing Radiosoundings, several diagnostic formulas for MH and the predictions of a meteorological preprocessor model MetPP-FMI.

2 Data and techniques

The data used in this work were obtained at the premises of Vaisala Oyj, Vantaa , Finland, during one year period 5 December 2001–10 November 2002.

2.1 Measurements

2.1.1 Ceilometer

The Vaisala single-lens ceilometer CT25K (Vaisala Oyj, 2002; Emeis et al, 2004) measures the optical backscatter intensity of the air at a wavelength of 905 nm (near infrared). Its laser diodes are pulsed with a repetition rate of 5.57 kHz. The lens has a focal length of 377 mm and an effective diameter of 145 mm. Laser beam full divergence and field-of-view divergence of the receiver are 1.4 mrad each. Because of the monostatic optical system and the small divergence multiple scattering effects are negligible and the Mie scattering with scattering angles between 179.9° and 180.1° is dominant. Additional technical characteristics are given in Table 1.

The CT25K samples the return signal every 100 ns from 0 to 50 μs, providing a spatial resolution of 15 m from the ground up to an altitude of 7500 m (Vaisala Oyj, 2002).

For safety and economic reasons, the laser power used is so low that the noise exceeds the backscattering signal. This can be overcome by summing a large number of return signals, so the desired signal will be multiplied by the number of pulses, whereas the noise, being random, will partially cancel itself. The degree of cancellation for white (Gaussian) noise equals the square root of the number of samples. However, this processing gain cannot be extended ad infinitum since the environment is constantly changing.

The backscatter intensity depends mainly on the particulate concentrations in the air. As the size of particles varies with their moisture content, the reflectivity is influenced by atmospheric humidity, too. Clouds, fog and precipitation inhibit measurements. The performance of the CT25K ceilometer is sufficient for analysing boundary-layer structures. Compared to more sophisticated LIDAR systems commonly used for these investigations it has several advantages, including the low first range gate, its ability to operate eye-safe and maintenance-free for several years in any climatic environment with just some regular window cleaning, and its comparably low price. Main disadvantage due to the low emitted power is its relatively low maximum range, but for mixing layer studies (mostly below 3 km) this does not present a problem.

Raw ceilometer profiles were obtained every 15 s (integrated over 65 536 individual pulses). For this study, the original ceilometer data were averaged over period of 30 min.

2.1.2 Radiosoundings

The reference mixing height was determined from the analysis of radiosoundings. Soundings were performed regularly during the observation period, mainly during working hours. The launching site was 100 m from the ceilometer. However, due to frequent cloudiness at the study site, a large amount of the soundings had to be rejected. The remaining 109 soundings were divided into convective (N=71) and stable (N=38) cases.

2.2 Method for estimating the mixing height from ceilometer measurements

The mixing height h was determined from the backscattering profile using the method described by Steyn et al. (1999). In this method an idealized backscattering profile $B(z)$ is fitted to measured profile by the formula

$$B(z) = \frac{B_m + B_u}{2} - \frac{B_m - B_u}{2}\mathrm{erf}\left(\frac{z-h}{\Delta h}\right) \quad (1)$$

where B_m is the mean mixing layer backscatter, B_u is the mean backscatter in air above the mixing layer and Δh is related to the thickness of the entrainment layer capping the PBL in convective conditions.

We define new constants $A1$ and $A2$ so that $A1=(B_m+B_u)/2$ and $A2=(B_m-B_u)/2$. An idealised profile structure corresponding Eq. (1) is illustrated in Fig. 1. In this idealised case the backscatter above mixing layer and inside mixing layer have constant values B_u and B_M correspondingly and MH is defined to be the height of the centre of the entrainment layer.

The fitting procedure was automated with Matlab 7.0 software package (Math Works Inc.). The parameter $A1$ in Eq. (1) is kept fixed during the fitting. However, the fitting is strongly dependent on the initial values; therefore it is more efficient if these values are chosen according to the initial order-of-magnitude estimate for the mixing height based on stability conditions and the structure of the backscattering profile.

If the mixing height is initially estimated to be low (less than 700 m), $A1$ is chosen to be the backscattering intensity near the surface. Otherwise $A1$ is defined as the mean backscattering intensity within the mixing layer. In such a case, a running mean is also used for smoothing the backscattering profile.

The effect of the choice of initial values (mainly $A1$) on an actual profile fitting is shown in Fig. 2. This case displays a strong gradient near the surface, topped by a layer of nearly constant backscattering. Another strong gradient can be observed at the top of the convective mixing layer (ca. 2000 m). If the value of $A1$ is chosen erroneously based on the lowest strong gradient ($A1=250$), the resulting mixing height

is too low, around 1000 m. If the choice of $A1$ is based on the second strong gradient corresponding to the mean backscattering in the layer below 2000 m ($A1=110$), also the mixing height is determined correctly to be ca. 1600 m.

