THE VERIFICATION OF SBL MODELS BY MOBILE SODAR MEASUREMENTS

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Abstract: Models of atmospheric pollutant transport need information about structure of atmospheric boundary layer (ABL). The most important characteristic for such applications is parameterization of stable boundary layer (SBL) and mixing layer height (MLH). Recently many different scheme were employed to calculate SBL height, but there are many problems with implication these models in environmental studies. Remote sensing of the atmospheric boundary layer using acoustic sounder provides an opportunity to assess the mixing height based on analyses of SODAR echo strength. During the night, with a steady state of stable boundary layer, mixing height is associated with a range of inversion layer. In the present study, an attempt is made to assess the stable boundary layer height over urban area based on seven different schemes. Furthermore, the relationship of mixing height form SODAR measurement and models is examined. The data gathered during field experiment in Wroclaw and Cracow are employed for the evaluation of models The evaluation of models employing data gathered during field experiment in Wroclaw and Cracow.

Keywords: stable boundary layer height models, mobile measurement of SBL, SODAR, Wroclaw, Cracow.

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Introduction

An accurate estimation of mixing height (MH) is very important for environmental studies, especially for and air pollution management. According to air pollution studies, the most important quantity is stable boundary layer (SBL) height h, due to its impact on pollution dispersion (e.g. Gryning et al., 1987). Despite of its importance there is still lack of unique definition of MH. Furthermore, height of mixing layer isn't obtained using standard meteorological observation and the calculation of the mixing layer height over an urban area brings a number of problems (Baklanov et al., 2006).

The measurements involving monostatic Doppler mini-SODAR were conducted during implementations of Research Project entitled "The spatial variability of the Atmospheric Boundary Layer over Wroclaw and Cracow". The measurement were carried out during the weather characterized by low wind and low cloud cover. The data about inversion depth over the cities was gathered during mobile measurements in points located in the different land-use areas. The main aim of the project was to determinate the depth of the ground based thermal inversion and its spatial variations and evaluation of simple diagnostic SBL models in urban areas. The data gathered during mobile session involving SODAR were used to verify SBL height models.

Background

Stable Boundary Layer models

In recent years many works have been done in parameterisation of MH, on the base of direct measurements or involving different schemes (Baklanov et al., 2008) There are two main approaches to calculating SBL height using: a) profile data about temperature, humidity, wind speed; b) surface turbulence variables. Several parameterisation for MH during stable conditions have been proposed. Many models for SBL height are semi-empirical and their universality is not a priori guaranteed for different location. In these studies, seven of simple models (Table 1) were examined involving SODAR data.

Table 1. SBL height equations

No.	SBL equations	References
1	$h = 0.4\sqrt{\frac{u_* \cdot L}{f}}$	Zilitinkevich S., 1972
2	$h = 2300.0 \cdot u_*^{1,5}$	Venkatram A., 1980
3	$h = u_* \sqrt{\frac{2}{f \cdot N}}$	Ventakram A., 1980
4	$h = 0.43 \cdot \left(\frac{u_* \cdot L}{f}\right)^{0.5} + 29.3$	Arya S. P. S., 1981
5	$h = L \cdot \frac{0.3 \cdot u_*}{\lvert f \rvert \cdot L} \cdot \frac{1.0}{1.0 + 1.9\frac{h}{L}}$	Nieuwstadt F. T. M., 1981
6	$\left\lvert \frac{fh}{0.5u_*} \right\rvert^2 + \frac{h}{10 \cdot L} + \frac{N \cdot h}{20 \cdot u_*} + \frac{h \cdot \lvert f \rvert^{0.5}}{(u_* \cdot L)^{0.5}} + \frac{h \cdot \lvert N \cdot f \rvert^{0.5}}{1.7 \cdot u_*} = 1$	Zilitinkevitch S., Mironov D., 1996
7	$h = \frac{0.74 \cdot u_*}{\lvert f \rvert \cdot \sqrt{1 + \frac{0.4^2 \cdot u_* \cdot \left(1 + 0.25 \cdot \frac{L \cdot N}{u_*}\right)}{0.74^2 \cdot \lvert f \rvert \cdot L}}}$	Zilitinkevich S. et al., 2002

where: h − mixing height, u_* − friction velocity, L−Monin-Obukhov length, N − Brunt−Vaisala frequency, f – Coriolis factor.

