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Towards estimating the mixing height in urban areas

Recent experimental and modelling results from the COST-715 Action and FUMAPEX project

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Abstract

The urban boundary layer (UBL) exhibits many differences in comparison with the rural homogeneous boundary layer due to the larger surface roughness and increased surface heating, and by horizontal inhomogeneity of meteorological fields and the mixing height (MH) caused by strong variations in surface roughness and heating from rural to central city areas. Most existing MH parameterizations have been developed for homogeneous terrain conditions, so their applicability for urban conditions should be tested and/or modified. This paper is one such attempt using recent experimental studies of the MH in European urban areas that were analysed within the COST-715 Action and FUMAPEX project. Based thereon, recommendations on the applicability and the improvement of existing pre-processors, schemes and models for the urban MH are suggested. A combined approach is recommended.

1. Introduction

The atmospheric boundary layer (ABL) is the layer near the surface in which heat, momentum and moisture are exchanged between earth and atmosphere, and where pollutants are dispersed. The ABL height follows a diurnal cycle and depends on meteorological parameters, surface turbulent fluxes and physiographic characteristics. Thus, in general it should be higher in urban areas than in the rural case.

As pollutants can be dispersed vertically, we also speak of the mixing layer. The mixing depth represents the height reached by pollutants after release from sources at ground-level. Upward dispersion is eventually limited by an inversion above the mixing layer and/or the decay of turbulence. Most dispersion models require an estimate of the mixing height (MH) or ABL height so that any effective limit on vertical spread can be modelled. The MH may be an input to the dispersion model, or calculated by specific routines within the model. Despite progress in numerical turbulent modelling during the last decades, the MH is still one of the critical parameters for most assessments of air quality**.**

The MH is not observed by standard measurements, so that it must be parameterised or estimated from profile measurements or simulations. The COST[1]-Action 710 (Seibert et al., 2000) reviewed different definitions and practical determinations of the MH from measurements, by modelling and parameterisation. Moreover, it identified and tested pre-processors and computer routines for deriving the MH and inter-compared some of these methods against some rural data sets. On the other hand, experimental studies of the mixing layer in the urban case gained momentum during the last decade (e.g., overview in Baklanov, 2002), identifying the special features of the urban MH and verifying (or improving) different methods for estimating the MH.

Against this background, the Working Group 2 of the COST-Action 715 ("Urban meteorology applied to air pollution problems", http://cost.fmi.fi/wg2/) focused on the specific problems of the surface energy balance and the MH in urban areas (Piringer, 2002; Piringer *et al*., 2002; Rotach et al., 2002a, b; Piringer and Kukkonen, 2002; Piringer and Joffre, 2005). Renewed interest in urban meteorology is also demonstrated by the Urban Research Meteorology and Environment (GURME) programme initiated in 1999 (GURME, 2003) under the WMO Global Atmosphere Watch programme.

In this paper, we will analyse the effects of urban characteristics on the MH, and assess different methods and models for estimating the MH versus new measurement data sets representing several types of urban conditions that are typical in Europe. The important questions to be addressed for analysing the urban MH are the following:

1. How much does the MH in urban areas differ from the rural MH ?
2. How does the temporal dynamics of the MH in urban areas differ from the rural MH ?
3. What methods for the MH estimation are most suitable for urban conditions ?

We will briefly review existing MH formulations and then test a set of these formulae against new urban data recently collected in Europe. This analysis will be followed by some recommendations on the applicability of the methods, and needs for further research and data.

2. Methods for estimating the urban MH

In this section, only a brief overview of methods to estimate MH will be given, as they are mostly well-known (see an extended discussion in Piringer and Joffre, 2005). The MH can be estimated or

[1] COST: European Co-operation in the field of Scientific and Technical Research (http://cost.cordis.lu/src/domain_detail.cfm?domain=7)

parameterised based on: (i) vertical profiles using various probing methodologies, (ii) surface meteorological measurements (e.g., friction velocity and stability), or (iii) numerical weather prediction (NWP) or other numerical models.

2.1. Experimental methods

In general terms, the MH can be estimated experimentally from measured vertical profiles by several means or criteria, e.g.:

- The level where turbulence or the heat flux diminishes to, say, ~5%, of its surface value;
- A level of discontinuity in the wind/temperature/dew point profiles (from radiosonde data);
- The level of strong back-returns from thermal discontinuities (inversions) or of strong decay of back-returns from thermal fluctuations (top of turbulent layer), from sodars and wind-profilers/RASS (Radio Acoustic Sounding System);
- The level of strong decay of aerosol back-scatter signal from lidar probing or ceilometer;
- The level of decay in turbulent motions as measured by pulsed Doppler lidars.

The first method would be the ideal one but requires turbulence profiles, which are seldom available.

2.1.1 Diagnosing the MH from radiosonde data

Radiosoundings could in principle be used for estimating the MH (including operational modelling) but sounding stations are usually located outside urban areas. However, in many European countries, they are getting ever closer to or inside growing urban agglomerations and therefore, for many cities, it is becoming reasonable to analyse radiosonde data for urban MH estimation by selecting wind direction sectors downwind of the city (see Section 4.2).

Under unstable conditions, the MH is often identified as the base of an elevated inversion or stable layer using the parcel (e.g., Holzworth, 1967) or advanced parcel (e.g. Stull, 1991) methods. The MH is sometimes identified as the height of a significant reduction of air moisture (the "humidity-jump" method, e.g., Lyra *et al.*, 1992).

A standard generic method for estimating the MH is based on the Richardson number approach. This approach includes several variants differing in the formulation, choice of the levels over which the gradients are determined and the value of the critical Richardson number, Ri_c: (i) the gradient Richardson number Ri, (ii) the finite-difference Ri-number, (iii) the bulk Richardson number, and (iv) the modified Richardson number method. However, the value of Ri_c is not a constant but apparently increases with increasing free flow stability N (the Brunt-Väisälä frequency) and most probably depends on the surface roughness length, the Coriolis parameter and the geostrophic wind shear in baroclinic flows (Zilitinkevich and Baklanov, 2002).

2.1.2 MH interpreted from sodar/lidar/radar/ceilometer

The different types of vertical profilers (sodars, lidars, radars, ceilometers, etc.) have the potential to provide better and more continuous information on the vertical structure of the ABL and to estimate the MH than radiosondes. Interpretation can be difficult when the lower atmosphere exhibits multiple layers. Their main weaknesses arise from the limitation on their use in urban areas (e.g. due to noise) and the need of expert personnel so that usually they are not in continuous operational use. However, they are sometimes used for some other purposes (e.g. for nuclear emergency preparedness systems or other monitoring purposes) and thus could be used for MH estimation in urban or semi-urban areas.

For **sodars**, the MH can be deduced from the vertical profile of the echo intensity or from a spectral analysis of the vertical velocity. Methods based on the former have been summarised by Beyrich (1997).

The **lidar** measures both Doppler wind velocity and back-scatter intensity. The back-scatter intensity is a function of the system properties, atmospheric attenuation (due to the atmospheric water vapour content), the returned power (and thus the measurement range) and the aerosol loading of the atmosphere. In urban regions, where atmospheric aerosol concentrations are high, there is a large back-scatter signal in most meteorological conditions.

Under well-established convection, **wind profiler radars** (WPR) can find the mixing height from the reflectivity (roughly the product of humidity gradient and turbulence intensity) profiles. Several examples of the MH estimation by wind profilers in different meteorological conditions are presented by Angevine (2003). He concluded that WPRs are very useful in the determination of the MH, but other instruments (e.g., ceilometers, etc.) greatly help in the interpretation, since simple automatic procedures are expected to work in only very simple situations.

Electromagnetic backscatter is generally the best option for determining the (high) afternoon CBL heights. Among this category, the **ceilometer** measures backscatter intensity. It is found to be a very useful instrument in clear sky conditions as it is the only instrument (compared to RASS/sodar) which gives directly the vertical aerosol profile. Ceilometers, originally designed just for cloud base height measurements, have become available also for atmospheric profiling (Rogers *et al*., 1997; Räsänen *et al*., 2000; Münkel *et al*., 2002). They have an improved vertical resolution (now about 15 m) and a much smaller lower detection range limit (now about 30 m above ground; Emeis *et al*., 2004).

The radio acoustic sounding system (**RASS**) is an extension to a coherent radar that allows for the measurement of the virtual temperature profile above the radar. RASS temperature retrievals are sensitive to the wind component parallel to the sound beam and the humidity. The influence of the wind on the measurements can be used to retrieve profiles of the horizontal wind components.

2.1.3 Commercial aircraft measurements / AMDAR Data Processing

New opportunities for estimating the MH and profiles of potential interest to meteorologists and air pollution scientists have recently arisen from the AMDAR system (Aircraft Meteorological Data Reporting; AMDAR, 2003). A joint European EUMETNET-AMDAR project (E-AMDAR, 2002) is looking at the use of data from civil aircrafts to complement to existing radiosoundings. This E-AMDAR system uses the aircraft sensors for measuring wind speed and direction, air temperature, altitude, a measure of turbulence and the aircraft position. Errors in reported wind and temperatures are comparable with those of radiosonde systems.

Some issues need however further consideration, including improvements in processing and the evaluation of AMDAR data relatively to other observations/model products. In the absence of radiosonde ascents over cities, AMDAR data offer useful profiles in the lower atmosphere. The standard objective methods for the determination of the MH from profiles (e.g., parcel method, Ri-number) may then be applicable to the AMDAR-data (see Piringer and Joffre, 2005).

2.2. Mixing height parameterisations

The most common approach used in dispersion models to get the MH values is its calculation from specific parameterisations and pre-processors. This approach can use *in situ* measurements or NWP-derived profiles. So far, parameterisations of the MH have been developed and validated mostly using rural homogeneous conditions, so that their applicability to urban conditions should be verified. Some authors have suggested specific methods for MH determination in urban areas. They can be classified in two main categories: (i) using a local correction to the heat fluxes and roughness to incorporate urban effects and, (ii) estimating the internal boundary layer (IBL) height growth as the flow moves over a city. In this section, we address the first category, usually based on classical methods for homogeneous terrain, but using urban values for the heat flux and roughness. The second category is based on the general methods for the growth of the IBL height following an abrupt change of surface roughness and heat and will be addressed in Section 2.3.

2.2.1 ABL formulae

For the estimation of the MH in urban areas, most authors use a standard 'rural' diagnostic method for stable conditions and a prognostic equation for unstable conditions (e.g., Seibert *et al*., 1998), but without any corrections for urban features. The most commonly used formulae are listed in

Appendix. The properties of the ABL are primarily described within the theoretical framework of similarity relations, by which the variability of the structure of the ABL can be explained by the variation in the scales of the phenomena.

The basic internal scaling quantities are the friction velocity u_* (or the convective velocity scale w_*), the temperature scale T_* and three length scales: the Monin-Obukhov (MO) length L, the vertical height z and the ABL height h. Additionally, the ABL structure is determined by the following external parameters: (i) the wind velocity at the top of the layer (or the geostrophic wind speed G), (ii) the Coriolis parameter f arising from Earth's rotation, (iii) the roughness of the surface described by the roughness length z_o, a measure of the height of typical surface irregularities, and (iv) the Brunt-Väisälä frequency N ($N^2 = \beta\ \gamma$, with γ the potential temperature gradient above the ABL), representative of the background stratification into which the ABL evolves.

In homogeneous steady conditions, the ABL structure and variability is expressed as a combination of dimensionless ratios of these scales. The most recent theories have used the length scale $L_N = u_*/N$ alongside the classical L to represent non-local effects through background stratification at the top of the ABL (Kitaigorodskii and Joffre, 1988; Zilitinkevich, 2002). Such expressions were shown to perform better than classical ones for rural data (Joffre *et al*., 2001; Zilitinkevich *et al.,* 2002; Zilitinkevich and Baklanov, 2002). If these parameters are to be useful for the description of the ABL structure and pollutant dispersion in a practical way, they must be available at any site.

2.2.2. Internal boundary layer development over an urban area

The second category of MH-schemes is based on a general method describing the growth of the IBL height following an abrupt change (smooth-to-rough) of surface roughness. Just a few authors have suggested such a method specifically for the urban MH.

Formulae for the IBL height developed principally for coastal sites (e.g., Panovsky and Dutton, 1984; Walmsley, 1989; Garratt, 1990; Wright *et al*., 1998) can be used in principle for the height of the urban IBL. For instance, Henderson-Sellers (1980) developed a simple model for the urban MH as a function of distance downwind into the city. Nkemdirim (1986) tested and further improved the Summers (1965) formulation for the urban MH:

$$h_\alpha = \left[\frac{2Q_{Hc}x_k}{\rho c_p \alpha U_a} \right]^{1/2} \qquad (1)$$

where Q_{Hc} is the cumulative heat flux over the urban fetch between x_0 and x_k, α is the difference between the dry adiabatic rate and the prevailing lapse rate at x_0, ρ air density, c_p specific heat and U_a is the reference wind speed upwind of the city (x_0). Formula (1) was verified for the cities of New York and Calgary. It was shown that it could be used for a rough MH estimation, but only for wind velocities $U_a < 4$ m/s.

Gryning and Batchvarova (1996) developed a zero-order scheme slab model for the IBL over terrain with abrupt changes of surface for near neutral and unstable atmospheric conditions (Eq. 12 in Appendix), which uses the mean wind components u and v in the IBL, and the mean vertical air motion w_s above the boundary layer that can be estimated from NWP data. The constants most suitable for this model are discussed in Källstrand and Smedman (1997). The model was solved numerically for the IBL height of an urban area with a coastline and showed good applicability (Batchvarova and Gryning, 1998; Batchvarova *et al*., 1999; Gryning and Batchvarova, 2001).

2.3. Applications of NWP model outputs

There is increasing interest in using numerical outputs from NWP models to generate formatted data that can be then easily input into air quality forecasting or environmental impact assessment models, and where the MH is an important requirement, alongside the stability. Although modern NWP models can approach the necessary resolution for the urban scale, the parameterisations of urban effects in most of the existing operational models are absent or greatly simplified. Therefore, it becomes important to 'urbanise' NWP models to enhance their suitability for urban MH calculation. Such work is currently realised within the EU-project FUMAPEX (Baklanov, 2003).

Nevertheless, one potentially promising method to estimate the MH or turbulence profiles for dispersion models is using output from meso-scale NWP models. This can be done using state-of-the–art turbulence closures in the meteorological models (with similarity formulations of the turbulent viscosity and diffusion) or directly in 3D atmospheric pollution models. Many advanced atmospheric dynamics and pollution models already follow this approach (e.g., Baklanov, 2000; Zhang *et al*., 2001; Kurbatskii, 2001). However, the complexity of prognostic turbulence closure schemes, the requirements for high grid spatial resolution and problems due to numerical diffusion in Eulerian models make this method too expensive for practical application for the time being. So, many dispersion models, especially regulatory models, are still not coupled to meteorological models. They are based on *in situ* measurements of meteorological characteristics and need the MH as an input parameter.