Though the ceilometer can observe the atmosphere up to 7500 m, it is not relevant to use the whole backscattering profile due to the strong white noise above 4000 m. Therefore, the maximum height of the used profile was set at 4500 m, but if the initial mixing height was lower than 1500 m, only the first 3000 m of backscattering profile was used.

2.3 Determination of the reference mixing height

2.3.1 Mixing height based on radiosoundings

In convective situations, the MH was estimated from radiosounding temperature profiles using the Holzworth-method (Holzworth, 1964, 1967). Its principle is to follow the dry adiabatic starting at the surface up to its intersection with the actual temperature profile (Fig. 3). Thus, the method determines the maximum mixing height. This method depends strongly on the surface temperature (Seibert et al., 2000), and a high uncertainty may occur in a situation without a clear inversion at the convective boundary layer top.

In stable situations, the Richardson number Ri method has traditionally been used for determining the mixing height (Vogelezang and Holtslag, 1996). This method determines the equilibrium mixing height rather than the actual mixing height (Zilitinkevich and Baklanov, 2002) since the MH h is identified as the level where Ri is equal or larger than a pre-fixed critical value. Thus, its accuracy is not very high, but the MH is not well defined either due to low and gradually decreasing turbulence intensity with height. In this project the Richardson number profile was determined by the formula of Joffre et al. (2001), which aims at smoothing out some of the inherent fluctuations (especially of

wind) between adjacent layers:

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

where 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.

Though the traditional value of the critical *Ri*-number is 0.25, there is evidence that it actually depends on various external conditions such as roughness and free flow stability or the Brunt-Väisälä frequency (Zilitinkevich and Baklanov, 2002). Several studies have found better fits with higher *Ri*-values, in general in connection with a larger-scale approach (Joffre, 1981; Maryon and Best, 1992). The critical value used here was 1.0. Figure 4 displays an example of an observed *Ri*-profile in Vantaa.

In absence of wind profile data, the reference mixing height was determined in three different ways using the sole temperature profile. In method 1, the MH was determined as the height of the surface inversion (Fig. 5a). In method 2, the MH was determined as the lowest level at which the virtual potential temperature begins to stray significantly from a linear profile (Wetzel, 1982; Fig. 5b). Under conditions of strong winds the potential temperature increases only slightly in the mixing layer (Zeman, 1979; Fig. 5c). This layer is capped by a quite shallow zone with a very sharp increase in temperature (Seibert et al., 1998). If the MH can be determined in more than one way, the average is used.

2.3.2 Mixing height estimated by the meteorological model MetPP-FMI

The mixing height was also determined using the preprocessor model MetPP-FMI (Karppinen et al., 1997). The details of the mixing height scheme can be obtained from Karppinen et al. (1998) and Seibert et al. (2000). The evaluation of the boundary layer height is based upon routine radiosounding data. The model utilizes the midday (12:00 UTC) and midnight (00:00 UTC) soundings. Its main principles are that, under

stable and neutral conditions, the MH is proportional to the friction velocity determined from the wind profile following the Monin-Obukhov similarity theory and to the heat flux integral (accumulated heat) as determined by the temperature difference between two subsequent profiles. Under unstable conditions, the MH is determined from the Tennekes (1973) model utilizing the measured temperature profiles and modelled stability parameters.

2.3.3 Diagnostic methods for determining mixing height in stable situations

In stable situations the mixing height is determined using three different diagnostic methods. The first method used is a heuristic model for the mixing height derived by Joffre and Kangas (2001):

$$h = C_{st} L_N^{3/4} L^{1/4} \quad (3)$$

where C_{st}=7.71 is an empirical constant, L is the Monin-Obukhov length and $L_N = u_*/N$, where u_* is the friction velocity and N the Brunt-Vaisala frequency, which is determined from the radiosonde temperature profiles on a 200 m thick layer about 100 m above the mixing layer.

The Monin-Obukhov-length L and the friction velocity u_* are determined iteratively from the two lowest radiosounding observations (approximately 5 and 15 m). It is clear that due to the known strong flings of the balloon in the first seconds of the sounding and to the sub-urban environment (heterogeneity), these estimates of u_* are very uncertain and results should be considered with care.

The second method determines the MH based on the classical neutral formula involving the friction velocity u_* and the Coriolis-parameter f (Rossby and Montgomery, 1935)

$$h = a \frac{u_*}{f} \quad (4)$$

The proposed values for the empirical constant a are scattered in the range of a=0.05–0.3. Here we have used the value a=0.14, corresponding roughly to the median of the values presented in literature and also coinciding with the value presented by Arya (1981) based on sodar data.