The calculations of the friction velocity and Monin-Obukhov length were made based on: 1) algorithm proposed by Smith (Smith 1990, after Mohan and Siddiqui, 1997) and 2) algorithm proposed by Hanna and Pain (1997). The first one was iterative method so that instability was found during night condition. Therefore, the second method was chosen for further calculations.

In order to calculate L, u_*, θ_* for stable boundary layer conditions the following parameters were taken as input data: z - wind speed height [m] , u_z- wind speed at z height [$m \cdot s^{-1}$], T - air temperature, 2 m a.g.l.[°C], z_0 - roughness length [m], N - cloudiness [0-8].

Mobile SODAR measurements

The research concerning the state of the atmospheric boundary layer involving SODARs (Bradley, 2008, Kalistratova, 1997) have been conducted for over 25 years (Pyka, 1991) in the Department of Climatology and Atmosphere Protection, Wroclaw University. In order to evaluate spatial distributions of parameters describing the ABL, investigations have been carried out in the mobile measurement regime using Mini-SODAR 1DDS (Fig. 1.).

The mobile SODAR 1DDS is a smaller version of the stationary model. It is installed on a trailer that can be towed by a car. 1DDS SODAR measures the strength of the returning echo, and as well as the speed of vertical movements of air. Its technical specification is presented in Table 2.

Mobile SODAR 1DDS (Netzel et al., 2000) used during the field experiments was towed by a mobile meteorological station (measuring car). This station was equipped with GPS for recording current position of the car and meteorological sensors measuring temperature and humidity.

SODAR sounding at the selected sites was made each time after stopping the mobile meteorological station within 10 to 15 minute periods. After that, the car with SODAR was on the move again and followed a prescribed route to the next measuring point. Such a group of measurement points situated along the route constitutes one survey session. The selected probing time allowed to gather enough data for later processing and it also guaranteed that the gathered data were free from the influence of acoustic interference from the surrounding space. Measurements were carried out during nights with the presence of temperature inversion in radiation conditions. Survey sessions were started not earlier than two hours after the sunset and at the time when the nocturnal stable inversion layer near the ground was considerably developed. The entire measurement session lasted from 3 to 4 hours.

Table 2. Operating parameters of SODAR 1DDS

Weight	about 50 kg (about 200 kg with trailer)
Electric power at the speaker's input	400 W
The frequency of the sound signal emitted	4000 Hz
The maximum range of probing	380 meters above the ground
Spatial sampling resolution	2 m (175 samples in a range of 350 m)
Sampling Frequency	0.5 Hz (samples are collected every 2s)

Figure 1. 1DDS SODAR antenna

In order to objectify and improve analyzing of SODAR records, the processing of SODAR data have been automated. Removing the signal interferences and determining the height of the inversion was realized as a script in GNU Octave system (Eaton, 2002). This script reads SODAR registration records and removes the vertical noise patterns. The inversion height was calculated based on the returning signal strength curve.

Observations Sites and Data

The data gathered during the field experiments conducted in Wroclaw and Cracow were chosen for validating parameterization schemes.

Wroclaw is located in the south-western part of Poland (51°N, 17°E) in the Lower Silesian region, by the Odra river. Wroclaw is generally flat, the altitude varying from 105 to 148 m a.s.l. Such environmental conditions make this city useful for assessing the impact of the urbanized area on local climate.

