H14-202
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 (MH). Recently many different scheme was 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 asses the mixing height based on analysing 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 six different schemes. Furthermore, the relationship of mixing height form sodar measurement and models is examined. The data gathered during field experiment in Wroclaw and Krakow are employed for the evaluation of models The evaluation of models employing data gathered during field experiment in Wroclaw and Krakow.

Key words: *stable boundary layer height models, mobile measurement of SBL, sodar, Wrocław, Krakow.*

INTRODUCTION
An accurate estimation of mixing height (MH) is very important for environmental studies especially for 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 by standard meteorological observation and the assess ofthe mixinglayeroveran urbanareacreates greatproblems (Baklanov et al., 2006).

Within Research Project "The spatial variability of the Atmospheric Boundary Layer over Wroclaw and Krakow" were conducted the measurements involving monostatic Doppler minisodar. The measurement carried out during the weather characterized by low wind and low cloud cover. The data about inversion depth over city was gather during mobile measurements in points located in 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. The data gathered during mobile session were used to verify SBL height models.

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

Table 12 Models equations

Model	Equation	Reference
Model 1	(1) $h = 0.4 \cdot \sqrt{\frac{u_* \cdot L}{f}}$	Zilitinkevich S., 1972
Model 2	(2) $h = 2300.0 \cdot u_*^{1.5}$	Venkatram A., 1980
Model 3	(3) $h = u_* \cdot \sqrt{\frac{2}{f \cdot N}}$	Ventakram A., 1980
Model 4	(4) $h = 0.43 \cdot \left(\frac{u_* \cdot L}{f}\right)^{0.5} + 29.3$	Arya S. P. S., 1981
Model 5	(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
Model 6	(6) $\left(\frac{f \cdot h}{0.5 \cdot u_*}\right)^2 + \frac{h}{10 \cdot L} + \frac{N \cdot h}{20 \cdot u_*} + \frac{h \cdot \lvert f \rvert^{0.5}}{(u_* \cdot L)^{0.5}} + \frac{h \cdot \lvert N \cdot f \rvert^{0.5}}{1.7 \cdot u_*} = 1$	Zilitinkevitch S., Mironov D., 1996
Model 7	(7) $h = \frac{0.74 \cdot u_*}{\lvert f \rvert \cdot \sqrt{1 + \frac{0.4^2 \cdot u_* \cdot \left(1 + 0.25 * \frac{L \cdot N}{u_*}\right)}{0.74^2 \cdot \lvert f \rvert \cdot L}}}$	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 (Hanna and Pain, 1997). The first one was iterative method so that instability was fund during night condition. Therefore, thesecond methodwas chosenfor further calculations.
The calculations of L, u_*, $\theta_*$for stable conditions the following parameters were taken as an input: z - wind speed height, u_z- wind speed at z height, T - air temperature [2m], z_0 - roughness length, 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 (Figure 1.).

Table 13. 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 43. 1DDS SODAR antenna

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 both the strength of the returning echo, and the speed of vertical movements of air as well. 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 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 us 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 begun not earlier than two hour 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.

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 a field experiment conducted in Wrocław and Kraków were chosen for validating parametrization 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.

Krakow is the second largest and one of the oldest cities in Poland, situated on the Vistula River in the Lesser Poland region. Geographic coordinates of the city center of Krakow are 50°04'N 19°56'E . The topography of city is varied, due mainly to the geological structure. The historical city center is located in the Vistula river valley and on Wawel hill and other parts of 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 (Figure 2. and 3., Table 3. and 4.).

Table 14. Description of the measurement site 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

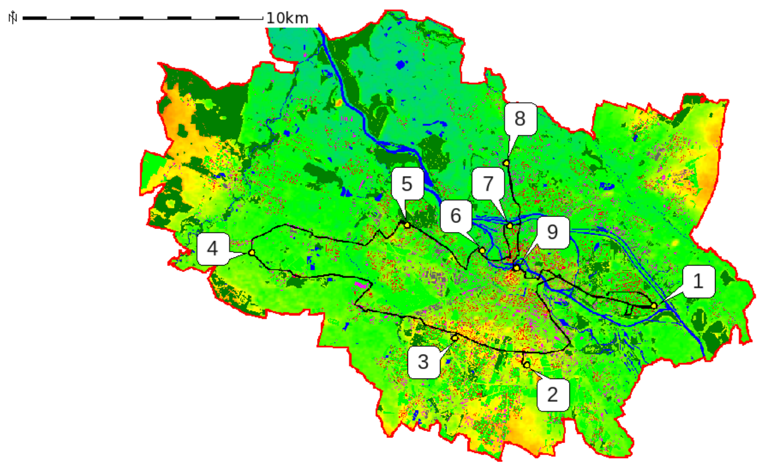

Figure 44. Localization of measurement points in Wroclaw

Table 15. Description of the measurement site in Krakow

No.	Station's Description in Krakow
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