The third method is a classical approximation for the height of the stable Ekman-layer (Zilitinkevich, 1972)

$$h = B_s \sqrt{\frac{L u_*}{f}} \tag{5}$$

We have used value B_s=2 for the empirical proportionality constant according to the original Zilintiekevich (1972) estimate.

3 Results and discussion

We present here the results of the comparison of ceilometer derived MH values with radiosounding estimates and various parametrisation scheme values. The analysis is performed separately for convective and stable conditions. This multi-estimate approach is partly driven by both the fuzziness of the MH concept and the inherent limitations of each single model or method.

3.1 Convective situations

The comparison between MH values estimated by the ceilometer and those from radiosoundings is shown in Fig. 6. A total of 71 clear sky cases were analysed. Fifteen observations were tagged and rejected from the statistical analysis because they represented low backscattering signal conditions near the surface. A regression line was fitted to the remaining 56 observations (blue dots) yielding:

$$h_{\text{ceilometer}} = (0.80 \pm 0.10) h_{\text{sounding}} + (47 \pm 89) \tag{6}$$

The correlation between the MH-estimates of these two methods is very significant (r=0.90; t=15.2; p<0.0001). Thus, the mixing heights predicted by the ceilometer agree well with the mixing heights determined by the parcel method. However, this holds true only for the situations where the aerosol concentrations are high enough to provide reliable backscatter profiles, this method can not provide information on the MH if the backscatter signal near the surface is too low (red dots in Fig. 6).

On the average, the mixing height determined from radiosoundings is 8% higher than the one determined by the ceilometer. This difference is rather small in spite of the fact that these two methods differ in the physical definition of the mixing height. The Holzworth-method determines the *maximum* height of mixing from the potential temperature profile, while the ceilometer "feels" the height at which the aerosol profile reaches the edge of the mixing layer (with the implied assumption that aerosol are scarcer above the MH). Thus, at least qualitatively, this observed difference has a reasonable physical explanation.

An example of a full 24-h period of ceilometer observations is displayed in Fig. 7. It can be easily seen how turbulence gets stronger and the MH grows as the sun rises. On the other hand, the unrealistically high MH values during night time (01:00–03:00 a.m.) provide a good illustration of a potential problem using this method operationally. In this case the algorithm used for obtaining the initial values of the profile fitting procedure leads to erroneous result, as the night time residual aerosol layer is interpreted as the real mixed layer. Although this kind of misinterpretation can be easily avoided if other meteorological measurements are considered in the MH assessment, further work is still required to achieve a completely automatic algorithm for mixing height determination.

3.2 Stable situations

3.2.1 Comparison of mixing height estimated by the ceilometer and radiosoundings

The comparison between the MHs measured by the ceilometer and those estimated from radiosoundings (through the *Ri*-method) is shown in Fig. 8. A total of 38 clear sky cases were analysed, of which only one was rejected from the statistical analysis due to low backscattering signal near the surface. The statistical analysis yielded the following regression line for the remaining 37 observations:

$$h_{\text{ceilometer}} = (0.62 \pm 0.16) h_{\text{sounding}} + (120 \pm 34) \quad (7)$$

The correlation between the two estimates is also in stable case very significant (r=0.80; t=7.9; p<0.0001). On average, the mixing height determined from the sounding is 25% higher than the one determined by the ceilometer. Thus, the agreement is less than for unstable conditions but this was expected as the height of the MH is less well-defined under stable conditions without marked discontinuities in meteorological and probably aerosol profiles.

Figure 9 displays a period with a marked surface inversion that occurred on 2–3 January 2002. In case of a cloudy situation the MH determined by the ceilometer is zero. It can easily be seen that the absolute difference between the MHs determined by the ceilometer, from the soundings and the preprocessor models are not very large, only 100–200 m. The relative difference, however, is much larger since the MH is shallow and at times the MH determined by the ceilometer is 3 times larger than the one determined by the preprocessor model.

On the basis of all the accepted stable situations, the lowest MH determined by the ceilometer is 140 m, though estimates from radiosoundings and the preprocessor model indicate lower mixing heights. This would indicate that the ceilometer method cannot determine the mixing height in very stable situations, or that the mixing height in such situations is higher than soundings and the preprocessor model seem to indicate. This is linked to the unresolved issue of the simulation of strong stable situations in

numerical weather prediction or dispersion models where standard schemes seem to indicate decaying turbulence with as a corollary weak surface fluxes and a shallow MH. On the other hand, scattered data seems to indicate that turbulence and surface fluxes can be sustained by non-local effects. Thus, none of the previous alternatives can be yet favoured.

3.2.2 Comparison with diagnostic methods in stable situations

In stable situations, as an additional test, mixing height values estimated from the ceilometer and determined by three different parametric methods were compared to the mixing heights determined from radiosoundings by the Richardson number method (Table 2). The MH based on the Richardson number method acts also here as the reference value.