Cracow is the second largest cities in Poland, situated on the Vistula River in the Lesser Poland region. Geographic coordinates of the city centre of Cracow are 50°N and 19°E. The topography of city is varied, due to the geological structure. The historical city centre is located in the Vistula river valley and on Wawel hill. Other parts of Cracow are placed on higher areas The city is surrounded from the north, south and west by the hills, and the differences between Vistula river bottom and the highest points reach about 200 m. The lowest point of the city has the height of 187 m a.s.l. and the highest 368 m a.s.l. (German, 2007).

The measurement points were located at fixed locations throughout the cities. These points were selected in order to obtain the data for different land use categories (Fig. 2. and 3., Table 3. and 4.).

Table 3. Description of the measurement sites in Wroclaw

No.	Station's Description in Wroclaw
1	6-storey residential blocks
2	10-storey residential blocks
3	parking near a market 4-storey residential blocks and villas
4	agricultural area near airport
5	10-storey residential blocks near park
6	parking near a market, 4-storey residential blocks
7	near Odra riverbank
8	parking near a market, industrial area
9	old town

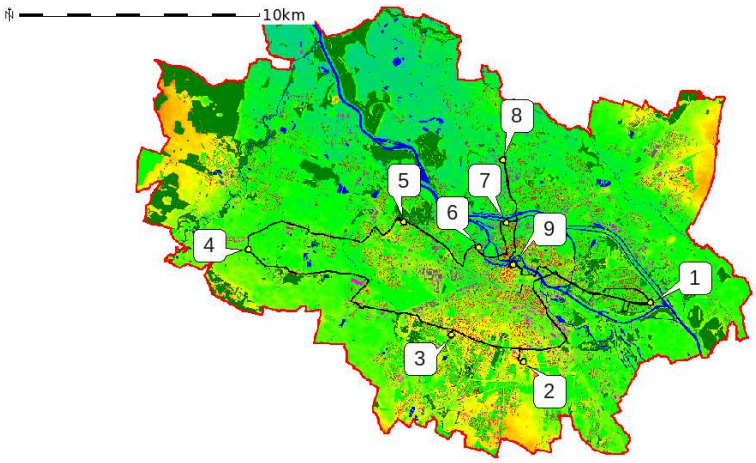

Figure 2. Localisation of measurement points in Wroclaw

Table 4. Description of the measurement sites in Cracow

No.	Station's Description in Cracow
1	6-storey residential blocks
2	agricultural area in the hills
3	city centre near Main Railway Station
4	station near Vistula riverbank
5	residential villas
6	villas and agriculture area (meadows)
7	park (forestry) in the hills
8	industrial area

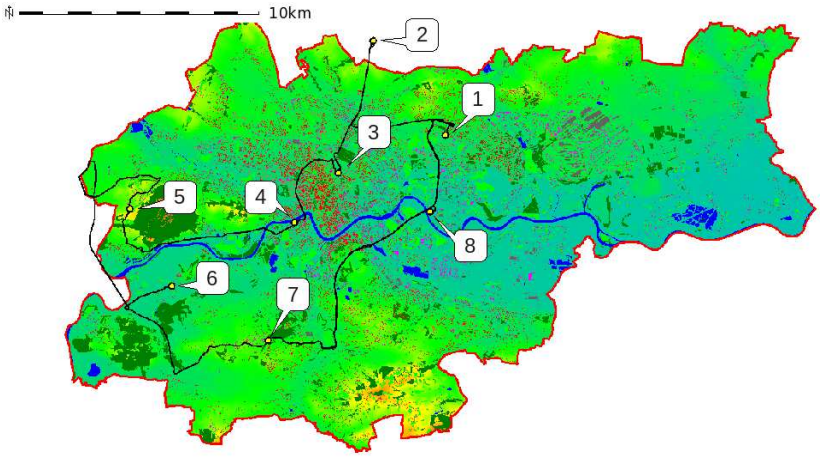

Figure 3. Localisation of measurements points in Cracow

Data

Mobile measurements of stable layer height were conducted involving SODAR system and standard meteorological measurement. The information on air temperature, relative humidity, and backscatter intensity form SODAR was collected during field experiment Some basic information about the weather conditions are presented in Table 5. Data gathered during selected days (Table 5.) were chosen for the further analysis.

