Mobile SODAR measurements as a source of information about spatial variability of nocturnal thermal inversion height.

Paweł Netzel, Anetta Drzeniecka-Osiadacz, Jacek Ślopek
Dept. of Climatology and Atmosphere Protection
University of Wrocław
Wroclaw, Poland
{pawel.netzel, anetta.drzeniecka-osiadacz}@uni.wroc.pl

Abstract—**The paper presents results of mobile SODAR measurements of spatial variability of inversion layer height during fair weather conditions. Variability of the inversion reached over 50% compared to the reference station. There was neither decay of inversion in the centre of the city, nor a significant increase of its height.**

I. Introduction

The Atmospheric Boundary Layer (ABL) is the lowest part of the atmosphere which is directly influenced by presence of earth surface within the time scale of about one hour or less [1]. The structure of ABL has considerable influence on meteorological and environmental issues, especially on air pollution dispersion. The Urban Atmospheric Boundary Layer is a specific case of planetary boundary layer due to large horizontal inhomogeneities. UBL is a complex 3-D structure, difficult in comprehensive description and interpretation of data [2, 3]. Most of parameterizations have so far been developed for the condition of a homogeneous terrain, so their applicability for urban surface should be verified [4]. The main deficiency of routine measurements of ABL is that they are limited solely to one point and are appropriate for finding the mixing height only for the site of sounding (is not possible to determine spatial distribution for ABL parameters). The use of a mobile remote sensing system is an interesting alternative to the traditional measurements of UBL [5].

Acoustic sounding using SODAR system (SODAR – SOund Detection And Ranging) provides a unique opportunity to get the continuous and reliable information about structure of the Atmospheric Boundary Layer, and thermodynamic state of the lower part of the atmosphere [6, 7]. The SODAR monitoring enables us to estimate occurrence, duration and range of temperature inversion. This type of information is crucial for estimating the ability of the atmosphere to disperse pollution. Since the first SODAR was developed by Mc Alister [8], several investigations have pointed out the ability of SODAR to monitor atmospheric processes in air pollution research [7, 9, 10, 11].

This paper presents the result of measurements conducted within the Research Project "The spatial variability of the Atmospheric Boundary Layer over Wroclaw and Krakow". The main aim of the study is assessment of the impact of the urbanized area on the formation of nocturnal boundary layer during fair weather conditions.

II. Data and Methods

A. Measurement site

The analyzed data were gathered during a field experiment conducted in Wrocław. The city is located in the southwestern part of Poland (51°N, 17°E) in the Lower Silesian region, by the Odra river. Wrocław is generally flat, the altitude varying from 105 to 148 m asl. Such environmental conditions make this city useful for assessing the impact of the urbanized area on local climate.

The measurement points were located at fixed locations throughout the city. These points were selected in order to obtain the data for different land use categories (Fig. 1., Tab. 1).

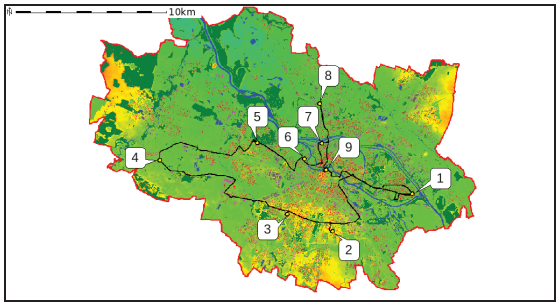

Figure 1. Localization of measurement points.

TABLE I. Description of measurement point

No.	Station's Description
1	6-storey residential blocks
2	10-storey residential blocks
3	parking near a market4-storey residential blocks and villas
4	farmland 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

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B. *Mobile SODAR measurements*

The research concerning the state of the atmospheric boundary layer involving SODARs [12, 13] have been conducted for over 25 years [14] 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.2).

Figure 2. 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.

TABLE II. 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)

Mobile SODAR 1DDS [15, 16] 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 radiation inversion. Survey sessions were begun not earlier than one 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.

C. *Processing the data from measurements*

Measurement data from nocturnal survey sessions were processed in four phases:

1. Removing the signal interferences (i.e. recorded noise of passing cars)

2. Establishing of the height of nocturnal thermal inversion near the ground

3. Adding temporal fixes

4. Recalculating to the relative scale

In order to objectify and improve analyzing of SODAR records (implementation of phase 1 and 2), the process has been automated. Removing the signal interferences and determining the height of the inversion was realized as a script in GNU Octave system [17]. This script reads SODAR registration records and removes the vertical noise patterns. The inversion height was calculated based on the returning signal strength curve.

An example of raw SODAR registration is shown in Fig. 3. The vertical axis corresponds to the height above ground level in the range 30-380 meters. The horizontal axis corresponds to individual measurements, single vertical column representing one measure. The strength of the echo is shown in shades of grey (the darker the colour - the stronger the echo).