The mixing height determined by the ceilometer has clearly the best correlation with the mixing height determined by the Richardson number method. Also the mean difference between the MHs determined by these two methods is the smallest.

4 Summary and conclusions

When comparing mixing heights determined by a ceilometer from those by soundings, one must remember that these two approaches observe different characteristics. Soundings define the height up to which mixing can happen, while the ceilometer estimates the mixing height from the point of view of aerosol profiles. The latter assumes that aerosols are primarily released from surface sources. On the other hand, aerosols can occur at elevated levels originating from distant sources or from the past history of the local PBL with a decoupling between the newly developing PBL and the fossil PBL.

Under convective situations, the mixing height determined by the ceilometer correlates well with the mixing height determined from radiosoundings with the parcel method (the correlation coefficient r=0.90). This can be considered as a reliable result

due to the large number of observations. There are, however, some differences between these two methods (see Fig. 6) especially in cases of large mixing height when the Holzworth method yields larger mixing heights than the ceilometer. This can be explained, at least qualitatively, from the fact that these two methods define the mixing height physically in a different way. The Holzworth-method determines the maximum height of mixing from the potential temperature profile, while the ceilometer gives the height where the aerosol profiles indicate the edge of the mixed layer (with the implied assumption that aerosol are scarcer above the MH).

Under stable situations, there is a good connection between mixing heights determined by the ceilometer and those estimated from soundings with the *Ri*-method. Even if there are fewer observations than in convective situations, this result can also be considered statistically reliable. In very stable situations, the mixing height determined by the ceilometer is higher than the one determined by parametric methods or estimated from soundings. Reliable conclusions, however, cannot be made because of only a few observations and the uncertainty with regards to turbulence structure and the MH under such situations.

Nevertheless, this study indicates that a ceilometer can be a suitable instrument for determining the convective mixing height. However, it cannot be used yet in a fully-automatic mode due to the need to cancel cloudy situations and the possibility of elevated aerosol layers outside the PBL. Compared to traditional, operational soundings, the advantage of the ceilometer is the possibility of obtaining MH information continuously with a very good vertical resolution.

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Table 1. Technical properties of the CT25K ceilometer.

Measurement range	0–7500 m
Resolution	15 m
Laser	InGaAs MOCVD laser diode
Wave length	905 nm
Pulse properties	100 ns, 1.6 μJ/pulse

Table 2. Comparison of MH-values estimated by the ceilometer and three parametric methods to MH-values determined from radiosoundings using the Richardson number method.

	Ceilometer	$C_{st}L_N^{3/4}L^{1/4}$	$a\frac{u_*}{f}$	$B_s\sqrt{\frac{Lu_*}{f}}$
Correlation coefficient	0.80	0.39	0.28	0.53
Regression line	$h_{ceil} = 0.62h_{Ri} + 121$	$h_{par1} = 0.44h_{Ri} + 45$	$h_{par2} = 0.40h_{Ri} + 103$	$h_{par1} = 3.5h_{Ri} - 181$
Mean difference	73	100	120	290

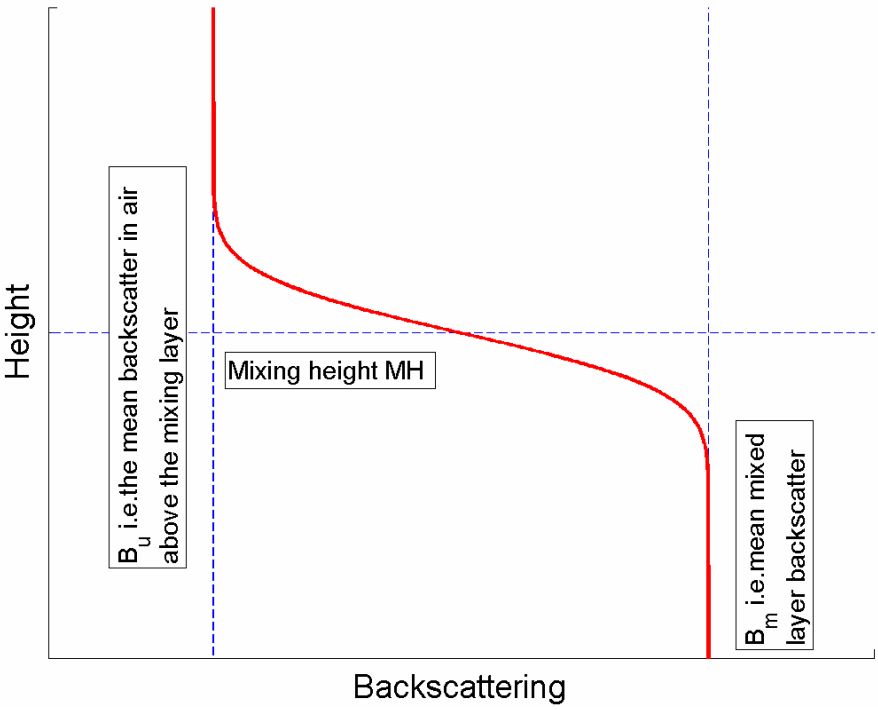

Fig. 1. An idealised backscattering profile.