The measurements were carried out during weather characterized by low wind and low cloud cover. The inversion depth from SODAR data was recognized as MH for the purposes of this study, according to the researches performed by Godłowska and Tomaszewska (2005).

In numerical simulation on urban areas, the two main aerodynamic parameters (roughness length z_0 and zero place displacement z_d) are important to properly estimation the impacts of urban areas on weather and climate, especialy in parameterisation of stable MH. The determination of z_0 and z_d was calculated from land cover and buildings geometry based on the method proposed by Gal, Sümeghy and Unger (Gal and Sümeghy, 2007, Gal and Unger, 2009) and implemented in GRASS environment (Netzel, 2011, Netzel and Ślopek, 2011).

Table 5. Dates and characteristic of measurements selected for analyses

Date	*City*	*Inversion height from SODAR [m a.g.l.]*			*Weather conditions*				
		Avg	Min	Max	T [ºC]	P [hPa]	V [m·s^{-1}]	DIR	N [0-8]
12.12.2008	Wroclaw	213.11	176.00	246.00	0.1	1020	1.5	NW	2
13.12.2008	Cracow	142.25	100.00	238.00	1.5	1014	3.6	NW	0
7.02.2009	Wroclaw	167.20	120.00	200.00	7.2	988	3.1	SE	7
3.04.2009	Wroclaw	166.50	104.00	214.00	9.0	1018	1.0	WNW	3
12.05.2009	Wroclaw	170.00	124.00	190.00	8.2	1023	0.5	NNW	0
13.04.2009	Cracow	99.50	30.00	150.00	6.0	1011	3.1	WNW	0