Fig. 4 shows the echo power curve obtained from the SODAR registrations. Such graphs were generated automatically by a script for inspection purposes. The horizontal axis represents the height above the edge of the antenna, and the vertical axis represents the strength of returning signal.

It was necessary to bring the data collected during each survey session to one moment in time because the measurements were performed consecutively along the route. It was achieved by performing again of the measurement that had been done at the starting point of a given survey session., Thus, that site effectively became the last point of the survey session. The difference between inversion heights measured at the first/last point (spatially the same point) gave us the correction ratio. Next, this correction ratio was linearly distributed in time and applied to the records from the remaining measuring sites. The starting point, used as a reference point, was chosen in such a way that it was the nearest point to the Observatory where the acoustic survey with static SODAR was being carried out. In Wroclaw, that was the site “1” approximately 1500 meters away east of Observatory of the Department of Climatology and Atmospheric Protection, University of Wroclaw.

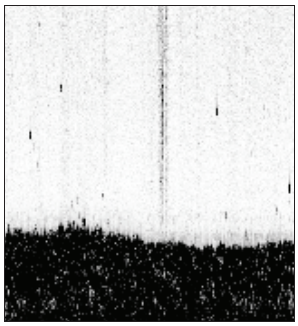

Figure 3. SODAR registration of strength of returning signal. Date: 19 August 2009, time: 21:14 – 21:24 UTC.

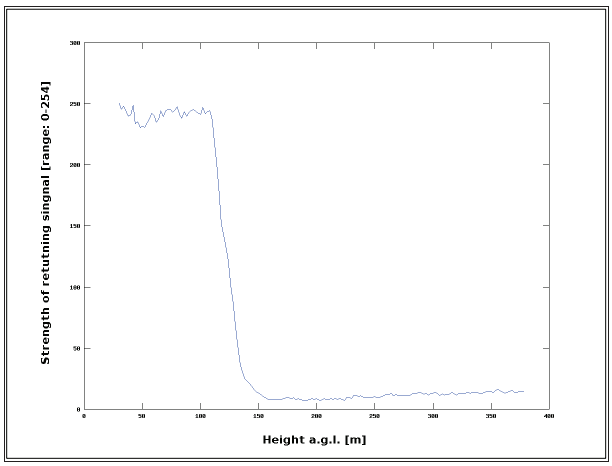

Figure 4. The curve of strength of the signal obtained by the analysis of SODAR registration. Date: 19 August 2009, time: 21:14 – 21:24 UTC. Sounding was on site no. 3.

In addition, the relative height of thermal inversion was calculated for every site along the route. This relative height (expressed as a percentage) was given in reference to inversion height at site no. 1.

III. Results

Ten measurement sessions have been made in Wroclaw. Data from each section were analyzed and placed in a spatial database. The results of the measurement sessions for the city of Wroclaw are summarized in Table 3.

For each measurement point, the average height (h), in metres, was automatically calculated and then a relative difference was determined with respect to point no. 1.

During ten mobile session, the typical situation was the presence of inversion layer at each point regardless of the land use cover and distance from the city centre. The average height of the inversion in Wroclaw during the fair weather conditions was about 150 m, height range was from about 80 m to over 200 m. However, the character and height of inversion layer differed from point to point. There was no clear relation between the land cover and height of the inversion. The maximum inversion height occurred in various parts of the city depending on wind direction.

TABLE III. The results of the measurement sessions

Date		Measurement points								
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
31.05.2008	h [m]	246	218	230	-	232	208	204	-	190
	h [%]	100	89	93	-	94	85	83	-	77
1.06.2008	h [m]	148	161	181	202	175	157	126	-	147
	h [%]	100	109	123	137	119	106	86	-	100
13.12.2008	h [m]	210	211	188	190	231	159	221	-	176
	h [%]	100	101	90	91	110	76	105	-	84
7.02.2009	h [m]	198	169	202	175	154	129	176	127	190
	h [%]	100	86	102	89	78	66	89	65	96
3.04. 2009	h [m]	148	116	122	104	150	192	214	198	178
	h [%]	100	78	82	70	101	130	145	134	120
12.05.2009	h [m]	156	188	174	186	190	184	158	124	-
	h [%]	100	121	112	119	122	118	101	79	-
19.08.2009	h [m]	114	112	137	186	168	158	160	147	167
	h [%]	100	98	121	164	148	139	140	129	147
26.09.2009	h [m]	108	112	118	86	128	111	96	72	122
	h [%]	100	104	110	80	119	104	89	67	113
31.10.2009	h [m]	94	86	88	83	144	131	117	86	103
	h [%]	100	92	94	89	154	140	125	92	110
9.03.2010	h [m]	92	82	98	74	104	111	143	148	140
	h [%]	100	90	107	81	113	122	156	162	152

Each measurement session was analyzed with respect to the synoptic situation. See figures 5a, 5b for an example of the results obtained during the measurement session on April 3, 2009. During that field experiment, the weather in Poland was influenced by a wedge of high pressure, which forced warm and dry air from SE direction (pressure: 1007.3 hPa, range of temperature from 22.2°C to 1.8°C, RH: 56%, wind speed 1.4 $m \cdot s^{-1}$ -with gusts up to 5.7 $m \cdot s^{-1}$).