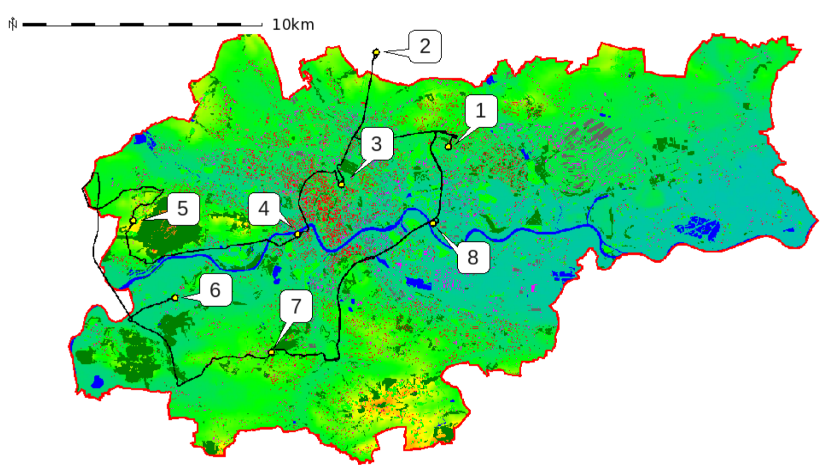

Figure 45. Localization of measurements point in Krakow

DATA

Mobile measurements of stable MH was conducted involving sodar system and standard meteorological measurement. Data about air temperature, relative humidity, and backscatter intensity form sodar were collected during field experiment. The measurements were carried out during weather characterized by low wind and low cloud cover. There are many controversies with describe MH during stable condition, but for our purposed the inversion depth from sodar data was recognized as MH (Godłowska and Tomaszewska, 2005).

Parameterization of stable MH was made using roughness length and zero place displacement, calculated form land cover and buildings geometry based on method proposed by Gal, Sümeghy and Unger (Gal and Sümeghy, 2007, Gal and Unger, 2009) and implemented in GRASS environment (Netzel, 2011).

Moreover temperature and wind speed from NOAA gridded data using baric surfaces 850 hPa and 950 hPa were used.
Data gathered during selected days (Table 3.) were chosen for the further analysis :

Table 3. Date of measurements selected for analyses

Date	**City**
12.12.2008	Wroclaw
13.12.2008	Krakow
7.02.2009	Wroclaw
3.04.2009	Wroclaw
12.05.2009	Wroclaw
13.04.2009	Krakow

RESULTS AND DISCUSSION

The results of parameterization formulas were compared with inversion height measured during mobile sodar sounding. Measurements carried out during the survey session in Wroclaw and Krakow, has produced 51 data about inversion height, which were used for further analysis. The results of the comparison are presented in table no. 4

Table 4. The relationships between inversion height calculated and measured by sodar

Model no.	Differences (model, SODAR):				Correlation coefficient R
	minimum	maximum	average	STD	
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

The correlation coefficient between calculated and measured inversion height varied form 0 up to 0.56, it is typical value (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, inversion height obtained form models 3 and 7 gave much higher values. The averaged inversion height form sodar was 161 m a.g.l., but for mentioned models was 383 m and 659 m (respectively). 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 4. Additionally, the regression line in the form y=ax, equation of the regression line and determination coefficient are placed on figure 4.

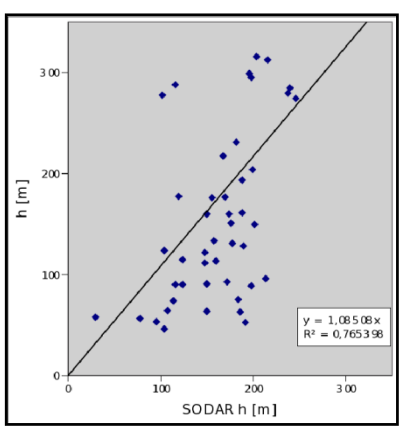

Figure 46. The relationship between stable mixing height calculated form models no. 6 and measured by sodar

SUMMARY

The stable boundary layer height was calculated using NOAA gridded data and surface measurement of temperature and wind speed. The direct measurement involving mobile mini-SODAR were used to estimate height of layers in areas with different types of land-use. The cases with well-defined stable boundary layer depth were used for detail analyses.

According to the verification of simple diagnostic models carried out with direct measurements of mixing height during stable condition, the best compliance is obtained for the model no. 6, proposed by Zilitinkevitch and Mironov (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.

REFERENCES

Arya, S.P.S., 1981: Parameterizing the height of the stable atmospheric boundary layer, *Journal of Applied Meteorology*, vol. **20**, 1192-1202.

Baklanov, A, S. Grimmond, A. Mahura and M. Athanassiadou, 2008: Urbanization Of Meteorological And Air Quality Models; Cost Action 728; Enhancing Mesoscale Meteorological Modelling Capabilities For Air Pollution And Dispersion Applications, 133.