3. Recent COST-715 related experimental studies of the MH in urban areas

COST-715 stimulated and partly initiated some field experiments in different European cities. In the following, we briefly introduce those that were used for the urban MH analysis in Section 4. A detailed description of the experiments is given in Piringer and Joffre (2005).

3.1. The Bologna experiment

Bologna is located in the south-eastern border of the Po Valley basin - Italy, close to hills with maximum heights around 300 m, where two small valleys enter the plain. Therefore, there is a combined effect of complex terrain features and urban influences on the ABL structure.

The Bologna experiment took place in 2001 and 2002 to investigate the surface energy budget and the mixing height, during summer and winter conditions. Measurements included a sonic anemometer, a high frequency hygrometer and a sodar located on the top of a building in Bologna city centre (Specola) and at the rural synoptic meteorological station of San Pietro Capofiume, where standard vertical soundings (TEMP) are also performed. The sodar and sonic data cover periods ranging between 20 and 30 days, mainly during May-August 2001 and January-March 2002.

MH estimates using the sodar in Bologna city centre were taken as the "reference" MH-value using the following method. In stable conditions, the MH is identified as a local minimum level of the structure parameter for temperature C_T^2, just above its first maximum from the surface (Klapisz & Weill, 1985): $MH_{stable} = z(C_T^2\text{=min})$. Under convective conditions, since the maximum measurement level reached by the sodar was always below the MH, a similarity method based on profiles of the vertical standard deviation σ_w was applied, as suggested by Seibert *et al*. (1998). In such conditions, the σ_w-maximum level is taken as the third of the MH, i.e.: $MH_{conv} = c \cdot z(\sigma_w\text{=max.})$, with an "empirical" factor $c \approx 3$. For neutral conditions the MH was not estimated from sodar measurements.

The MH and surface energy budget parameters from the Bologna experiment were also compared with simulations by the mass-consistent meteorological pre-processor CALMET-SMR running daily at the ARPA regional meteorological service (Deserti *et al*., 2001).

3.2. The BUBBLE experiment: Basel

The Basel UrBan Boundary Layer Experiment BUBBLE (Rotach *et al*., 2004, 2005) in Switzerland was a long lasting and detailed experimental (full-scale and wind tunnel) as well as numerical modelling effort to better understand the (thermo)dynamics of the UBL. For a period of one year, two 'urban' surface sites were constantly operated within Basel with 6 levels of turbulence observations up to more than twice the local building height. For the same period of one year, a wind-profiler near the city centre yielded the mean wind profile as well as some turbulence information with a 43 m vertical resolution every 1/2 hour. Also an essentially co-located aerosol lidar gave information time series on the aerosol distribution (vertical resolution: 10m) in the lower urban atmosphere and hence allowed derivation of the 'Aerosol Mixing Height' (as a surrogate for the UBL height).

Urban Aerosol Mixed Layer (AML) heights were determined from the derivative of the logarithm of the range-corrected lidar signal. In this approach, a level is identified as the AML height if it exhibits the lowest substantial gradient (i.e., a local minimum in the derivative) with an additional constraint of continuity in time. Furthermore, an intensive observing period of some five weeks in summer 2002 involved additional observations including one RASS (urban site), two sodars, (rural) and a tethered balloon (urban).

3.3. ATHIBLEX/MEDCAPHOT experiments: Athens

The MEDCAPHOT-TRACE experiment took place in the Greater Athens area for 30 days during the summer of 1994, and encompassed a variety of meteorological situations (Ziomas, 1998). The purpose was to study the chemical and meteorological evolution of ozone and related compounds under various synoptic and local meteorological conditions.

Meteorological measurements included: near-surface wind measurements performed on small masts at 11 locations, turbulence measurements with two sonic anemometers at two sites (one within the city at the National Observatory of Athens (NOA, 4 km inland from the shoreline station), the other one 13 km inland in a suburban area (Marousi), and profiles of wind speed and direction, air temperature and humidity up to 500 m height with tethersondes at both sites. Additionally, regular radiosoundings were performed twice a day at the old Athens Airport near the coastline. Besides, 27 stations of air pollution monitoring were operated within the Greater Athens area. Instrumentation for air quality consisted of ground-based air pollution measuring systems, integrated-path air pollution measuring systems (DOAS), and ground-based laser remote sensing systems (lidar). In addition, two sodars were in operation, one at a semi-urban background site (University campus), the other on the Penteli mountain (450 m height) in the NE of Athens. These data were completed by 9 aircraft flights measuring air pollution and meteorological parameters during a period of 10 days.

Atmospheric turbulence and vertical profiles of various meteorological parameters over the area (mainly at NOA and Marousi) were investigated by Batchvarova and Gryning (1998) The collected data were re-examined by Dandou *et al.* (2004) using numerical simulations to identify urban effects on meteorological parameters. The simulations were carried out with an urbanised version of MM5, in which changes were introduced in both the thermal and the dynamical parts (Section 4.3.1).

3.4. **Göttinger Strasse,** *Hannover, Germany*

In the framework of the project VALIUM (Validation of instruments for environmental policies), long-term meteorological and air quality measurements were carried out in the street canyon "Göttinger Strasse" in the town of Hannover in Northern Germany from spring 2001 to spring 2003. The horizontally averaged roughness length of the more or less urban area within a radius of 10 km is about 1 m.

A sodar was placed about 550 m upstream (with respect to the most frequent wind direction, which is Southwest) of the street canyon. The sodar used was a METEK DSD3x7 mono-static Doppler sodar (Reitebuch and Emeis, 1998) having three antennas with seven sound transducers each (i.e., a device that serves both as a loudspeaker and as a microphone, depending on the phase of the measurement cycle), working at about 1500 Hz. The instrument is optimised for long-range detection up to 1300 m above ground in ideal conditions without external noise sources.

The MH was determined from the Hannover sodar data by employing two empirical criteria.

1) The height H_1 of a sharp decrease in the acoustic backscatter intensity $R(z)$ usually indicates the top of a turbulent layer:

$$H_1 = z, \quad \text{where } (R(z) < 88 \text{ dB} \quad \text{and} \quad R(z+1) < 86 \text{ dB} \quad \text{and} \quad R(z+2) < 84 \text{ dB}) \qquad (2)$$

Here the dB threshold values are arbitrary because the received backscatter intensities $R(z)$ are specific for the given sodar (no absolute calibration).

2) The height(s) H_2 of secondary maxima of the backscatter intensity for surface inversions and elevated inversions; these maxima are not related to high turbulence intensities:

For *elevated* inversions we select a height $z = H_2$ lying between positive and negative gradients of (R(z), denoting an increasing backscatter intensity below and decreasing intensity above:

$$H_2 = z, \quad \text{if } (\partial R/\partial z(z+1) < 0 \quad \text{and} \quad \partial R/\partial z(z-1) > 0 \quad \text{and} \quad \sigma_W < 0.70 \text{ ms}^{-1} \qquad (3)$$

Here restriction is to moderately low σ_w values.

For *surface* inversions (usually nocturnal):

$$H_2 = z, \quad \text{if } (R(z) > 105 \text{ dB} \quad \text{and} \quad \sigma_W < 0.3 \text{ ms}^{-1}) \qquad (4)$$

Here restriction to low σ_w values avoids high backscatter intensities and high turbulence intensities (high σ_w) associated with super-adiabatic temperature profiles near the ground in strong insolation.

The search for H_1 and H_2 is done separately. In both cases the search starts from below. If the criterion is fulfilled the search stops. If the search for H_2 detects a surface inversion it stops, too, and does not look for further elevated inversions. The MH is then defined as:

$$MH = \min(H_1, H_2) \qquad (5)$$

In case that neither H_1 nor H_2 is found, the MH cannot be determined from the sodar data. This happens, e.g., during the afternoon of warm and sunny days when the CBL top is higher than the range of the sodar. This does not necessarily mean that there is no inversion at all. More details can be found in Emeis and Türk (2004).

3.5. **Jægersborg,** ***Copenhagen***

An inter-comparison of methods on the mixing layer under urban conditions (Baklanov and Kuchin, 2004) was performed for the Copenhagen metropolitan area. The Jægersborg radiosounding station is situated inside Greater Copenhagen and can be considered as an urban (or semi-urban) site. It is situated on a small hill (40 meters above sea level) with a relatively homogeneous and open surface (~100m), and surrounded by urban areas from S, SW, and SE-directions; semi-urban and rural areas from NW and N-directions, and by a forest park in the coastal area with the Øresund water surface from the NE-direction.

Several years statistics of radiosounding profiles from the Jægersborg station were analysed. This station is included in the WMO database, but DMI radiosounding stations use a higher vertical resolution than the WMO standards, therefore, the original highest resolution data were used.

3.6. CALRAS data set: Munich

As a result of the Mesoscale Alpine Programme MAP, the MAP data centre (www.map.ethz.ch) issued the comprehensive Alpine radiosonde data set CALRAS (*Comprehensive Alpine Radiosonde;* Häberli, 2001) for the period 1991–1999 with additional stations in Central Europe.

CALRAS also includes quality controlled, high resolution radiosounding data for large cities in and around the Alpine area.

For the case of Munich, MHs were calculated for all cases when the radiosoundings sampled the urban plume downwind of the city and for opposite cases when rural areas upwind of the radiosonde site had influenced the profile. The observed wind direction at 500 m above ground served as an indicator to determine whether the radiosounding was mainly within the urban plume ("urban" profile) or in air from the countryside before arriving at the sounding site ("rural" profile).

3.7. Helsinki

Ceilometer and vertical soundings data from the Helsinki area were used to test the applicability of the ceilometer for determining the MH. One typical problem for lidars, its ability to measure in the lowest few hundred meters due to inadequate optical overlap, is overcome with the Vaisala CT25K single-lens design (a pulsed diode, InGaAs, lidar-based ceilometer operating at 905 nm with a measurement range of 7.5 km), with which the highest signal-to-noise ratio is achieved at the lowest levels. This permits determining, e.g., the nocturnal boundary layer better than before. Furthermore, since in an urban environment the atmosphere is always more or less turbid, this will provide more detectable signals than in a clear atmosphere, hence providing a clear opportunity for using ceilometers for measuring and predicting urban pollution levels and the urban MH.

Measurements used in this study were carried out in 2002 at the test field of Vaisala Ltd, in the northern suburban area of Helsinki, using a Vaisala CT25K ceilometer pointing in a near-vertical direction. Routine soundings carried out every workday provided reference information, and all standard meteorological parameters including visibility and present weather were recorded continuously nearby (ref. http://www.vaisala.com/weather). Data were recorded at 15-second intervals and stored for later analysis. The surroundings are suburban-rural, 15 km north of downtown Helsinki and the southern coast of Finland. No major industry is present in the neighbourhood.

4. Data validation of Mixing Height schemes and models

This section focuses on recent studies mainly undertaken by COST-715 members (a review of other experimental studies of the MH in urban areas is available from Baklanov, 2002). A variety of MH data estimated with different instrumentation (see Section 2) was available to the working group, and these were compared to estimates from various schemes and NWP models. In spite of various limitations in the available data, which will lead to large uncertainties when statistical measures are applied, these comparisons enable to analyse the effects of some of the urban characteristics and to preliminarily assess different methods for estimating the MH for several types of urban areas.

4.1. Diurnal and annual variability

In clear sky conditions, the daily course of the MH can be best deduced from lidar or ceilometer data. Figure 1 illustrates an example of the daily cycle of the aerosol concentration over Basel during BUBBLE (Rotach *et al.*, 2005); the diagnosed aerosol mixed layer (AML) height shows the typical development and decay of the convective boundary layer (CBL) throughout the day. While the given situation yielded quite clear results concerning the AML height, a more complicated aerosol structure can sometimes be observed. During the night, several elevated layers of high aerosol concentrations may be present in the residual layer and sometimes up to three local minima in the derivative of the concentration profile are observed. Interestingly, quite often there is a pronounced local minimum in the derivative of the lidar signal at about 2.5-3 km (see Fig. 1), most of the time well above the readily determined AML height. This example reflects the usual difficulties in interpreting data and estimating the MH, a quantity for which there is as yet no unique definition.

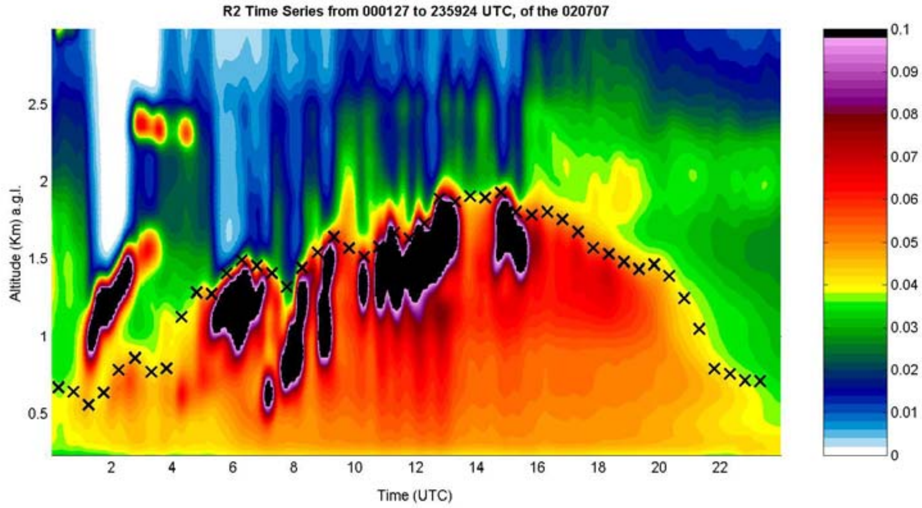

Figure 1. Lidar scans of the backscatter from the atmosphere on 7 July 2002 at a site in central Basel, Switzerland. The colour coding is proportional to the aerosol concentration (black=clouds). Crosses indicate the diagnosed Aerosol Mixed Layer height from the derivative of the logarithm of the range-corrected signal. Data courtesy Valentin Mitev and Giovanni Martucci, Neuchatel-Observatory.

