Temperature and Relative Humidity Vertical Profiles within Planetary Boundary Layer in Winter Urban Airshed

Jan Bendl ¹, Jan Hovorka ¹

¹ Air Quality Laboratory, Institute for Environmental Studies, Faculty of Science, Charles University, Benatska 2, 128 01, Prague 2, Czech Republic
bendlhonza@gmail.com

Abstract. The planetary boundary layer is a dynamic system with turbulent flow where horizontal and vertical air mixing depends mainly on the weather conditions and geomorphology. Normally, air temperature from the Earth surface decreases with height but inversion situation may occur, mainly during winter. Pollutant dispersion is poor during inversions so air pollutant concentration can quickly rise, especially in urban closed valleys. Air pollution was evaluated by WHO as a human carcinogen (mostly by polycyclic aromatic hydrocarbons) and health effects are obvious. Knowledge about inversion layer height is important for estimation of the pollution impact and it can give us also information about the air pollution sources. Temperature and relative humidity vertical profiles complement ground measurements. Ground measurements were conducted to characterize comprehensively urban airshed in Svermov, residential district of the city of Kladno, about 30 km NW of Prague, from the 2nd Feb. to the 3rd of March 2016. The Svermov is an air pollution hot-spot for long time benzo[a]pyrene (B[a]P) limit exceedances, reaching the highest B[a]P annual concentration in Bohemia – west part of the Czech Republic. Since the Svermov sits in a shallow valley, frequent vertical temperature inversion in winter and low emission heights of pollution sources prevent pollutant dispersal off the valley. Such orography is common to numerous small settlements in the Czech Republic. Ground measurements at the sports field in the Svermov were complemented by temperature and humidity vertical profiles acquired by a Vaisala radiosonde positioned at tethered He-filled balloon. Total number of 53 series of vertical profiles up to the height of 300 m was conducted. Meteorology parameters were acquired with 4 Hz frequency. The measurements confirmed frequent early-morning and night formation of temperature inversion within boundary layer up to the height of 50 m. This rather shallow inversion had significant influence on air quality due to inversion cap over the valley. Nevertheless, formation of an inversion showed strong diurnal variability. For example, on the 18th Feb. early morning shallow inversion quickly disappeared within less than 2 hours. According to this study tethered balloon measurements has proved to be a good tool for completion comprehensive ground air quality measurements.

1. Introduction
In Central and Eastern Europe, local heating is often major source of winter urban air pollution, especially in small cities with family houses heated by solid fuel as the case study from the Czech Republic has shown [1]. Wood, black and low-quality brown coal is mainly burned in the Czechia. Despite law some people burn also waste, which is common alarming phenomenon mostly in poor districts. Other sources of air pollution are traffic, industry and in the microscale also cigarette smoke, cooking etc. Long-range transport and atmospheric processes also plays its role. In the process of
combustion polycyclic aromatic hydrocarbons (PAHs) adsorbed on aerosol particles are produced. Some PAHs are highly carcinogenic, e.g., benzo[a]pyrene (B[a]P), and with other toxic organic compounds pose the greatest risk to human health from the particulate matter (PM), which is aerosol particle size dependent [2]. Therefore, outdoor air pollution was classified by International Agency for Research on Cancer (IARC) as a carcinogenic to humans [3].

PMx and PAHs health limits are exceeded in urban areas especially in winter during inversion situations and unfavourable micro-scale geomorphology like closed valleys. The planetary boundary layer (PBL) is a dynamic system with turbulent flow where horizontal and vertical air mixing depends mainly on the weather and geomorphology. Normally, air temperature from the Earth surface decreases with height but inversion situation may occur, mainly during winter. During inversion and smog, the valleys are filled with fumes from all the low emission height sources and PM concentration are rising. Inversion layer height and time of its occurrence are the key factors, which affect air quality inside the valley. Pollutant dispersion is much higher above the inversion layer. By the inversion layer height observation, we can estimate the area for which ground air pollution monitoring inside the valley is relevant. Moreover, inversion layer over the valley minimizes long-range transport influence so we can neglect it in source apportionment studies.

Tethered balloon measurements can answer mainly these questions: What is the inversion layer height? How often these situations occur? What is the dynamics of inversion layer formation? For which area are ground air quality measurements relevant?