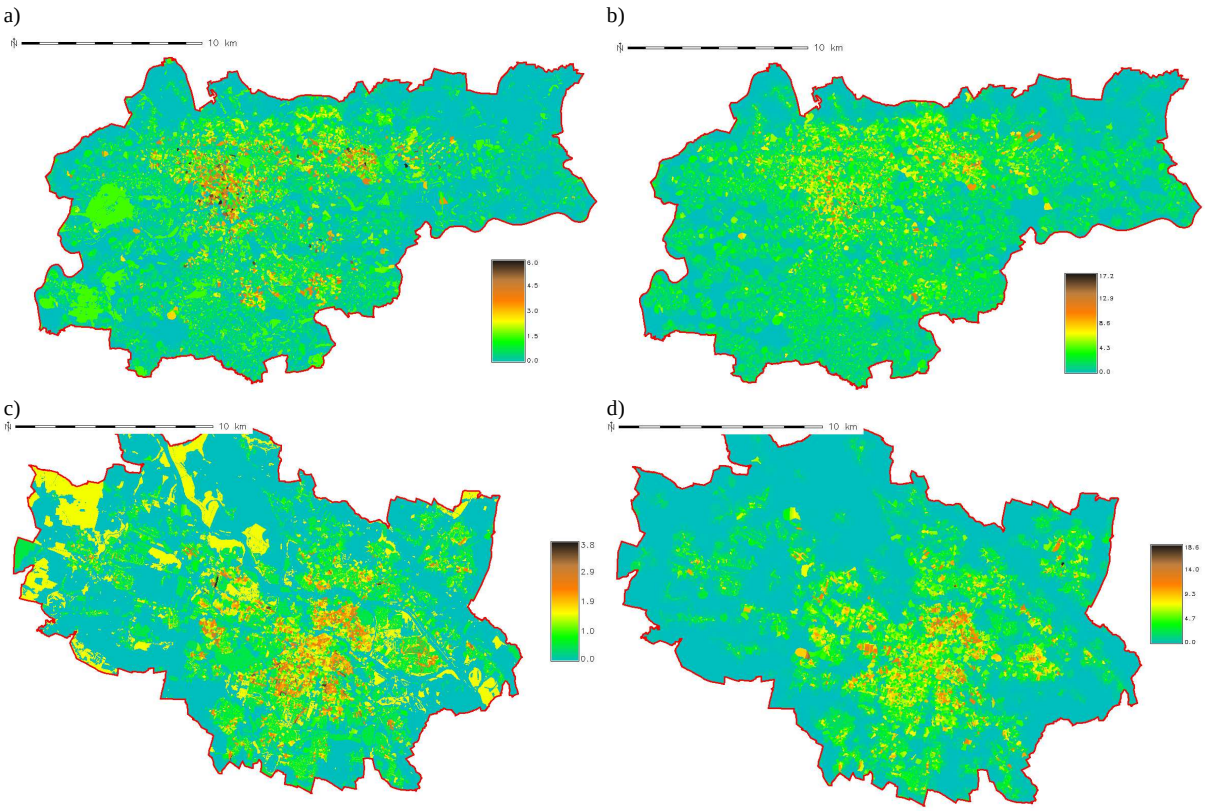

Figure 4. Spatial distribution of roughness length z_0 (a, c) and zero plane displacement z_d (b, d) calculated for Crakow (a, b) and Wroclaw (c, d).

Roughness length (z_0) in Wroclaw doesn't exceed value of 3.83 m. The areas in which z_0 is close to the value of 1.0 m are dominant in this city. In Cracow roughness length takes maximum value of 5.96 m and areas with z_0 not greater of 2.0 m are dominant.

Zero plane displacement coefficient (z_d) in Wroclaw reaches the maximum value of 18.63 m, but the terrains with values up to 3.0 m are dominant within the city area. In Cracow, calculated maximum value of z_d is 17.23 m. Within the city area terrains with z_d which don't exceed values of 4.0-4.2 m are dominant.

The z_0 and z_d coefficients were used in tested equations for mixing height calculation. Moreover temperature and wind speed from NOAA gridded data using baric surfaces 850 hPa and 950 hPa were used.

Results and Discussion

The results of parameterization formulas were compared with inversion height measured during mobile SODAR sounding. Some unreliable data from SODAR measurements carried out in Wroclaw and Cracow were removed during data pre-processing. Thus, 51 of all data concerning inversion height have been used for further analysis. The results obtained from the comparison of inversion height from measurements and models are presented in Table 6.

Modelled mixing height versus mixing height measured by mobile SODAR is illustrated on Figure 5. Additionally, regression line is drawn. The colour of regression lines corresponds to the colour of the data series calculated by the models.

The correlation coefficient between calculated and measured inversion height vary form 0 up to 0.56, which is typical value (e.g. Vickers and Mahrt, 2004). Moreover, it should be emphasize the data were obtained in areas with different land-use. The best correlation was achieved for models no. 3, 6 and 7. However, within these models, the inversion height obtained from models 3 and 7 gave much higher values of the inversion height than model 6. The averaged inversion height form SODAR was 161 m a.g.l., but for mentioned models was 383 m and 659 m (respectively).

Table 6. The results of evaluation of inversion height calculated and measured by SODAR

Model no.	*Differences (model, SODAR) [m]*				*Correlation coefficient R*
	minimum	maximum	average	Standard deviation	
1	60.95	928.50	400.90	214.66	0.48524
2	−93.75	1799.78	487.24	570.69	0.53946
3	−84.16	735.74	222.15	229.37	0.55725
4	109.22	1035.98	472.35	231.07	0.48524
5	300.35	794.67	607.86	119.42	0.00724
6	−139.41	275.45	18.26	101.10	0.55624
7	4.71	1332.39	498.58	385.54	0.55907