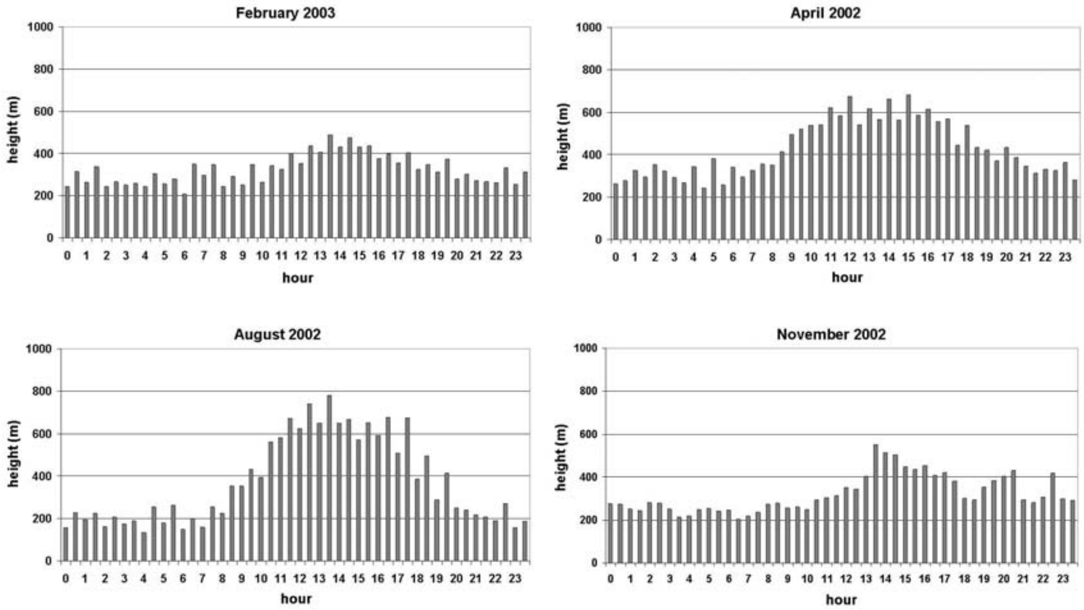

Figure 2: Mean daily course of the MH (in m), computed from Eq. (5). The temporal resolution is one half hour (from Emeis and Türk, 2004).

Figure 2 shows the mean daily course of the MH in Hannover determined by careful sodar data analysis from Eq. (5). The strongest and smallest diurnal amplitude are found in August and November 2002, respectively. This is connected to the incoming solar radiation, which was highest in August (28 days with sunshine, among which 19 days had more than four hours of sunshine). Similarly, February 2003 (22 days with sunshine, and 12 with more than four hours of sunshine), April 2002 (22 days with sunshine, 14 with more than four hours) had also a large number of sunny days. They also exhibit a clear diurnal course but with a smaller amplitude. November 2002 had only 15 days with some sunshine, and only 6 days with more than four hours of sunshine. Dry air masses led to large differences between the daytime maximum temperature and the night-time minimum temperature in August 2002. This difference was regularly 10°C or even larger. In April 2002 this difference was only around 8°C. This strong diurnal course of near-surface temperatures led to the small MH values in August 2002 at night-time, even lower than during the other months.

The yearly course of the MH – near its daily maximum – can be derived from 12 UTC radio-soundings. Midday MH values have been determined for Lisbon for the period 1st April, 1999 to 31st July, 2001 (28 months). The MH was estimated by the parcel method as the intercept of the dry adiabatic lapse rate from the maximum daily air temperature with the vertical air temperature profile of the 12 UTC radiosounding at Lisbon airport, located in a suburban area. The Lisbon radio-sounding station is located on the northern limit of the urban area, roughly 6 km from the center of the town. The station is located in the airport area with flat terrain on the west side, where the runways are located. In the other directions (namely to the east, south and north), the station is surrounded by buildings, of height between 10 to 40m and not exceeding the station level. Most of the streets around the airport have small trees along their sides. The results presented in Fig 3 show the large day-to-day variability of the MH, which is due to seasonal and synoptic conditions. The seasonal variability is on the other hand rather moderate due to the modulating effect of the nearby ocean.

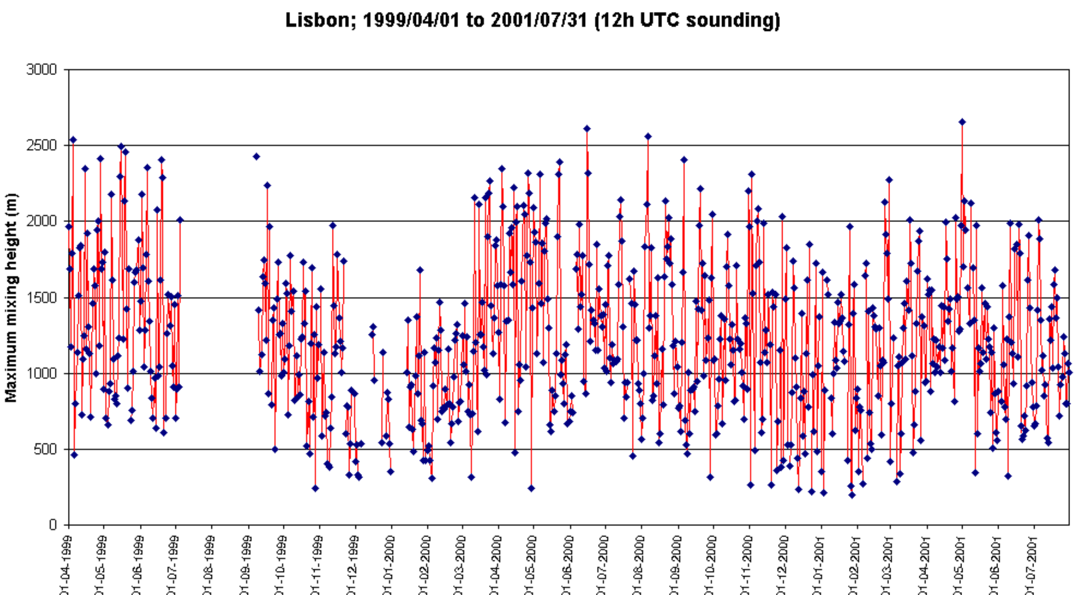

Figure 3: MH estimates at the Lisbon airport, derived from 12 UTC radiosoundings.

Geographical/climatic peculiarities of cities (e.g., flat terrain vs. mountain valleys, coastal vs. continental cities, northern vs. southern cities) can also affect the formation of the UBL. For example, the stably stratified nocturnal boundary layer (SBL) is not common in US cities (Bornstein, 2001) or in many downtown areas of Central European cities like Marseille, Basel, Birmingham. This is mainly the result of the large amount of stored heat released at night yielding only an elevated nocturnal inversion layer. However, especially for Northern European cities, the nocturnal SBL is very common (e.g., for Finland, Karppinen *et al.*, 2001). The temperature profiles in Fig. 4 show clearly the stably stratified nocturnal UBL in Northern European cities. Apart from the geographical characteristics, other factors such as the density, height and materials of buildings, population, traffic load or anthropogenic heat can obviously affect the behaviour of the local UBL.

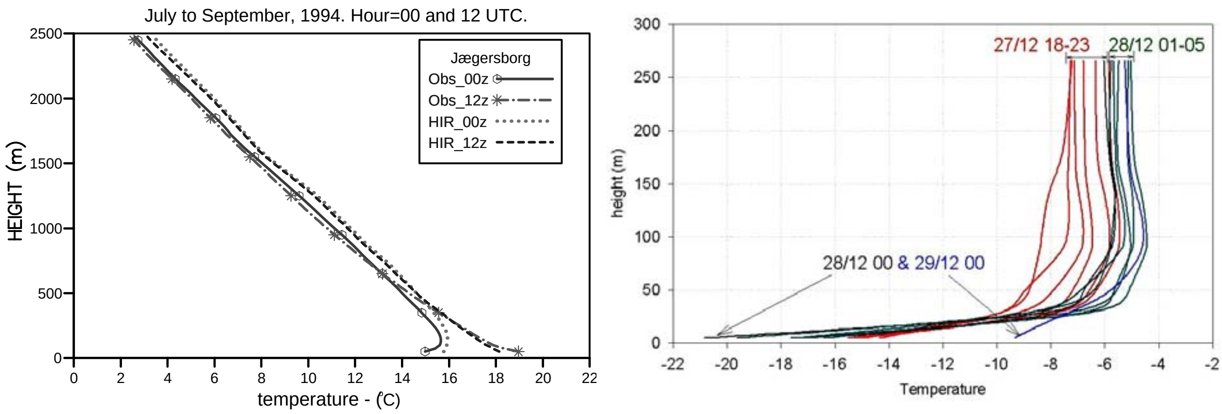

Figure 4. Vertical temperature profiles for North-European cities. *Left***:** The 3-month mean measured (Obs) and modelled (HIR) profiles of temperature at 00 and 12 UTC for the radiosonde station Jægersborg in the metropolitan Copenhagen area (Rasmussen *et al*., 1999). *Right*: Evolution of a temperature inversion during an air quality episode in December 1995 for the Helsinki metropolitan area. The curves are numerical fits of the data measured at the Kivenlahti mast (Karppinen *et al*, 2002).

4.2. Detecting urban effects on the MH with radiosonde profiles

4.2.1 CALRAS data - Munich

Using the CALRAS dataset, Baumann-Stanzer and Piringer (2003) investigated the ability of routine radiosoundings launched downwind of Munich city to "see" urban effects on the MH (i.e., an expected increase of the MH). The methods used here to diagnose the MH from radiosoundings were explained in Piringer and Joffre (2005). The differences for each method versus the advanced parcel method (APa) by day, or the bulk Richardson number method (with $Ri_c = 0.25$) by night, are calculated on the basis of common data pairs (see results in Table I). The humidity-jump method is only calculated in convective conditions as defined by positive w_* in the advanced parcel formula.

The expected effect of increased MHs when the urban plume meets the radiosonde flight-path is detected by all the methods tested:

- In winter daytime (Table Ia), the "urban" MH ~530-1350 m is almost twice as large as the "rural" one for all the methods tested. Four methods gave average "rural" MH ~400-500 m, except the humidity-jump method (Hu) at 868 m; the parcel method (Pa) and the humidity-jump method giving the lower and upper bounds, respectively.
- In summer daytime (Table Ia), still larger urban MH ~1000-1500 m are calculated by all five methods. However urban – rural differences are lower in percentage terms for summer (when compared to winter), but The Heffter and humidity-jump methods (He, Hu) give then the largest urban MH estimates, on average.
- In winter night-time (Table Ib), two methods were tested on midnight radio-soundings and we again found there were significantly larger urban MHs ~240-560 m, than the rural MHs ~120-180, especially with the Heffter method (He).
- In summer daytime (Table Ib) urban MH ~210-400 m, whilst rural MH ~80-180 m, a very similar result.

The results of the MH statistics presented in Table I depend much on the methods used. On the one hand, the differences are due to the fact that different meteorological parameters are used to deduce the MH: e.g., critical inversion (Heffter, 1980) and parcel methods rely on temperature, Richardson methods depend on wind and temperature while the humidity-jump approach relies only on humidity. On the other hand, the MH statistics summarise different numbers of cases, because not all of the methods tested can provide results for all profiles.

TABLE I: Average MHs (in m above ground) for Munich diagnosed from radiosoundings by the Heffter (He), the bulk Richardson number (Ri), the parcel (Pa), advanced parcel (APa) and humidity-jump methods (Hu).

a) Daytime

	Winter / Rural					Winter / Urban					Summer / Rural					Summer / Urban				
Method	He	Ri	Pa	APa	Hu	He	Ri	Pa	APa	Hu	He	Ri	Pa	APa	Hu	He	Ri	Pa	APa	Hu
No of cases	142	138	91	91	74	116	117	88	88	61	54	51	52	51	34	210	203	230	230	132
MH mean	482	421	381	496	868	962	728	531	727	1347	1134	1290	857	1039	1109	1506	1431	1021	1207	1516
MH stand. dev.	524	445	389	452	651	635	606	358	433	766	681	826	568	561	706	550	623	482	469	637
Differ. to APa	105	132	-115	0	358	385	255	-196	0	518	204	464	-203	0	31	333	324	-186	0	258
No of data pairs	90	86	91		61	81	82	88		52	48	44	51		32	206	199	230		132

b) Night-time

	Winter / Rural		Winter / Urban		Summer / Rural		Summer / Urban	
Method	He	Ri	He	Ri	He	Ri	He	Ri
No of cases	161	161	123	124	186	187	192	195
MH mean	120	181	564	241	78	177	392	213
MH standard deviation	184	83	572	148	76	106	503	101
Difference to Ri	-60	0	322	0	-99	0	182	0
No of data pairs	161		123		186		192	

Among the temperature-profile related methods available for daytime conditions, the Heffter method often gives on average the largest estimates, followed by the advanced parcel and the simple parcel method. When doing dispersion calculations, worst-case estimates of concentrations are thus best obtained using the simple parcel method in convective conditions. The average MHs with the Ri-number method are within the range of the temperature-based methods. The average MHs obtained by the humidity-jump method are comparable to the temperature-based methods in summer, but considerably larger in winter. Thus, under summer convective conditions, the capping inversion is often accompanied by a significant reduction in air moisture, whereas in winter a significant drop in humidity is frequently found at much larger heights than the capping inversion.

At night, the average Heffter MHs (He) are lower than those of the Ri-method for the rural and higher for the urban case. From the large differences seen especially in the "urban" case, the Heffter method tends to over-estimate the MH. It would appear that diagnostic formulations are difficult to recommend for night-time MH estimation.

4.2.2 Copenhagen data

Radiosounding data from the year 2001 at the Jægersborg station in Copenhagen were used to estimate the MH (Baklanov and Kuchin, 2004) and to test the same diagnostic MH methods as in 4.2.1 for Munich and additionally the maximum low-level jet velocity method (Vmax), as well as several parameterisation methods (see the Appendix): the method of Arya (1981: AR81) and the empirical method of Benkley and Schulman (1979, BeSc79). The bulk Richardson number method (Ri) also used $Ri_c = 0.25$. Results are presented in Table II.

TABLE II: Mixing heights for the Copenhagen area: mean value (in m), standard deviation (Std Dev) and number of profiles (*N*) for urban, and semi-urban/rural sectors, assessed separately for the SBL (mostly night-time cases) and the CBL (mostly daytime cases).