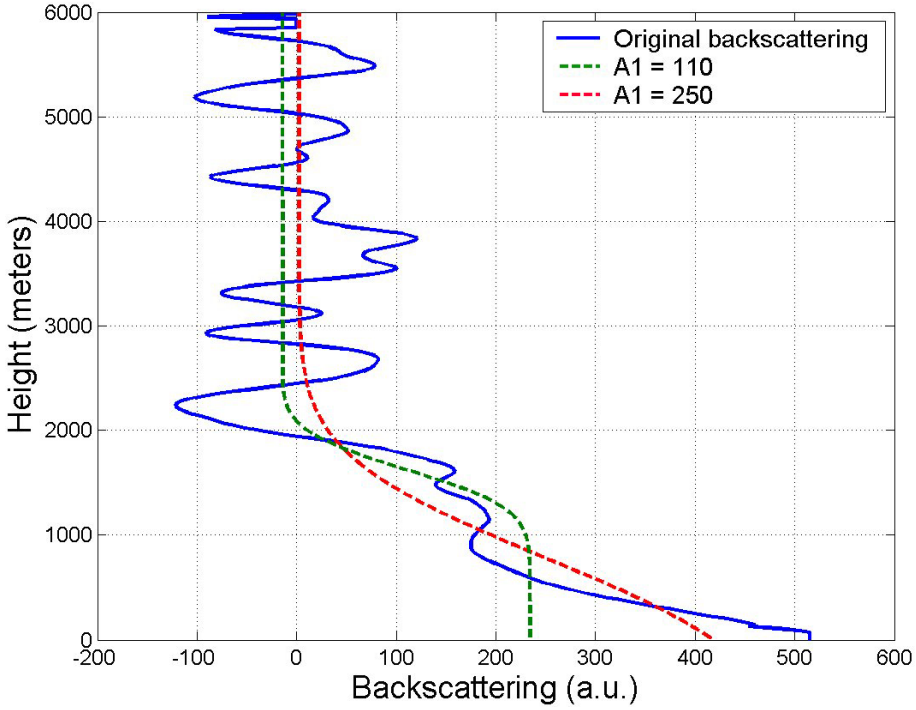

Fig. 2. Illustration of the effect of parameter *A*1 on the fitting procedure. The backscattering is expressed in arbitrary units (a.u.).

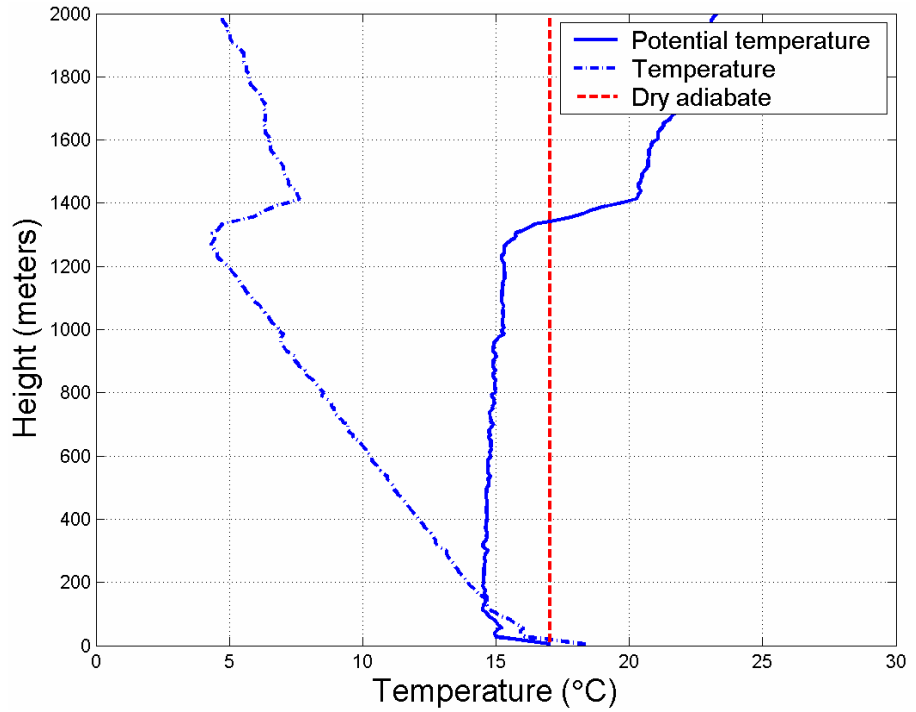

Fig. 3. Illustration of the Holzworth-method. Temperature profile at Vantaa, 29 May 2002 08:56 UTC.