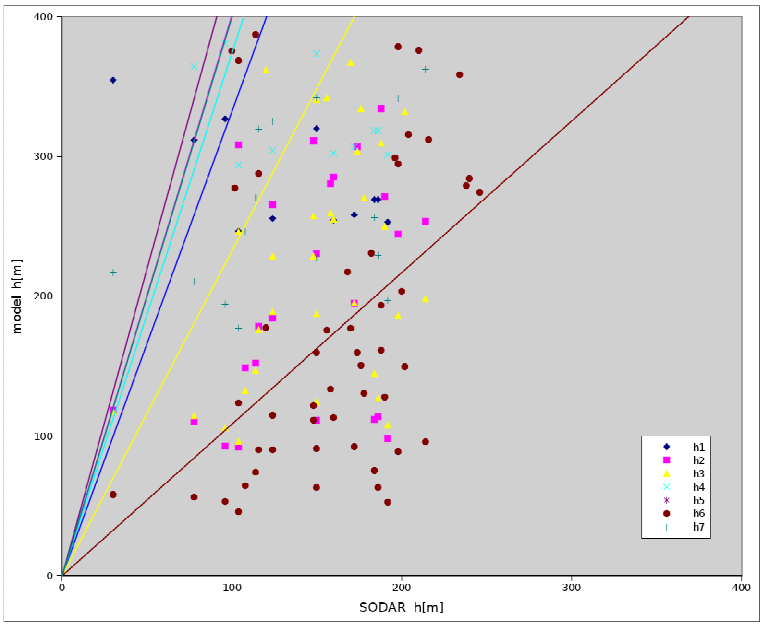

Figure 5. Modelled mixing height versus mixing height measured by mobile SODAR.

The model no. 6 showed the best compliance with measurements. The average height of mixing layer was 179 m, and the regression slope was 1.08 (for the model 3 and 7 respectively 2.33 and 3.99). The relationship of mixing layer height calculated from the formula 6 and obtained from the acoustic survey is shown in Figure 6. Additionally, the regression line in the form of y=ax, equation of the regression line and determination coefficient are placed on figure 6.

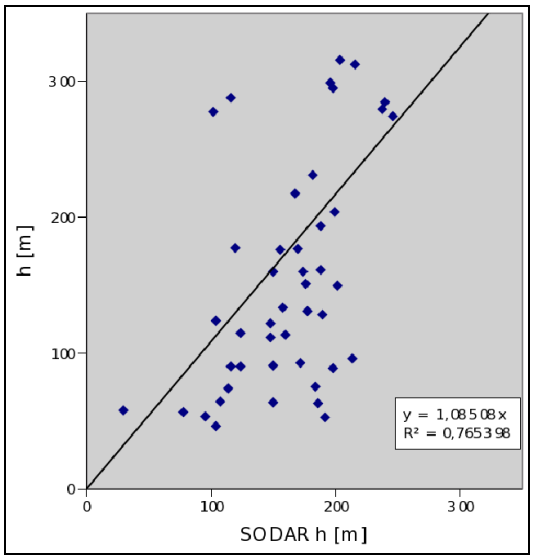

Figure 6. The relationship between stable mixing height calculated from model no. 6 and measured by SODAR.

Summary

Temperature and wind speed from NOAA gridded data and surface measurements were used for calculating the stable boundary layer height. The direct measurements involving mobile mini-SODAR were used to estimate height of stable layers in areas with different types of land-use. The well-defined cases of inversion height h are compared with 7 various formulations for the equilibrium depth of the stably stratified boundary layer.

The best compliance of mixing layer height calculated in simple diagnostic models with data from measurements was obtained for model no. 6 proposed by Zilitinkevitch and Mironov (1996). In general, other formulas performed poorly and often grossly overestimated the stable boundary layer height. The above study indicated that the inversion height was significantly different depending on the land-use cover and distance from the densely built-up areas. Therefore, using data from only a single site can provide incomplete information about inversion height above the city. Due to the fact that these are the input data in air pollution dispersion models can lead to false results.

Acknowledgements

The work was supported by the Polish Ministry of Science and Higher Education project No. N 305 099 32/3408. This paper is a revised and expanded version of a paper entitled “The Verification of SBL Models by Mobile SODAR Measurements”, presented at the 14th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Kos (Greece), October 2-6, 2011.

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