Sector	Statistics	SBL					CBL				
		Ri	*AR81*	*BeSc79*	*Vmax*	*Hu*	*Ri*	*BeSc79*	*Pa*	*APa*	*Hu*
Urban	*Mean*	261	783	764	593	456	799	918	718	900	532
	Std Dev	197	444	474	192	260	415	440	445	494	238
	N	114	114	114	114	44	61	61	61	61	29
Rural	*Mean*	189	451	595	552	462	965	920	898	1130	634
	Std. Dev	175	255	410	199	260	368	387	403	403	255
	N	122	122	121	122	59	80	80	80	80	21

Table II suggests that the effect of the urban sector on the average SBL MH values is significant for all the tested methods except the Hu method. The average MH values of the urban sector are *ca.* 100 m higher than the average rural MH. The Ri-method gives the lowest MH values in both sectors (261/189 m). Of course, without direct measurements of the MH, no conclusion about the correct value of the MH can be made. However, a previous analysis of the bulk Ri-number method and a comparison with MH measurements by sodar (Zilitinkevich and Baklanov, 2002) showed that this method underestimates the MH for the SBL. This should require a revision of the critical value of the Ri-number. Two other methods (AR81 and BeSc79), based on mere surface level measurements, probably strongly overestimate the urban MH (783 and 764 m for the urban sector). The Vmax method yields intermediate MH-values. The Hu method shows unexpectedly similar results. However, it is not recommended to use this method, because it is usually used only for neutral and convective conditions.

In contrast to the SBL cases that displayed significant urban effects, the CBL cases showed the opposite effect with higher MHs in the rural/semi-urban cases. This, at first sight unexpected result, can be partly explained for the Copenhagen area by its coastal position. For convective conditions, the anthropogenic heat flux does not play a dominant role compared to the sensible heat flux, so that sea breeze effects, which are important for the rural sector, are stronger than the urban effects. A similar effect was observed in the case of Athens (see 4.4.1) where the urban parameterization scheme in the MM5-model gave lower MHs, in closer agreement with the measurements**.**

To minimise uncertainties, it is thus recommended to combine the Ri-number and parcel methods for diagnosing the MH from radiosounding profiles for both urban and non-urban CBL conditions.

4.2.3 Sodar and radiosondes data from Bologna

An inter-comparison between various MH-formulae listed in the Appendix was performed for the period January-February 2002 at three urban sites in the city of Bologna and a rural site outside Bologna. These formulae were calculated using "surface" turbulence parameter data (u_*, L and w_*,), while radiosonde profiles from the rural San Pietro Capofiume site (SPC) were used to determine *N*. The inter-comparison focuses on the urban-rural differences between MH formulae estimates and those from a sodar, separately for stable (SBL), convective (CBL) and neutral (NBL) conditions. The sodars were located on the top of a building in Bologna city centre and at ground level at the rural station. The comparison is illustrated through box plots for the various MH schemes for urban and rural conditions (Fig. 5). All the urban data, collected at three sites, were merged into the same box to obtain a sufficient number of data.

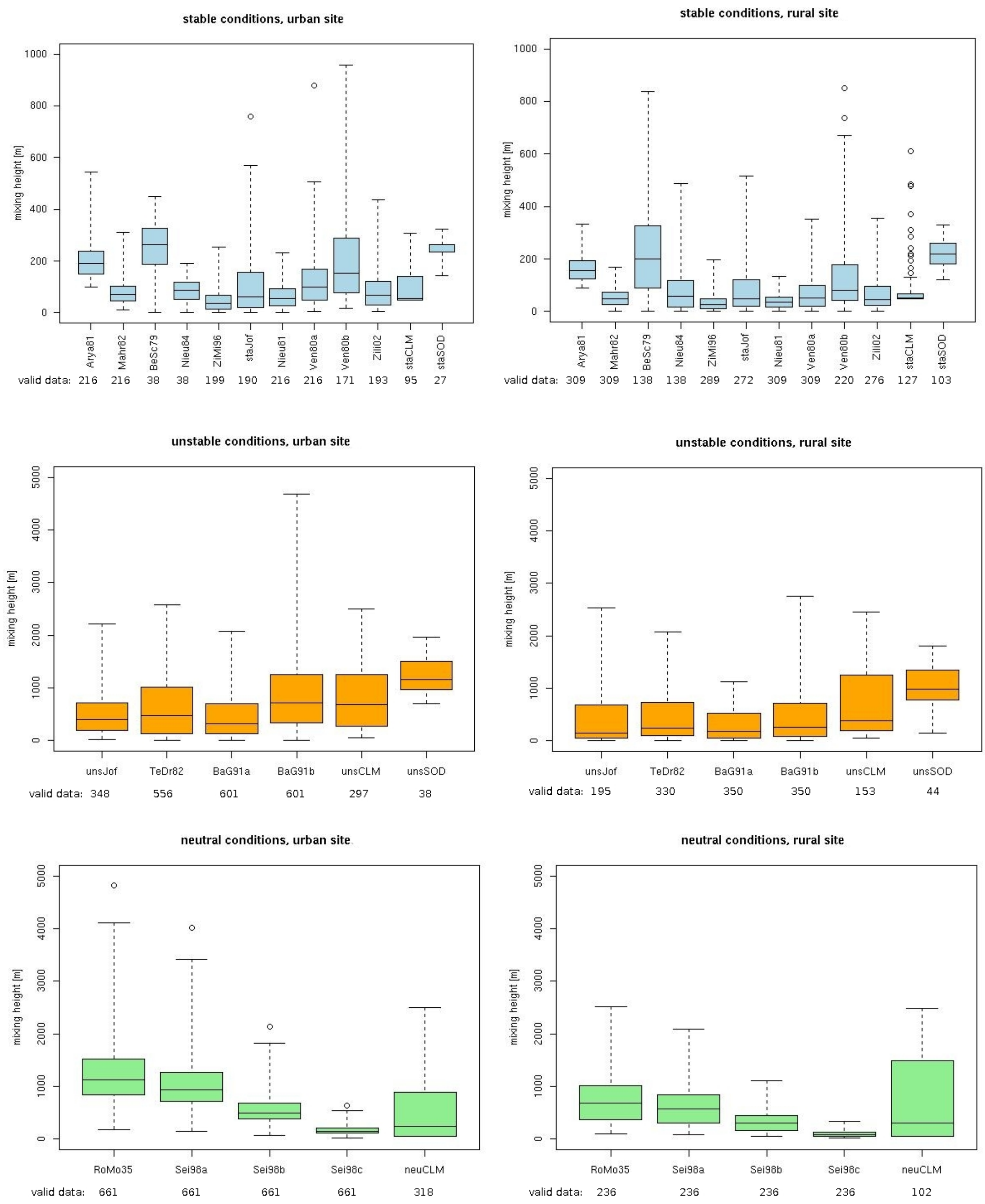

Figure 5. Box-plot of the MH calculated by the different methods listed in the Appendix under stable (upper panel), unstable (mid panel) and neutral (lower panel) conditions at the Bologna urban site (left) and at the rural site of S. Pietro Capofiume (right). Each box represents from bottom: 1st Quartile, Median and 3rd Quartile. The whiskers extend to the most extreme data points which are no more than 4 times the inter quartile range from the box. Open circles represent outliers. SOD refers to the sodar-estimated MH and CLM indicates the MH from the CALMET-SMR operational pre-processor. The numbers of valid data in each box are indicated under the boxes.

Figure 5 displays the expected increase of the MH from stable to unstable conditions. Furthermore, the urban MHs are higher than the rural ones for most methods. It can be noted that apart from outliers, the range of MH values is limited for some of the methods, while some others display a broader variability This and the occurrence of outliers are discussed for each method in the next sections. Nevertheless, one remarkable aspect of Fig. 5 is that there is a rather clear internal consistency between the various schemes, though some are based on different theoretical background, whilst the sodar cluster of MH values clearly departs from the latter. This would be an indication that sodar data alone are definitively not appropriate for an accurate assessment of the MH even under stable conditions.

Box plots put also in evidence that the various methods have different frequency distribution of MH-values. It appears that the median is near the lower quartile in most cases as can be seen in Fig. 6, which shows an example of typical CBL and SBL frequency distribution for both the urban (right) and rural (left) cases.

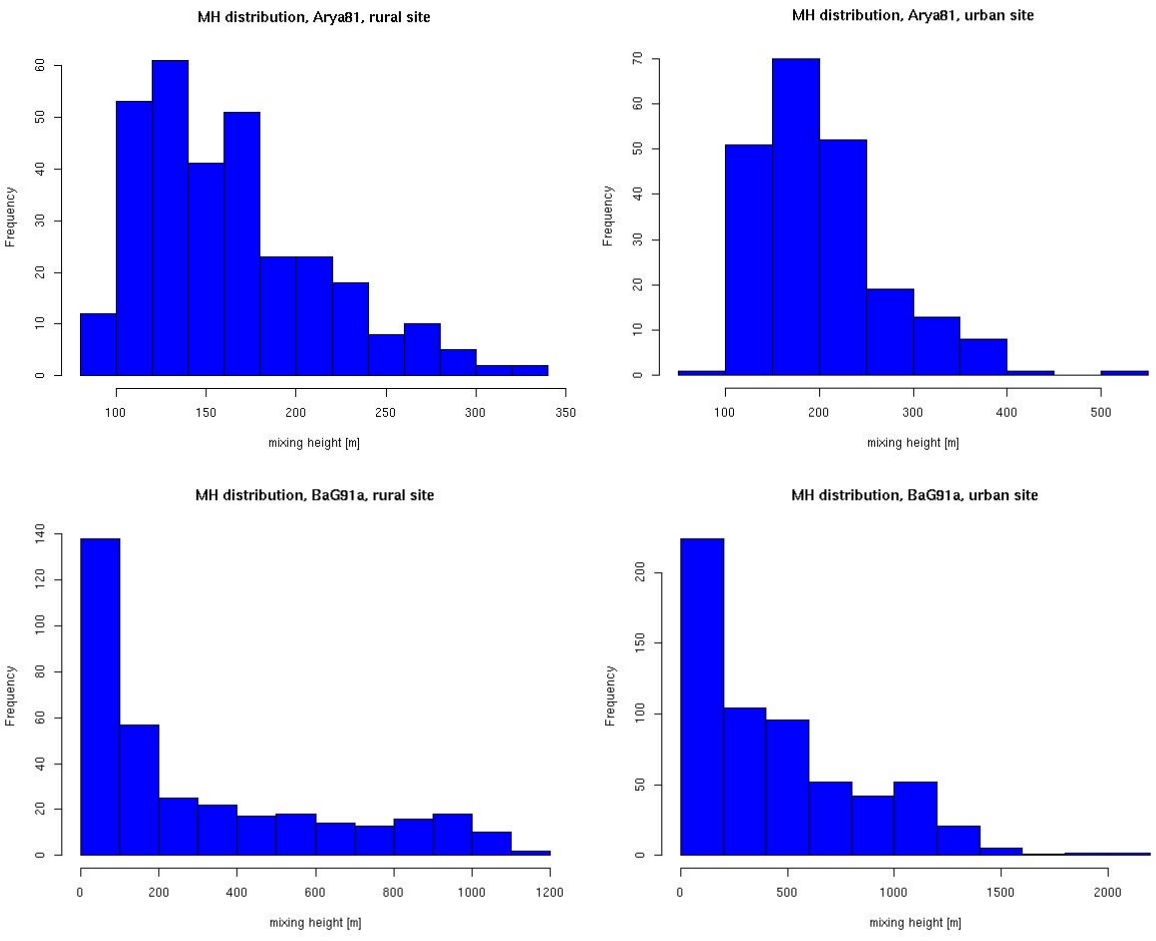

Figure 6. Examples of typical frequency distributions for a convective formula (BaG91a) and for a stable formula (Arya81) at the urban sites (right) at the rural site (left).

(a) MH-data vs. SBL diagnostic formulations

It should be noted that the first four schemes in the upper panel of Fig. 5 (stable conditions) are listed in the Appendix for neutral conditions but are tested here for stable conditions as was done for the Milan (Lena and Desiato, 1999) and Cabauw experiments (Baklanov, 2001). The number of data considered is in most cases around 200. However, the number of data drops to 30 for Sodar, BeSc79 and Nieu84, because some of the required input data for these formulae were missing during the campaign.

TABLE III: Comparative rural-urban evaluations of different SBL height equations versus some measurement datasets.

Formula code [Eq. #] cf Appendix	Urban, Bologna (4) (Feb. 2002)			Rural, Bologna (4) (Jan. 2002)			Urban, Milan (3) (May-Aug.1996)			Rural, Cabauw (years 1977-1979)		
	Bias	RMS error	Corr. coef	Bias	RMS error	Corr. coef	Bias	NMS error(5)	Corr. coef	Bias	RMS error	Corr. coef.
Arya81b (1) [4]	-	-	-	-	-	-	-264	1.69	0.43	64.0	218	0.27
Ven80a [2]	-74	151	0.12	-210	263	-0.18	-	-	-	-	-	-
Ven80b [3]	-12	144	-0.01	-185	255	-0.21	-	-	-	-	-	-
Nieu81 [5]	-154	166	0.09	-224	270	-0.04	-	-	-	-	-	-
Zili72a [1]	-	-	-	-	-	-	-4.2	0.65	0.43	24.4	173	0.27
Arya81(2) [15]	-11	80	0.11	-111	192	-0.17	-72	1.69	0.43	103	86.3	0.48
Mahr82(2)[16]	-141	154	0.11	-215	264	-0.17	94	0.42	0.39	-24.4	18	0.48
BeSc79(2) [17]	-	-	-	-108	297	-0.34	52	0.25	0.39	208	264	0.48
Nieu84a(2)[18]	-	-	-	-227	318	-0.26	215	2.1	0.34	6.27	13.9	0.48
ZiMi96 [6]	-178	188	-0.01	-225	277	-0.18	-	-	-	-33.8	33.8	0.38
Zili02 [7]	-148	164	-0.03	-219	284	-0.17	-	-	-	6.21	19.2	0.60
staJof [9]	-108	173	-0.09	-212	281	-0.18	-	-	-	-	-	-

(1) Modified version of Zilitinkevich's (1972) formula with re-estimated constants.
(2) This equation was developed for neutral conditions, here used also for stable conditions.
(3) Based on the MH values from sodar data (see Lena and Desiato, 1999).
(4) Based on MH values from sodar data (see section 3.1) rural data refer both to summer and winter conditions, urban data refer to winter conditions.
(5) NMSE is the normalised mean square error.

It can be seen from Fig. 5 that the median value of the urban MH is always greater than the median value for rural conditions. The largest difference is for the "Ven80b" formula (+ 73.5 m) and the smallest for the "staCLM" method (+ 3 m). The MH estimated by sodar ("staSOD") is slightly greater for the urban case (+ 14 m).