Baklanov, A., S.M. Joffre, M. Piringer, M. Deserti, D.R Middleton, M. Tombrou, A. Karppinen, S. Emeis, V. Prior, M.W. Rotach, G. Bonafè, K. Baumann-Stanzer and A. Kuchin, 2006: Towards estimating the mixing height in urban areas, *Scientific Report 06-06,* Ministry of Transport and Energy, Copenhagen, 41.

Eaton, J., 2002: GNU Octave Manual, Network Theory, *ISBN 0-9541617-2-6. URL http://www.octave.org.*

Gál,T. and J. Unger, 2009: Detection of ventilation paths using high-resolution roughness parameter mapping in a large urban area,*Build. Environ.*,**44**, 198-206.

Gal, T. and Z. Sümeghy, 2007:Mapping the roughness parameters in a large urban area for urban climate applications, *Acta Climatologica et Chorologica*, Universitatis Szegediensis, **40-41**, 27-36.

German, K., 2007: Środowisko przyrodnicze Krakowa i jego wpływ na warunki klimatyczne. [in:] D. Matuszko (ed.) – Klimat Krakowa w XX wieku. *Wyd. IGiGP UJ*, Kraków, 11-19.

Godłowska, J. and A.M. Tomaszewska, 2005: Porównanie głębokości warstwy mieszania określonych na podstawie sodaru i pionowego profilu temperatury potencjalnej, *Wiadomości IMGW*, tom **XXVIII** (XLIX), 1, 63-71.

Gryning, S.-E., A.A.M. Holtslag, J.S. Irwin and B. Sivertsen, 1987: Applied Dispersion Modelling Based on Meteorological Scaling Parameters, *Atmos. Environ*., **21**, 79-89.

Hanna, R.S. and J.R. Pain, 1989: Hybrid Plume Dispersion Model (HPDM) Development and Evaluation, *Journal of Applied Meteorology*, vol. **28**, 206-224.

Kalistratova, M.A., 1997: Physical Grounds for Acoustic Remote Sensing of the Atmospheric Boundary Layer, Acoustic Remote Sensing Applications, Singal E.P. (ed.), Narosa Publishing House, 3-34.

Kaszowski, W. and M. Hajto, 2006: Metody określania głębokości warstwy mieszania – pomiary teledetekcyjne a formuły parametryzacyjne, *Wiadomości IMGW*, tom **XXIX** (L), 3-4, 53-57.

Mohan, M. and T.A. Siddiqui, 1997: Applied Modeling of Surface Fluxes under Different Stability Regimes, *Journal of Applied Meteorology*, vol. **37**, 1055-1067.

Netzel, P. (ed.), 2011: Analizy przestrzenne z wykorzystaniem GRASS, *Rozprawy Naukowe Instytutu Geografii i Rozwoju Regionalnego,* **15**, Uniwersytet Wrocławski, 35-43.

Netzel P., S. Stano and M. Zarębski, 2000: Trójmonostatyczny sodar dopplerowski 3DDS, Wiad. IMGW, T **XXIII**, 3, 131-136.

Nieuwstadt, F.T.M., 1981: The steady state height and resistance laws of the nocturnal boundary layer, theory compared with Cabauw observations. *Boundary-Layer Meteorology*,**20**, 3-17.

Pyka, J.L., 1991: Warunki termiczne warstwy granicznej we Wrocławiu w świetle pomiarów sodarowych, *Acta Univ. Wrat., Prace I.G., ser. A*, **5,** 275-287.

Smith, F.B., 1990: Atmospheric structure, Proc. Air Pollution Modelling for Environmental Impact Assessment, Trieste, Italy, International Centre for Theoretical Physics, 201–236.

Venkatram, A., 1980: Estimating the Monin-Obukhov length in the stable boundary layer for dispersion calculations, *Boundary-Layer Meteorology*, **18**, 481.

Vickers, D. and L. Mahrt, 2004: Evaluating formulations of stable boundary-layer height, *Journal of Applied Meteorology*, vol. **43**, 1736-1749.

Zilitinkevich, S., 1972: On the determination of the height of the Ekman boundary layer. *Boundary-Layer Meteorology*, **3**, 141-145.

Zilitinkevich, S. and A. Baklanov, 2002: Calculation of the height of stable boundary layers in practical applications, *Boundary-Layer Meteorology*, **105(3)**, 389-409.

Zilitinkevich, S., A. Baklanov, J. Rost, A.-S. Smedman, V. Lykosov and P. Calanca, 2002: Diagnostic and prognostic equations for the depth of the stably stratified Ekman boundary layer, *Quart. J. Roy. Meteorol. Soc.*, **128**, 25-46.

Zilitinkevich, S. and D. Mironov, 1996: A multi-limit formulation for the equilibrium depth of a stably stratified boundary layer, *Boundary-Layer Meteorology*, **81(3-4)**, 325-351.