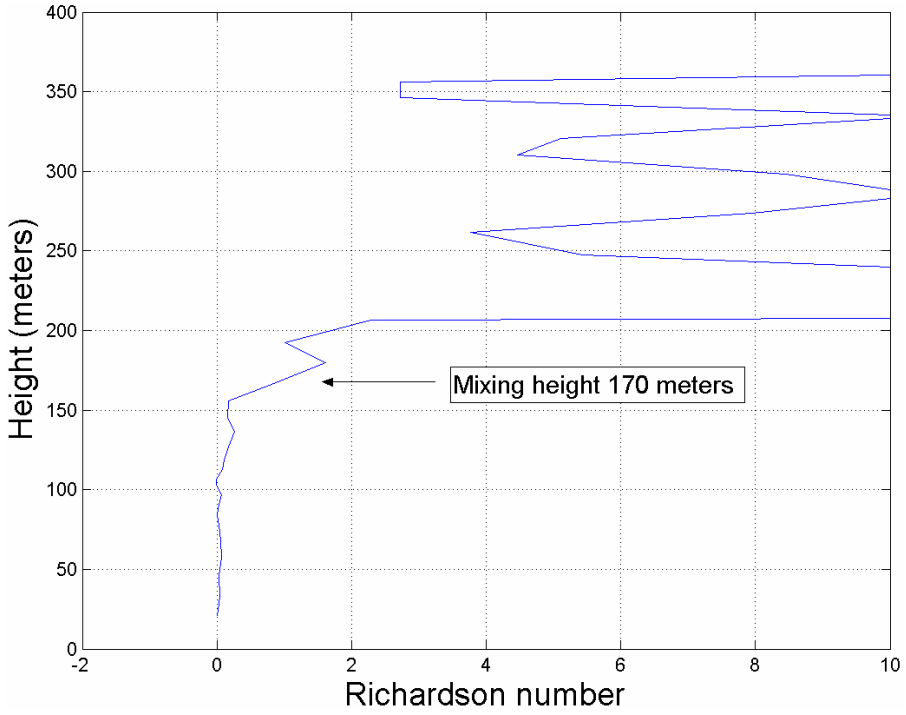

Fig. 4. An example of the Richardson number profile at Vantaa, 4 January 2002 07:17 UTC.

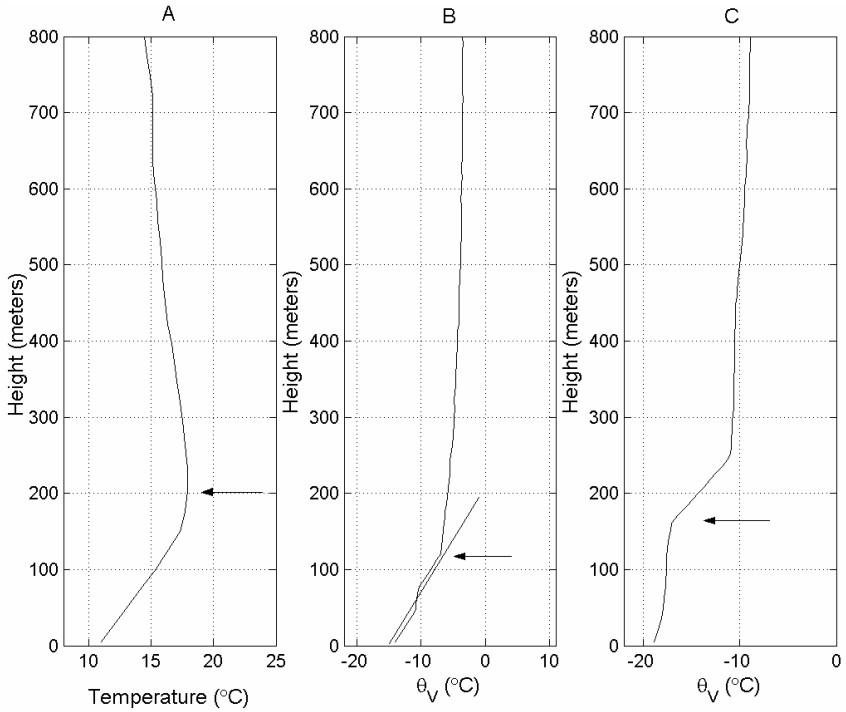

Fig. 5. Three ways for determining the reference mixing height from temperature profiles: **(a)** the height of the surface inversion (5 September 2002 06:06 UTC), **(b)** virtual potential temperature non-linearity (1 February 2002 07:02 UTC) and **(c)** strong winds – sharp virtual temperature increase above MH (2 January 2002 06:16 UTC).