The box extremes (1st and 3rd quartile) show that some formulae provide MH estimations that range between ca. 80 and 300 m (Ven80b urban, and BS79 rural) while other formulae are characterized by a very narrow range of values (for examples ZiMi96, Mahr82 and Nieu8 ranges between around 10 and 70 m). At the rural site, the CALMET pre-processor sometimes considers as convective periods that are classified as stable by the other methods, thus leading to a large number of outliers in Fig. 5. BS79 and Nieu84 formulae give very low values when the wind speed is very low. Such conditions often occur in the Po Valley where the measurements were made. The formulae

ZiMi96, staJof, Nieu81, and Zili02 also gives low MH in very stable conditions, when the measured L is very small (around 10^{-4} m), while Ven80a gives low values when u_* is small.

Since sodar-derived MH values can be considered independent from the MH estimates from the parametric methods that use surface data, some statistical indexes such as the bias, root mean square error RMSE and the correlation coefficient were calculated from these two sets of MH-values (Table III). For the Bologna data set, these statistics were considered only for formulae for which at least 10 pairs of data were available. The number of data pairs in most cases is only about 20. Some previous similar comparisons, whereby the MH was also determined by sodar, with urban data in Milan (Lena and Desiato, 1999) and a rural data in Cabauw in the Netherlands (Vogelezang and Holtslag, 1996; Zilitinkevich and Baklanov, 2002; Baklanov, 2001) are also presented in Table III for comparison.

Results show that all algorithms provide MH values that are poorly related with sodar MH estimated for both urban and rural conditions. The weak correspondence between parametric MHs and sodar MHs is partly due to, as described in Section 2.2, the simplicity of the algorithms for nocturnal conditions. On the other hand, sodar data also have known deficiencies, so that no firm conclusions can be drawn.

These results corroborates the results of Seibert *et al.* (1998) who found that the tested algorithms did not yield very satisfactory results either, for rural and/or homogeneous conditions. Thus, this low correlation with the sodar derived MH is not very surprising and probably not just due to the urban features. A slight improvement, compared to urban conditions, can be noted for the formulation of Zilitinkevich *et al.* (2002) that performed much better than the other formulations against data for the rural sites.

(b) MH-data vs. CBL prognostic and diagnostic formulations

For CBL conditions, we compared four different formulae (see Appendix) with sodar estimates and MH-values calculated from the CALMET-SMR pre-processor. The number of data considered is around 600. The number of data drops to 40 for the sodar method.

Figure 5 (mid-panel) shows that the urban-rural difference between the MH median values ranges between +460 m for the “BaG91b” method and 142 m for the “BaG91a” method, while this difference for sodar values is +164 m. The range of urban MH estimates is maximum for the “BaG91b” and “unsCLM” formulae and minimum for the “unsJof” and sodar methods. This behaviour is different at the rural site where the range of values from “unsJof” increases while the range of “BaG91b” decreases. The BaG91a and BaG91b formulae gives sometimes zero values, probably due to the method employed to estimate the potential temperature gradient γ above the ABL. Some formulae give sometimes very high values like 5000 m (e.g., BaG91b urban). These outliers can occur when the formula gives a strong increase of MH from one time step to the next (e.g., Arya81 around 12Z in the top panel of Fig. 8). To avoid these discontinuities in the time evolution of the MH, an upper limit to the hourly increment of MH was set to 1000 m.

The typical daytime course of the MH calculated with the various algorithms during winter (left) and summer (right) at the rural (top) and urban sites (bottom) is illustrated in Fig. 7, for a "mean day" (i.e., the average of all the half hour values during the whole measurement period). The expected daily course is more or less caught by all the formulae, though large discrepancies may occur, and this more as the day evolves. The Batchvarova and Gryning (1991) formula BaG91a has a slow growth during the morning and stays stationary during the afternoon. The second Batchvarova and Gryning (1991) formula BaG91b reaches high values at the urban sites and keeps growing during the afternoon, while at the rural site it stays stationary during the afternoon. The MH calculated by Tennekes and Driedonks’ (1981) scheme grows during the first part of the afternoon not only at the urban but also at the rural site. Joffre and Kangas’s (2002) mixing height often decreases during the afternoon and lead to fluctuating values. In all the conditions shown, the CALMET calculations, which show the smoothest behaviour, are closest to the Tennekes and Driedonks formula (Eq. 10 in Appendix).

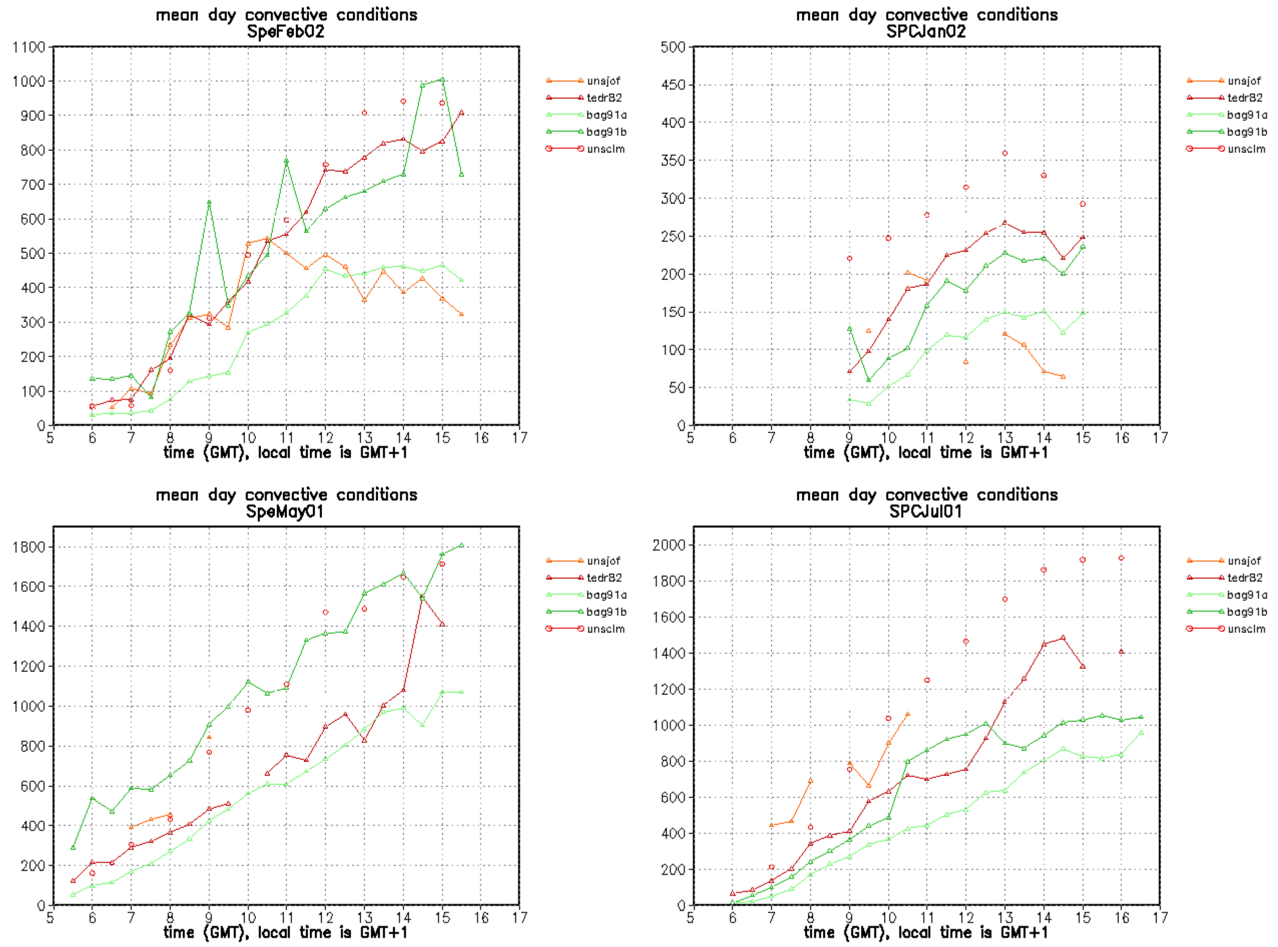

Figure 7. Mean daily course of the MH calculated with 5 different algorithms (orange = Joffre and Kangas (2002); red = Tennekes (1973), Tennekes and Driedonks (1981); green = Batchvarova and Gryning (1991), their two different formulae; open red circles = CALMET). Upper panel: winter, lower panel: summer, left: Urban, right: Rural. Note that the plots do not have the same vertical scale.

The discrepancies between the various methods can be seen in the time evolution of the calculated MH-values (Fig. 8) for two summer days at the rural site (top) and a winter day at an urban site (bottom). All the days shown are sunny with low winds (the wind speed is < 3 m/s during the summer days and < 6 m/s during the winter one) and with prevailing convective conditions during the day. For summer conditions, CALMET (dark red open circle in the plots) has often a strong growth until 17.00 LST and a sudden decrease after sunset. The MH growth estimated by the Tennekes-Driedonks' scheme (dark red triangle) and in particular by Batchvarova-Gryning's formulae (dark and light green triangle) is weaker in the afternoon. In summer, the MH evaluated by the sodar profiles (black closed circles) stays closer to these three methods, rather than to CALMET values, whereas on the winter day, daytime CALMET and sodar estimates are rather close. In this case, daytime MH estimates by Batchvarova-Gryning and by Joffre-Kangas are considerably lower than those of the other methods applied.

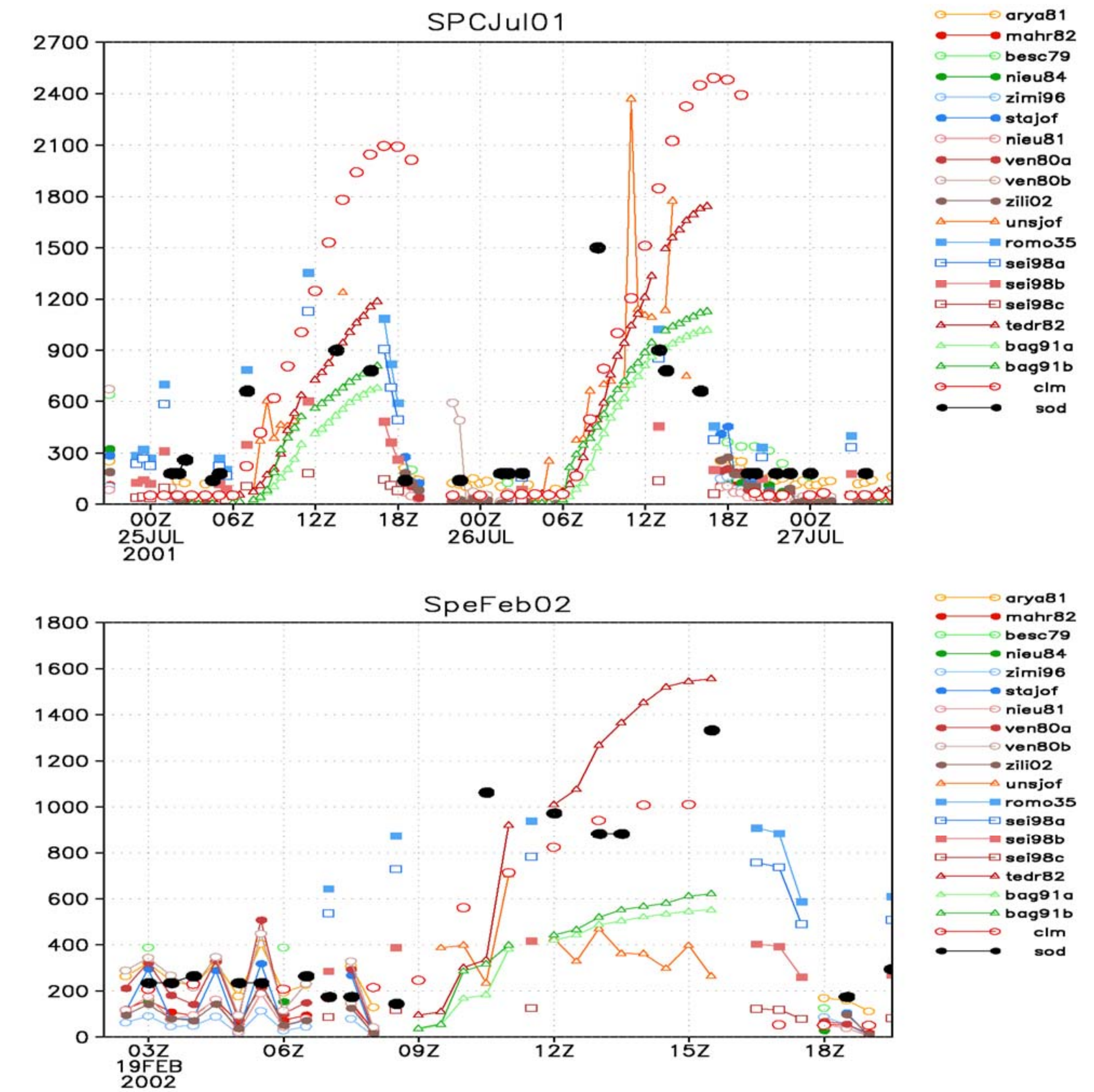

Figure 8. Temporal evolution of the MH estimated with different methods for Bologna. Top, two summer days at the rural site SPC; Bottom, a winter day at the Specola urban site. Open red circles = CALMET; close black circles = sodar; close blue squares = Rossby & Montgomery (1935); open blue squares = Seibert *et al.* (1998); dark green triangles = Gryning and Batchvarova (1991); light green triangles = Gryning and Batchvarova (1996); open orange triangles = Joffre and Kangas (2002).

When comparing these various convective algorithms with sodar derived MH-values, they all show very poor correlation (correlation coefficients range between -0.3 and 0.1) and a negative bias (e.g., the sodar-derived MH is generally greater than MH estimated by the 5 formulae), with the only exception of CALMET in rural summer conditions. However, it is expected that the sodar is still less appropriate for determining the MH under unstable conditions than in stable conditions due to the fact that the daytime MH is frequently beyond the sodar vertical range.

(c) MH-data vs. neutral ABL diagnostic formulations

For the neutral MH, we compared four different methods with MH calculated from the CALMET-SMR pre-processor. The neutral ABL was not estimated from sodar data. All the tested "neutral" formulae simply differ by a multiplicative factor (see Appendix). The number of data considered is around 600 for the urban case and 200 for the rural case. The number of data drops respectively to 300 and 100 for the CALMET method.