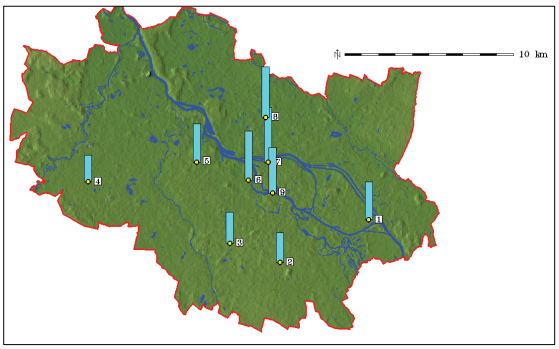

Figure 5a. Height (in meters) of nocturnal thermal inversion near the ground measured at the SODAR survey sites. Date: 3 April 2009.

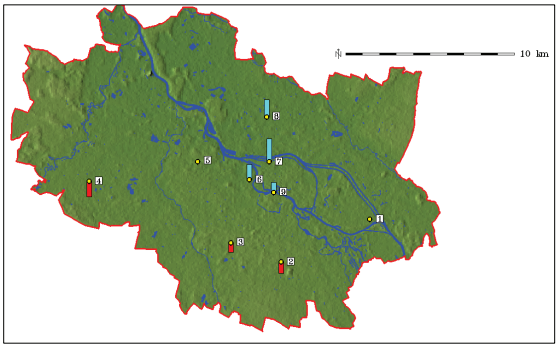

Figure 5b. Differences (in percentages) between height of nocturnal thermal inversion near the ground to the height in measurement site no 1. Date: 3 April 2009.

During this session the range of inversion height was from about 100 m (site no. 4) to above 200 m agl (site no. 7). The greatest height of ground-based inversion was recorded at the city centre, and slightly north of the centre.

The calm weather with well-developed inversion favoured the occurrence of high concentrations of pollutants (PM_{10}, NO_x). Daily average concentration of PM_{10} was 65.2 $\mu g \cdot m^{-3}$ - 3.Apr.2009 and 84.1 $\mu g \cdot m^{-3}$ - 4.Apr.2009, highest concentrations were registered during night (Fig. 6).

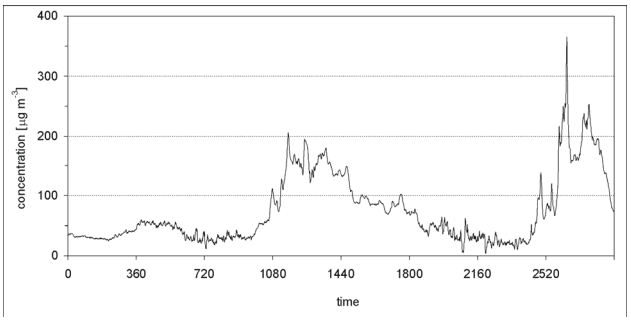

Figure 6. The course of PM_{10} (as 1-minute average), measurement site no. 1. Date: 3-4 April 2009.

Measurements of air pollutant concentrations (data gathered by Environmental Inspection), carried out at three measuring points in Wroclaw indicate differences arising not only from the emission rate but from mixing layer height's spatial variability (Fig. 5c)

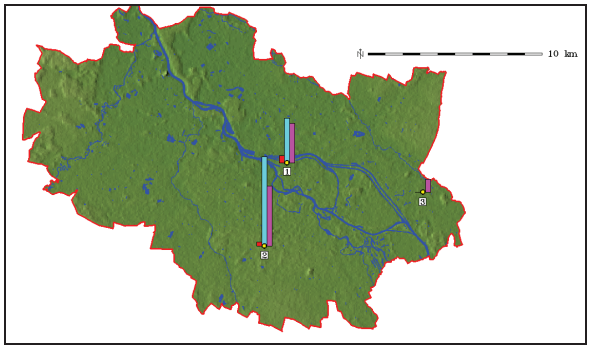

Figure 7. Differences between air pollution concentration (SO_2 –red, NO – cyan, NO_2 - magenta). Date: 3 April 2009.

IV. Summary

The mobile acoustic survey in Wroclaw has demonstrated strong spatial heterogeneity of nocturnal thermal inversion near the ground. Spatial distribution of nocturnal thermal inversion can be explained by such phenomena as the formation of urban heat island and deformations resulting from air flow. The area of maximum height of the inversion moves in the direction of advection. Such situation is crucial in determining the conditions of pollutant dispersion, particularly for high emission sources (e.g., chimneys) situated within the inversion layer.

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