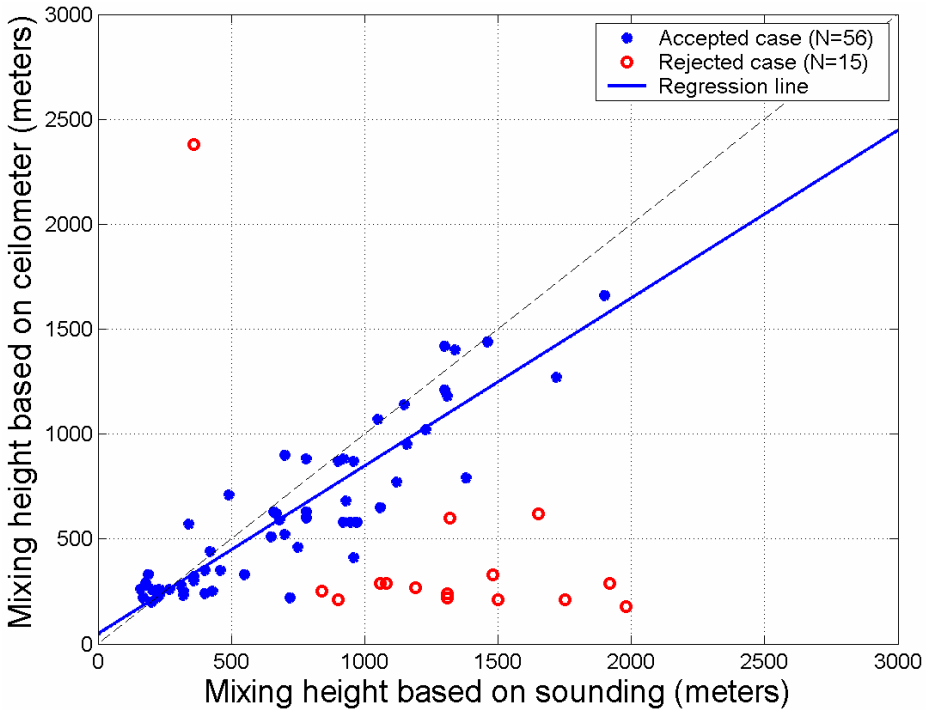

Fig. 6. Comparison between mixing heights determined by the ceilometer and radiosoundings (Holzworth method) in convective situations. Data points marked as hollow circles represent conditions with low backscattering signal.

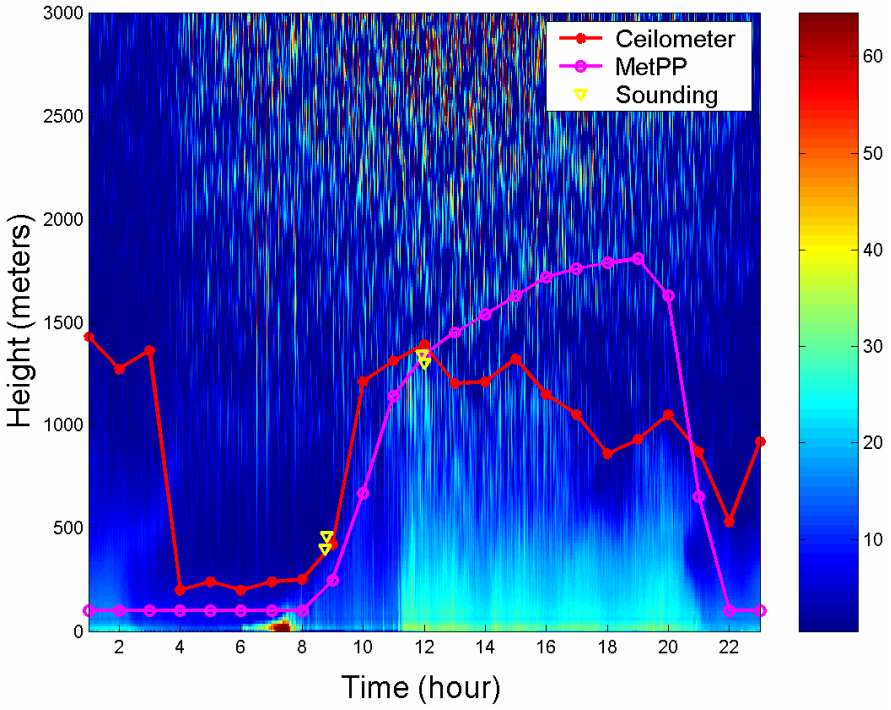

Fig. 7. A 24-h period of ceilometer echo intensity observations at Vantaa, 29 May 2002. The height of the MH determined by the ceilometer, the parcel method and the preprocessor (MetPP-FMI) are superimposed on the ceilometer raw echo data.