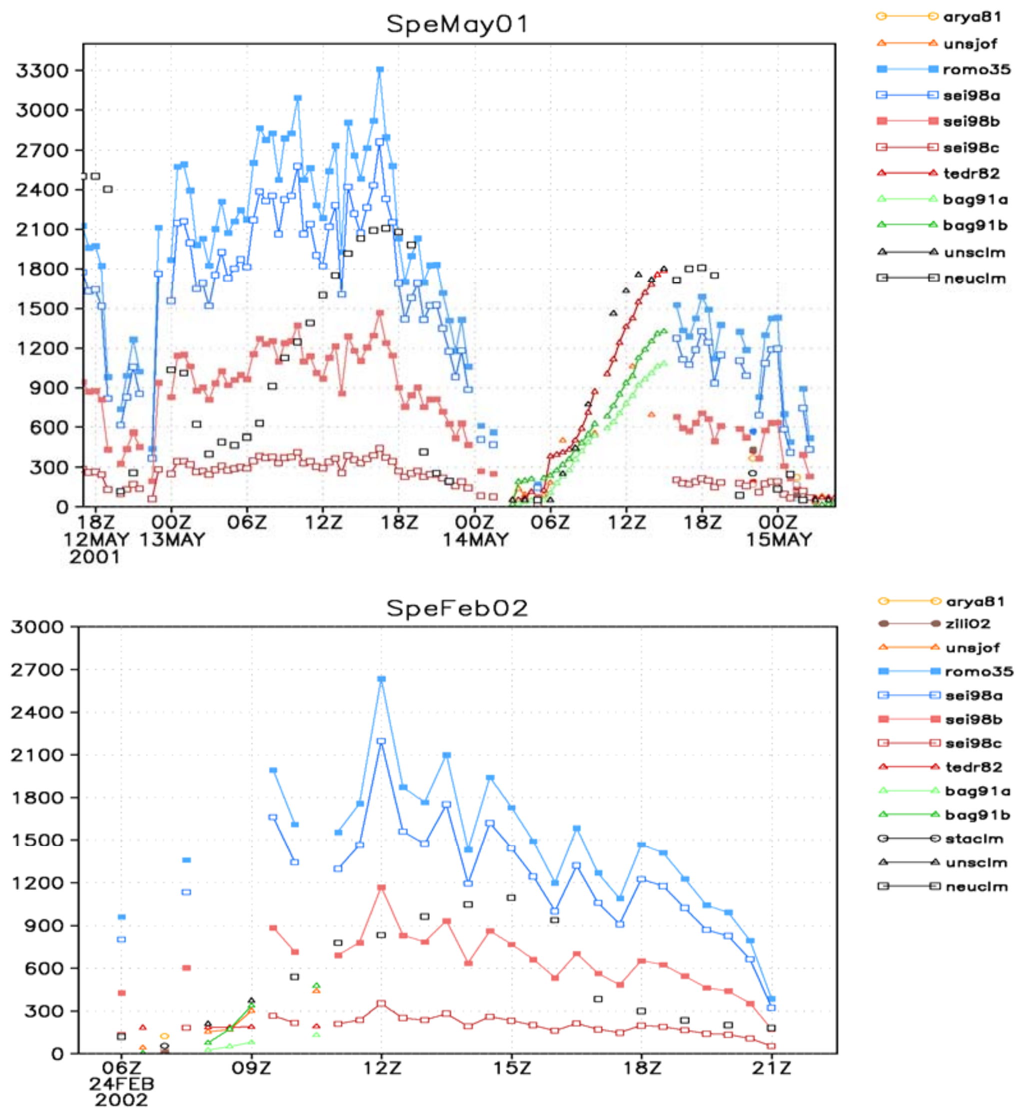

Figure 9: MH estimated with different methods at the Specola urban site during two late spring days (Top) and a winter day (Bottom). Neutral boundary layer: blue closed squares (Rossby & Montgomery, 1935), blue open squares (Sei98a), dark red closed squares (Sei98b), dark red open squares (Sei98c), where Sei=Seibert *et al.* (1998). Convective boundary layer: red close triangles (Tennekes & Driedonks, 1981), red open triangles (Joffre & Kangas, 2002), green close triangles (Batchvarova & Gryning, 1991), green open triangles (Gryning & Batchvarova, 1996), black open squares and triangles = CALMET-preprocessor.

The box plot (Fig 5, lower panel) shows that the difference between the urban MH median values and rural MH median values range between 435 m for the "RoMo35" method and 58 m for the "Sei98c" method. In contrast with these results, CALMET calculations provide rural MH values 55 m higher than urban ones. Apart from CALMET, the range of MH estimates in urban conditions is maximum for the "RoMo35" and minimum for the rural "Sei98c".

In late afternoon and evening hours, neutral conditions often occur during the transition from unstable to stable conditions. Under such conditions, the MH decreases through the evening. This typical course is illustrated in Fig. 9, During the two late spring days (13-14 May), the ABL was mostly neutral due to moderate wind conditions (wind speed between 5 and 9 m/s in Bologna), except for the period between 06:00 and 15:00 LST on May 14, when the ABL became convective. All the algorithms catch the transitions between the decreasing neutral ABL during the night and the increasing convective ABL after sunrise. On February 24, with moderately windy (6 m/s), the ABL was neutral for the whole period. The comparison in Fig. 9 shows that RoMo35 and Sei98a (blue closed and blue open squares) always give the highest MH, while Sei98c (dark red open squares) the smallest MH. CALMET (black open squares) mainly shows a smoothed behaviour that is rather more sensitive to the thermal terms than to the mechanical ones.

4.2.4 Ceilometer and radiosonde data from Helsinki

First results of the radiosonde–ceilometer comparison from Helsinki (Section 3.7) show that under clear sky conditions the MHs determined from ceilometer based aerosol profiles, utilising a slightly modified method of Steyn *et al.* (1999) and CBL-height estimates based on radiosounding data (with the Holzworth method) are in quite good agreement. The analysis included *ca*. 60 convective cases obtained during 2002. The rejected cases in Fig. 10 corresponded to very low aerosol concentrations in the mixed layer that led to a very weak aerosol backscatter signal in the lowest layer.

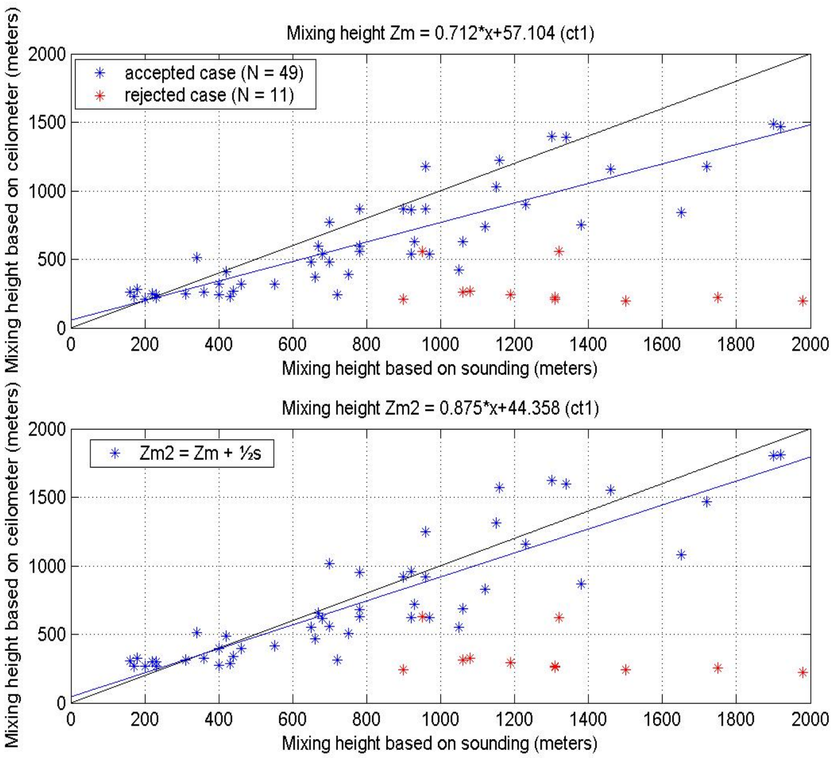

Figure 10. Comparison of MHs estimated from radiosoundings and ceilometer aerosol profiles in Helsinki, 2002. Upper panel: ceilometer-based mixing height *Zm* defined as the height of the midpoint of the entrainment layer, lower panel: ceilometer-based mixing height *Zm2* defined as the height of the top of the entrainment zone (*s* is the depth of the entrainment zone).

For stable conditions, the MH determined from radiosoundings (with the Ri-number method) showed a somehow lower correlation but with only 30 cloudless cases. Though the mean difference between the two estimates was not large (80 m), this may be relatively large for shallow stable ABLs. For the shallowest MH cases, the ceilometer always overestimated the radiosounding estimates.

Thus, the ceilometer can be a useful instruments for determining the MH but, again, it cannot be used automatically without a careful assessment of the prevailing conditions (clouds, surface backscattering, initial guess), which otherwise could lead to spurious values.

4.3. Comparison of numerical pre-processors and NWP models vs. data

4.3.1 Mixing height estimates from NWP/meteorological models: Athens

The possibility of applying numerical meso-meteorological models to the estimation of the urban MH will be considered here, using the example of Athens city and its surroundings. The purpose was to evaluate the effects of features such as complex topography and strong changes in surface roughness from sea-land and urban-rural on the evolution of the MH. The MH formation becomes a complicated process where such features coexist.

The Penn State/NCAR Mesoscale Model MM5 (Anthes and Warner, 1978) was applied in three different configurations:

1. The original version of the MM5 model with as ABL scheme the high resolution non-local NCEP MRF (National Center for Environmental Prediction / Medium Range Forecast Model). This scheme is based on the Troen and Mahrt's (1986) representation of counter-gradients and K-profiles in the well-mixed CBL (Hong and Pan, 1996). Here urban areas are represented as bare soil but with specific urban surface characteristics and physical parameters, such as roughness length, albedo etc. In this non local MRF scheme, the MH is a function of the critical bulk Richardson number.
2. A second "urbanised" version of MM5 whereby urban features were introduced both in the thermal and the dynamical parts (Dandou *et al.*, 2004). In particular, the urban heat storage was incorporated via the Objective Hysterisis Model (OHM) of Grimmond *et al.* (1991), whilst the anthropogenic heat energy from Athens was introduced following Taha (1998). Furthermore, the surface stress and heat flux computed by the model were updated to better represent rough surfaces under unstable conditions, according to Akylas *et al.* (2003). The whole scheme was supported by detailed spatial information on land use cover derived from satellite image analysis.
3. A third version isolated the topographic influences on air motions in the city basin, based on the original version of case 1, but where Athens was replaced by dry cropland and pasture surface, as in the surrounding areas.

Note that in rural areas, all three configurations had the same land use cover.

During the MEDCAPHOT campaign conditions, all three cases show the simulated MH is noticeably higher in urban areas than in the rural case, especially during daytime (Fig. 11).

In case (2) one main difference brought about by the "urbanised" MM5 version is the increased MH during the night (due to heat storage and anthropogenic heat terms). During daytime, the MH is slightly lower than calculated by the original version and there is a delay of two hours for the maximum value to be reached. On the other hand, the urban features do not affect the MH-values for the non-urban site.

For case (3) when the urban area is replaced by a dry cropland and pasture area, MH-values are much lower (~300 m) compared to the ones from the original version; nevertheless, the maximum MH-values are still formed in the Athens basin due to the surrounding topographical features. This unrealistic run illustrates that in a complex situation, urban influences coexist with other mechanisms. These results corroborate the findings of Martilli et al. (2002) with a similar set up.

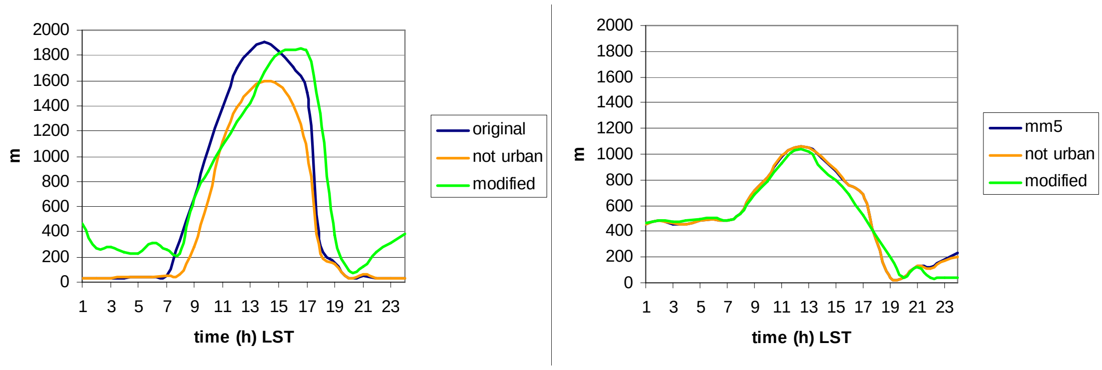

Figure 11. The diurnal variation of the mixing height (m) at the NOA station in the city centre of Athens (left) and the rural station of Spata (right), produced by the original MM5/MRF model (dark blue line), the urban area replaced by a dry cropland and pasture area (orange line) and the modified "urbanised" MM5/MRF model (green line) on 14.9.1994.

Figure 12 shows the night-time spatial distribution of the MH for the original case (1) and the modified one (2), respectively. The increase of the MH in the Athens area compared to the surroundings is clearly visible.

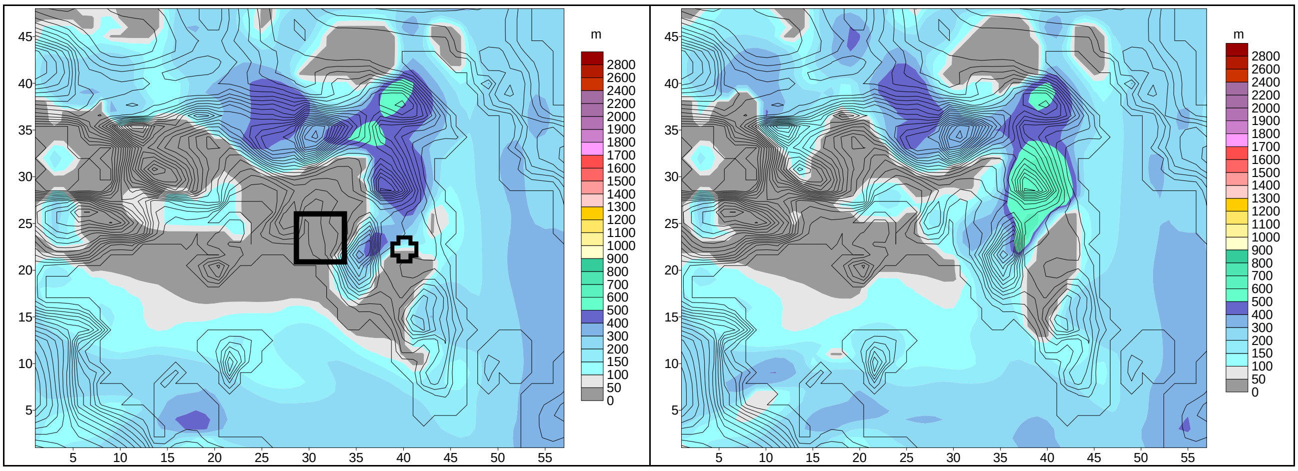

Figure 12. Spatial distribution of the mixing height calculated by the original (left) and modified (right) MM5/MRF model, at 23:00 LST on 14.09.1994. The axes represent number of grid cells of 2 km each. Central Athens is indicated by a box and the rural Spata station is indicated by a cross in the middle of the left figure. The urban NOA station is inside the box.

During daytime, the urban MH-values covered a larger domain, in contrast to the original model, corresponding to the urban coverage as observed from satellite images. Nevertheless, the maximum urban MH value is now substantially lower than the one calculated with the original model version (Fig. 13). This feature is accompanied by a decrease of the modelled temperature and a reduction of the momentum and heat fluxes (Dandou *et al.*, 2004). It is only the modifications in the surface energy balance that have produced this significant decrease of the MH over the city area, which is explained by the absorbing role of the urban heat storage term. This arises from the fact that the changes in the dynamical part, introduced by Dandou *et al.* (2004), result in a substantial increase of the MH in rural areas where low winds under convective conditions prevail. This is apparent in the plain north of the mountainous area (Fig. 13b), where the MH is increased by more than 500 m in some areas.

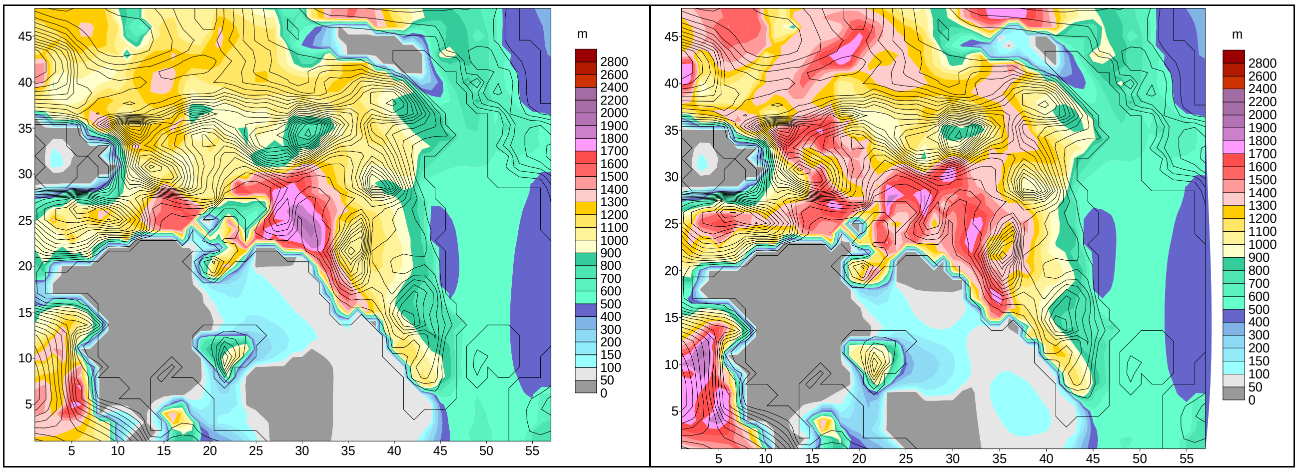

Figure 13. Spatial distribution of the MH over Athens calculated by the original (left) and modified (right) MM5/MRF model, at 14:00 LST on 14.09.1994.

4.3.2. Sensitivity study with the ADMS met-processor: London

The ADMS Model (details: www.cerc.co.uk) is a regulatory model with applications in the U.K. and elsewhere for assessing local air quality and for environmental impact assessments. It contains a meteorological pre-processor which uses synoptic observations to calculate the stability (Monin-Obukhov length L). The model offers other facilities for data input, including the use of two roughness lengths. This means the value of the roughness at the anemometer position may be different from that where the dispersion is to be calculated. This option is designed for the usual situation where the data are from an airport but the air pollution must be calculated in the city. We explore here the effects of this urbanising option, and a related one that restricts the conditions from going too stable, representing some urban effect on stability.

MHs for 6th-27th July 2003 were calculated using the ADMS model pre-processor, as part of an urban lidar study (see Piringer and Joffre, 2005) for the following cases, plotted as three time series in Fig. 14:

1. Uniform rural conditions (z_o=0.1 m assumed everywhere): green.
2. Uniform urban conditions (z_o=1.0 m assumed everywhere): pink.
3. Transition from rural conditions (z_o=0.1 m at anemometer site) to urban conditions (z_o=1.0 m over the urban site) for dispersion met pre-processor calculations: blue.

Figure 14 shows that for all the days tested, a uniformly rural roughness gave the lowest values of MH, whilst the uniformly urban roughness gave the largest MH values. On the windier days the values of the ‘urban’ MH exceeded 2500 m, and this was judged somewhat unlikely. Therefore the transition case is of great interest; it was intended to be more physically representative, and does indeed yield values of MH which are increased only moderately over the uniformly urban case. This is judged to be more realistic, but field data are needed to validate these results.

Counter-intuitively perhaps, the errors in MH for dispersion calculations might be larger when an urban roughness is assumed everywhere rather than if a rural roughness were used everywhere including within the city. This is because at the anemometer site, too great a roughness would mean the model mis-interprets the effective strength of the wind. In short, if Case 3 seems physically most appropriate for urban dispersion, Case 1 might be the next best option, and Case 2 the least appropriate. Overall, these few results indicate that in estimating an urban mixing height, the manner in which the roughness length parameter z_o is used to represent site conditions merits careful attention and field validation. The dual roughness option seems to have most merit here.

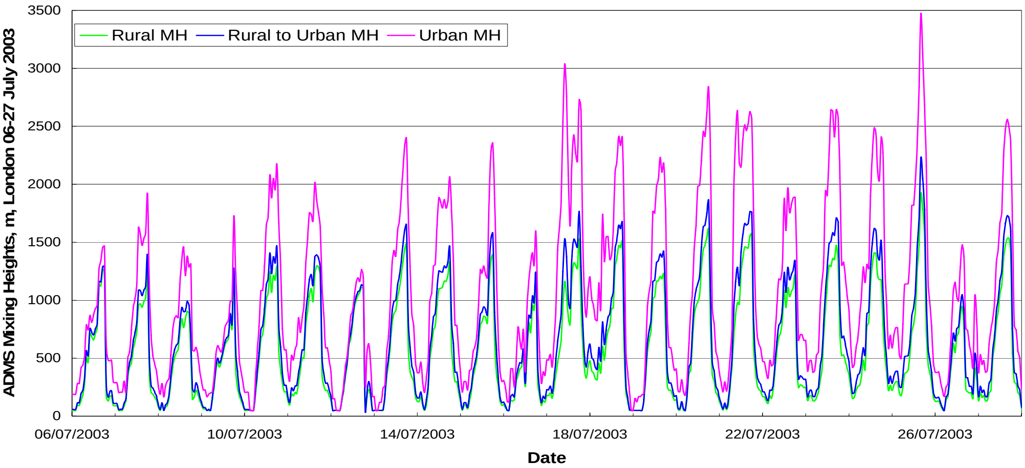

Figure 14. ADMS mixing heights using London Heathrow observations, 6-27 July 2003. Cases (1): rural roughness z_o=0.1 m (green); (2): urban roughness z_o=1.0 m (pink); (3): rural roughness z_o=0.1 m at airport with urban roughness at city z_o=1.0 m (blue).

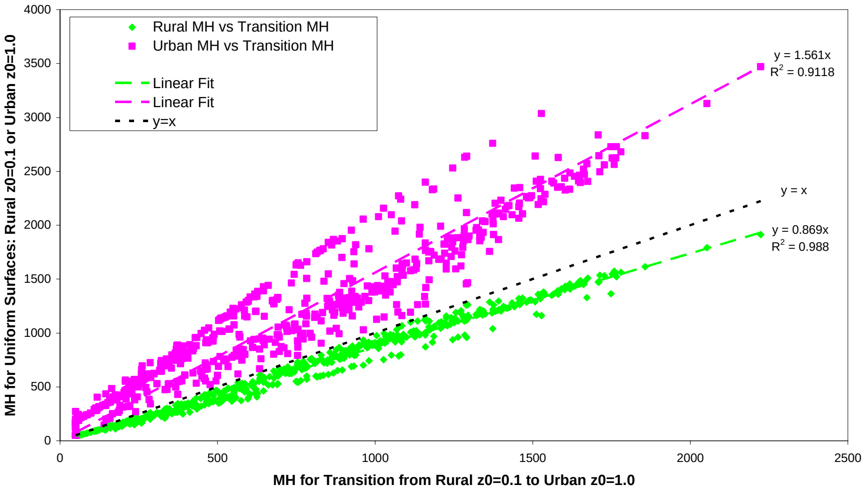

Figure 15. Comparisons of ADMS mixing heights using London Heathrow observations, 6-27 July 2003. Green: Case 1 versus Case 3 (‘rural’ versus ‘rural to urban’ transition); Pink: Case 2 versus Case 3 (‘urban’ versus ‘rural to urban’ transition).

The model also has a stability limit, and Case 3 above was then re-calculated with a limit imposed on the MO-length L ($L \geq 100$ m in stable conditions), to simulate the fact that urban atmospheres tend to be less stable than rural ones. This limit prevents diagnosis of the most stable situations, so only operates in such conditions. During some nights, the effect of less stable nights was to make the calculated MH slightly larger by 10-30 m. Similar minor changes were observed in Cases 1 & 2 when the limit was applied.

Finally, the results from Cases 1-3 were compared directly using scatter plot (Fig. 15). Here the transition Case 3 is plotted horizontally and serves as our reference data for comparison purposes. The uniform Cases 1 and 2 were plotted vertically. All the data points for 01-31 July 2003 are drawn in Figure 15 and the best fit lines through the origin show the all ‘rural’ results (green) are ~10% smaller, whilst the all ‘urban’ results (pink) were ~56% greater, than the rural-urban transition Case. This is the kind of shift in magnitude that merits field investigation.

In conclusion, the greatest sensitivity seen here with ADMS was that an increased z_o at the anemometer site is to make the modelled urban MH much larger, and care should be taken to ensure that a suitably small roughness length is used for the site where meteorological data are observed, along with a suitably larger one for the city. A modest increase in the shallow overnight MH was produced when L was constrained to prevent it being diagnosed as very stable. These sensitivities merit further field investigation.

5. Discussion

Results presented in Section 4 lead us to the conclusion that no single method or device can determine hourly MH values in a city on a continuous basis, say over the period of one year. There is no "MH – meter" (Seibert et al., 2000), so complete and accurate daily or yearly courses of MH would be difficult to obtain. Hourly values of MH are however a necessary input for many dispersion models, and in the absence of reliable data, they are often obtained by not well verified assumptions (e.g. a fixed MH value is set for each discrete stability class) or parametric formulae (Piringer and Joffre, 2005). However, in some specific field experiments, the combination of several instruments has shown more potential to compensate for limitations of individual devices. However, there is still a need for close monitoring by an expert to judiciously apply the right device to the right situation.

Whereas the course of the MH on sunny days or in clear nights is in principle well-known and can be parameterised if the conditions in a city are not too complex, there is still uncertainty on what the MH is like in cloudy, windy and rainy conditions, which comprise the vast majority of cases in temperate and Northern climatic regions. Even less known is the impact of these uncertainties on concentration fields calculated by dispersion models. Another major concern is obtaining "the" representative value of hourly MH for a city as most dispersion models can only incorporate meteorological information from one single point in the domain.

If instrumentation is used to determine the MH, this involves analysing vertical profiles of temperature, humidity, and wind, or interpreting vertical profiles of the intensity of back-scattered signals. They cause uncertainty and thus often deliver very different estimates of MH for which Section 4 gives several examples. Of the simple diagnostic relationships used with radiosonde profiles, the parcel methods under convective conditions or the Ri-number methods both for convective and mechanical turbulence, seem to give the most plausible results in many cases. When using a prognostic equation for the MH growth in unstable conditions, large discrepancies depending on the algorithm can occur, as demonstrated in Figs. 7–9. In stable conditions, calculated MHs with all methods often fall into a coherent range, but their correlation is often poor.

Several groups in Europe use sodars to estimate the MH. The experience of COST-715 WG 2 is ambiguous as far as the quality of sodar-derived MH is concerned. In principle, sodar has the potential to deliver hourly MH at low cost in a variety of cases except after noon when the MH is generally higher than the sodar probing range and in the absence of thermal or mechanical turbulence, e.g., in entirely adiabatic conditions which sometimes occur during the evening transition or occasionally in strong winds or rain. As displayed in Figs. 2, 7 and 8, careful sodar data analysis can yield at least plausible results for the average daily course of MH for selected periods. However, the comparison between diagnostic MH estimates and sodar in Section 4.3 proved a rather good internal consistency between the various schemes, whilst the sodar cluster of MH values clearly departs from values derived with these schemes. The RASS extension to sodar makes possible direct (virtual) temperature measurements, but this technology is still at the beginning, and no systematic evaluation of RASS temperature profiles and related MH determination was available to COST-715.

The actual city influence on the MH can be indirectly determined by estimating MH from radiosoundings representing alternately "urban" and "rural" sectors, i.e. if the wind sweeping over the radiosounding site has crossed the adjacent city or not (Section 4.2.1). This investigation showed that MH does depend on the upwind fetch, and that urban MHs tend to be often higher than rural ones. However, the departures between MH estimates from different methods can be large, even on average, and, more important, the performed comparisons reported here were not simultaneous. This again highlights the fact that representative and long-lasting experimental MH determination directly in cities, although desirable, is difficult to be undertaken and has to be awaited from future, carefully planned field experiments. For instance, Collier *et al.* (2005), Middleton and Davies (2005) have investigated dual Doppler scanning lidars for studying the MH at urban-rural transition. Such technology can scan a region of several km^2, but the data require judicious interpretation.