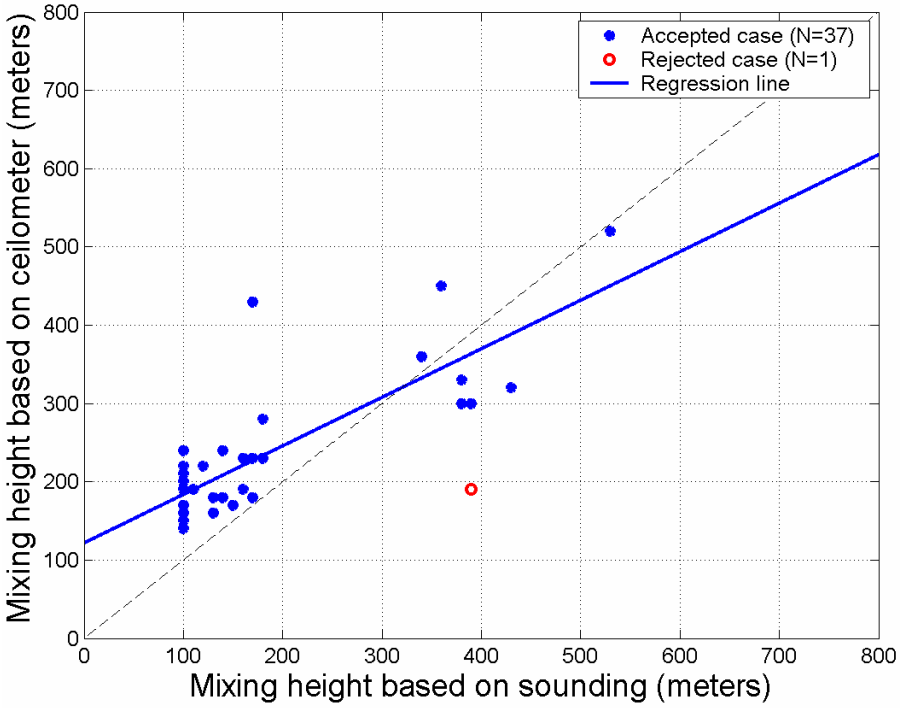

Fig. 8. Comparison between mixing heights determined by the ceilometer and radiosoundings (*Ri*-method) in stable situations (blue stars). The hollow circle corresponds to a case with low backscattering signal near the surface.

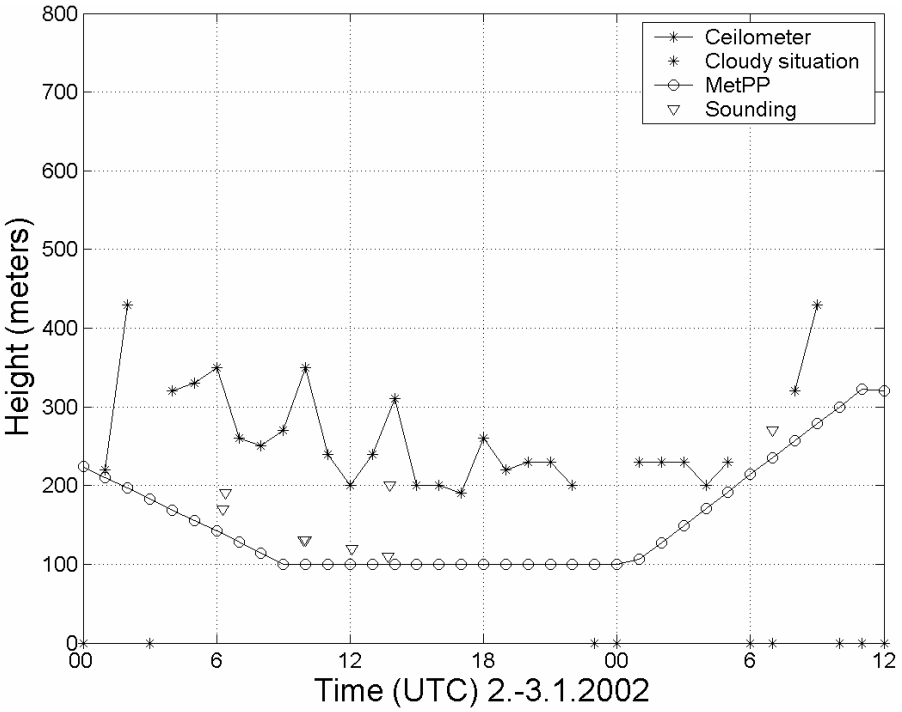

Fig. 9. Mixing height as determined by different methods or schemes during a surface temperature inversion (2–3 January 2002).