A few tests of the applicability of the simple scaling formulae of the Appendix for specific urban sites have so far yielded inconclusive results due to the lack of real reference MH values (e.g., Berman *et al*., 1997; Lena and Desiato, 1999). However, a comprehensive analysis of their applicability has yet to be carried out. The main problem of such diagnostic methods is their assumption of horizontal homogeneity and temporal non-stationarity of the UBL and the non-local character of the urban MH formation. Therefore, it is difficult to expect that they are applicable to city peripheries (with sudden changes of roughness), whereas they might be used in central (relatively homogeneous) areas of certain European cities, since the physical mechanisms behind the MH formation are the same there as for other types of surface. However, this weak agreement with measured urban MHs is not only due to the urban features since they do not yield very satisfactory results either for rural and/or homogeneous conditions (Seibert *et al.*, 2000; Baklanov, 2002; Zilitinkevich and Baklanov, 2002).

Nevertheless, the mechanisms involved in the formation of the daytime MH (or CBL) are better understood than the corresponding ones at night time. For SBL cases, it is reasonable to use MH methods, which consider either vertical profiles, or roughness with surface fluxes as input parameters, since, in the latter case, the heat flux and roughness can be corrected for urban conditions. On the other hand, it is strongly recommended that more emphasis be given to improving the methods for the night time urban MH.

Mesoscale NWP models have the potential to provide the temporal evolution and the spatial distribution of the boundary layer in a specific area, even if the structure of the terrain is complex (Section 4.3.1). We have shown that the urban MH may be generated directly by the NWP model as a local boundary layer depth or inferred from NWP output profiles by analogy with the methods used for measurements. Any model can be applied for a desired configuration and results can then be compared graphically and statistically, at least at selected receptor points that often are meteorological stations or measurement sites. However, anywhere in the domain apart from the stations, an assessment of the reliability of the MH results is difficult and generally only a comparison of the effect of the different model assumptions on MH results is possible (as in Section 4.3.1).

Despite the increased resolution of existing operational NWP models, their urban and non-urban "areas" mostly contain similar sub-surface, surface, and boundary layer formulations. These do not account for specific urban dynamics and energetics or for their impacts on the simulation of the ABL and its various characteristics (e.g. internal boundary layers, urban heat island, precipitation patterns). Additionally, NWP models are not primarily developed for air pollution modelling and their outputs need to be designed into suitable inputs for urban and meso-scale air quality models. Therefore, a revision of the traditional approach to urban air pollution forecasting is required. The main objectives are to improve meteorological forecasts for urban areas, to connect numerical weather prediction models to urban air pollution and population exposure models, to build improved Urban Air Quality Information and Forecasting Systems, and to demonstrate their application in cities subject to various climatic conditions. Currently this work is realised within the EU project FUMAPEX (Baklanov, 2003).

The meteorological variables routinely calculated by operational meteorological models do not always provide all the necessary meteorological quantities required to determine all scaling parameters. Moreover, the values provided by NWP models for turbulence scaling parameters can sometimes be not suitable for dispersion calculation due to, e.g., change of spatial scale and resolution of the considered air pollution phenomena. Thus, additional calculations and interpolation of data from routine meteorological stations may be necessary.

6. Findings and Recommendations

The investigations presented here revealed merits and shortcomings of current instruments, schemes for analysing their data and numerical models of the met pre-processor type as well as NWP to determine the MH in urban areas. Our major findings are summarised, and recommendations for further studies are given in the following.

When modelling the MH, the mechanisms involved in the formation of the daytime MH are better understood than the corresponding ones at night-time. It is therefore strongly recommended that more emphasis should be given to improving the methods for the night-time MH determination.

Inter-comparisons of various diagnostic MH-formulations against estimated MH data (mainly from sodar and radiosounding) led to rather unsatisfactory results, due to large scatter and bias and low correlation. However, it is very important to acknowledge that the MH-estimates cannot be considered as the empirical "truth" as they have their own theoretical and practical limitations, especially when profiles are not analysed individually but through an automatic algorithm or threshold procedure (critical Ri, first maximum echo level, etc.).

On the basis of the data analysis performed above, it is difficult to recommend any formula above another. Such a goal can be achieved only through detailed analysis of individual profiles using in parallel the different profiling techniques. Nevertheless, general suggestions, concerning the applicability of 'rural' methods of the MH estimation for urban areas, are the following.

- Routine radiosonde measurements and AMDAR data can be used for estimation of the MH in urbanised areas provided such stations are close to cities and the wind fetch is from the city. For more accurate results, finer vertical resolution is required, especially during stable conditions.
- The nocturnal UBL forms when anthropogenic/urban heat fluxes are zero or positive, in contrast to the negative 'non-urban' surface heat fluxes, and hence, the applicability of standard methods for the SBL estimation in urban areas is less promising.
- For estimation of the daytime MH, applying standard rural methods is more acceptable than for the nocturnal MH (Seibert *et al*., 2000), provided they allow for the urban heat storage as well as changed surface characteristics.
- Uncertainties in diagnosing the CBL MH from radiosounding profiles for urban and non-urban conditions can be minimised by using a combination of the Ri and Parcel methods.
- For the convective UBL the simple *slab models* (e.g. Gryning and Batchvarova, 2001) were found to perform well.
- The determination of the SBL height needs further data, developments and verifications versus urban data. As a variant of the methods for stable MH estimation, the new Zilitinkevich *et al*. (2002) parameterisation can be suggested in combination with a prognostic equation for the horizontal advection and diffusion terms (Zilitinkevich and Baklanov, 2002).

Nevertheless, significant new experience, information and data have been gained during recent field experiments, such as BUBBLE in Basel, studies in Bologna, Copenhagen, Hannover, Helsinki and Athens, most of them generated or stimulated by the COST-715 activity.

Though very simple and cheap, sodar data should be considered with great care and without extrapolating beyond the physical range of acoustic signals. Sodars and sodar-RASS determine MH from thermal characteristics of the ABL, lidars and ceilometers from the aerosol content profile. In very clean air the optical backscatter may vanish, while aerosols may linger after turbulence has decayed. Nevertheless, with care in interpretation, as long as aerosols are a good tracer of the mixing-layer, ceilometers are probably the simplest means to monitor MH (Emeis *et al*. 2004).

It can be considered that the MH is still a useful concept in the context of simpler regulatory dispersion models, although not a very accurate one. No direct evaluation of the MH is necessary regarding the dispersion of traffic-originated pollution within the roughness sub-layer (e.g., within a street canyon). On the other hand, at the urban and meso-scales, the MH is an important parameter for practically all air pollution applications. This is especially true for urban pollution episodes.

Concerning numerical weather prediction models, it is not so clear whether the MH is sufficiently accurate to be useful at the present stage of development of knowledge. Meso-meteorological and NWP models with modern high-order non-local turbulence closures give promising results (especially for the CBL), however currently the urban effects in such models are not included or included with great simplifications (Baklanov *et al.*, 2002). Therefore, it is very important to test different MH schemes not specifically designed for the urban environment against urban MH or IBL schemes for different data sets from different urban sites (in priority for nocturnal conditions) to assess the possible improvements. It would be also helpful to know which of the parameterisations are the most sensitive to changes of which environmental variables.

Nevertheless, more specific methods for determining the MH over urban areas and adapted to available empirical devices are needed. Additionally, horizontal heterogeneity and the vertical structure of the ABL over urban areas have also to be taken into consideration to interpret data and derive MH-schemes.

Concerning further needs from experimental studies, we can conclude that more climatological information on the urban MH, its daily and yearly course as well as differences according to typology and climatic conditions is needed. The instrumental requirements in order to estimate the MH may be different for day- and night-time. They may also differ with some meteorological situations. During daytime, a larger vertical range in combination with a coarser vertical resolution is required compared to night-time. A combination of sodar-RASS and ceilometer, located at a representative site in the city, might be promising to capture MH in the majority of cases. Last but not least, siting criteria for near-surface urban stations are urgently needed and would need to be endorsed by WMO. Sites should be characterised with the help of aerial photos, local surveys, maps and GIS databases.

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Appendix: Some formulations for estimating the MH:

Reference [code]	**SBL height equations**
1. Zilitinkevich (1972)	$h = c_2\left(\frac{u_* L}{f}\right)^{1/2}$, $c_2 \approx 0.4$ (varies as 0.13÷0.72 according to different authors)
2. Venkatram (1980) [Ven80a]	$h = 2300\, u_*^{1.5}$
3. Venkatram (1980) [Ven80b] (2)	$h = u_*\sqrt{\frac{2}{fN}}$
4. Arya (1981) (after Zilitinkevich, 1972)	$h = a\left(\frac{u_* L}{f}\right)^{1/2} + b;\qquad a = 0.43, b = 29.3$
5. Nieuwstadt (1981) [Nieu81]	$h = L\frac{0.3u_*}{\lvert f\rvert L}\frac{1.0}{1.0+1.9\,h/L}$
6. Zilitinkevich & Mironov (1996) [ZiMi96]	$\left(\frac{fh}{0.5u_*}\right)^2 + \frac{h}{10L} + \frac{Nh}{20u_*} + \frac{h\lvert f\rvert^{1/2}}{(u_* L)^{1/2}} + \frac{h\lvert Nf\rvert^{1/2}}{1.7u_*} = 1$
7. Zilitinkevich *et al.* (2002) [Zili02] (1)	$h = \frac{C_R u_*}{\lvert f\rvert}\left[\left(1 + C_h\frac{w_h}{u_*}\right)\Big/\left(1 + \frac{C_R^2 u_*(1 + C_{uN} NL/u_*)}{C_S^2 L\lvert f\rvert}\right)\right]^{1/2}$ with: $C_R = 0.4$, $C_S = 0.74$, $C_{uN} = 0.25$ and $C_h = 0.3$.
8. Zilitinkevich & Baklanov (2002)	$\frac{\partial h}{\partial t} + \mathbf{V}\cdot\nabla h = -C_E\,\lvert f\rvert\,(h - h_{CQE}) + K_h\nabla^2 h$ with $C_E \approx 1$.
9. Joffre and Kangas (2002) [staJof]	$h = \frac{b'}{2a'}\mu_N\left\{-1 + \left[1 + \frac{4a'm'}{b'^2}\mu_N^{-2}\right]^{1/2}\right\}L_N$ with: a'=0.12 ; b'=2.85 ; m'=24 (very rough surface)

Where u_{10} is the wind speed at 10 m height; $\mathbf{V}=(u,v)$ is the horizontal velocity vector, K_h is the horizontal diffusivity, h_{CQE} is the equilibrium MH calculated from a diagnostic formulation (e.g., Zilitinkevich *et al.*, 2002), $\mu_N = L_N/L$, $L_N = u_*/N$ (N is the Brunt-Väisälä frequency), f is the Coriolis parameter, and w_h is the large-scale vertical velocity at the SBL upper boundary.

(1) In the Bologna experiment, formula 6 was applied supposing $w_h \approx 0$.

(2) In the Bologna experiment was also tested the Venkatram (1980) formula using only the friction velocity $h = 2300\, u_*^{1.5}$. This formula is referred to as Ven80a.

Reference [code]	**CBL height equations**
10. Tennekes (1973); Tennekes and Driedonks (1981) [TeDr82]	$\frac{dh}{dt} = \frac{S}{\Delta\theta}$; where $S = A\overline{(w'\theta')}_o + \frac{B\,u_*^3}{\beta h}$ $\frac{d\Delta\theta}{dt} = \frac{\gamma S}{\Delta\theta} - \frac{\overline{(w'\theta')}_o}{h} - \frac{S}{h}$; where: $A = 0.2$; $B = 5$.
11a. Batchvarova and Gryning (1991)	$\frac{\partial h}{\partial t} = (1 + 2A)\frac{\overline{(w'\theta')}_o}{\gamma h} + 2B\frac{u_*^3}{\gamma\beta h^2}$, where: $A = 0.2$, $B = 2.5$

[BaG91a]	
11b. Batchvarova and Gryning (1991) [BaG91b] (3)	$\frac{\partial h}{\partial t}=\left(\overline{w'\theta'}\right)_0\left[\frac{\gamma h^2}{(1+2A)h-2kBL_*}+\frac{Cu_*^2}{\beta(1+A)h-kBL_*}\right]^{-1}$ *where:* $A=0.2$; $B=2.5$; $C=8$.
12. Gryning and Batchvarova (1996)	$\left\{\frac{h^2}{(1+2A)h-2B\kappa L}+\frac{Cu_*^2}{\gamma\beta[(1+A)h-B\kappa L]}\right\}\left(\frac{\partial h}{\partial t}+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}-w_s\right)=\frac{\left(\overline{w'\theta'}\right)_o}{\gamma}$, with $A = 0.2, B = 5, C = 1.3$
13. Joffre and Kangas (2002) [unsJof]	$h=\frac{b''}{2a''}\mu_N\left\{1+\left[1+\frac{4a''m''}{b''^2}\mu_N^{-2}\right]^{1/2}\right\}L_N$ with a´´=0.1 ; b´´= - 0.85 ; m´´=12

Where γ is the potential temperature gradient above the ABL ($N^2 = \beta\ \gamma$), $\beta = g/T_0$ the buoyancy parameter, $\Delta\theta$ the temperature jump in the entrainment layer at the ABL top, $\left(\overline{w'\theta'}\right)_0$ -the surface sensible heat flux ($=Q_H/\rho c_p$), w_s the vertical synoptic velocity above the ABL. Equation (13) was derived for moderate unstable conditions (both buoyant and mechanical production of turbulence) but not for convective conditions.

(3) In the Bologna experiment formula 12 was applied supposing $w_s \approx 0$ and neglecting the horizontal advection term $u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}$, the constants were set as: $A=0.2$, $B=2.5$, $C=8$, after Georgieva *et al.* (2003).

Reference [code]	**Neutral ABL height equations**
14. Rossby & Montgomery (1935) [RoMo35] (4)	$h=c_N\frac{u_*}{\lvert f\rvert}$, where: $c_N = 0.3$ ($c_N = 0.04$-0.3 according to Seibert *et al*., 1998)
15. Arya (1981) [Arya81] (5)	$h=0.089\frac{u_*}{f}+85.1$
16. Mahrt (1982) [Mahr82] (5)	$h=0.06\frac{u_*}{f}$
17. Benkley & Schulman (1979) [BeSc79] (5)	$h=125u_{10}$
18. Nieuwstadt (1984a,b) [Nieu84] (5)	$h=28u_{10}^{3/2}$

Developed for neutral conditions, Eq.(14–18) have been used also for stable conditions by some authors.

(4) In the Bologna experiment c_N was set equal to 0.25, 0.133 and 0.04 as suggested by Seibert *et al.* (1998), these formulae are referred respectively with Sei98a, Sei98b, Sei98c codes.

(5) In the Bologna experiment, formulae (14-18) have been applied also to the SBL.