2. Material and methods

Comprehensive characterization of urban aerosol was conducted in residential district of the city of Kladno Svermov, about 30 km NW of Prague, from the 2nd February to the 3rd of March 2016. The Svermov is an air pollution hot-spot for long time benzo[a]pyrene limit exceedances, reaching the highest B[a]P annual concentration in Bohemia – west part of the Czech Republic. Svermov is the residential district of Kladno city and is situated in a shallow valley. The volume of the valley was estimated according to the contours of the map and approx. height of 50 m to 120 900 000 m³.

Five minute integrates of aerosol number size distributions in the range of 14 nm – 10 000 nm (by TSI SMPS, APS), CO, NOx, SO2, O3, CH4, NMHC (by HORIBA), meteorology parameters: ambient temperature (T), relative humidity (RH), atmospheric pressure, global radiation (GR), precipitation were measured at the isothermic station placed at the sports field in Svermov (GPS: 50°10'0.421" N, 14°6'41.965"E).

Simultaneously, measurements with tethered balloon were conducted in the immediate vicinity to the station. Total number of 53 series of vertical profiles for temperature (T), relative humidity (RH), pressure up to the height of 300 m within the atmospheric boundary layer was conducted by tethered, helium-filled balloon with a volume of 2.3 m³. Balloon can carry two instruments and point-of-view camera. Meteorology parameters (temperature, relative humidity, atmospheric pressure) were acquired with 4 Hz frequency by Vaisala radiosonde. Heights were calculated from the atmospheric pressure data according to Wallace and Hobbs [4] by the equation:

\[ h = \frac{R}{g} \left( \frac{p_0}{p} \right) \ln \left( \frac{p_0}{p} \right) \]  

where \( R \) is the general gas constant, \( g \) is the acceleration of gravity, \( p_0 \) is the atmospheric pressure on the ground and \( p \) atmospheric pressure at the height \( h \), \( T \) is the average temperature in the layer \( p_0-p \).

Balloon take-off is practically possible only when the wind speed <1.5 m s⁻¹. Higher wind speeds prevent reaching the maximum height of 300 m. Whereas strong wind indicates well-mixed boundary layer, it is not a disadvantage in the view of inversion layer observation. Unrolling of Dyneema rope was fast for capturing the whole vertical profile at the short time and only way up was plotted to graphs, similarly to practice with weather balloons.
3. Results and discussions
Total number of 53 vertical profiles by tethered balloon were made. Figure 3 left (7. 2. 2016) shows the normal situation where air temperature from the Earth surface decreases with height with small
fluctuation near ground till 15 m. In average temperature decreased by 0.9 °C per 100 m height while relative humidity raised from 67 to 76 % (3.2 % per 100 m in average) during this profile. On February 7 was calm SW wind with median 0.6 ms⁻¹, temperature median was -0.4 °C, relative humidity median 92 %, global radiation 7 Wm⁻² and PM₁₀ daily median was 48 µgm⁻³.

**Figure 3.** Temperature (T/°C) and relative humidity (RH/%) versus height (m), 7. 2. 2016 (left), 25. 2. 2016, 13:50-13:55 (right), Kladno-Svermov

During 25th January, there were similar meteorology conditions: WS median 0.5 ms⁻¹, the same SW direction, T median -4.2°C, RH median 80 %, GR median 8 Wm⁻² but PBL up to 300 m was less stable which is evident from the figure 3 right. PM₁₀ median was 25 µgm⁻³ which is almost twice a lower concentration. Ground concentration of measured gases were SO₂ 1.7 ppb, O₃ 34.6 ppb, NO₂ 4.5 ppb, NO 0.02 ppb, CH₄ 1.7 ppm.

Stronger N wind at the height of 200 – 270 m was indicated by the balloon wobbling, which was visible from the ground.

The different situation is on figure 4, which represents dynamic change during 18th January.

Left graph shows morning temperature inversion up to 30 m, the layer between 30 and 50 m is almost isothermal and second inversion follows up to 80 m. The third inversion from the ground is from 95 to 120 m height. Balloon was launched from 7:56 to 8:04 up to only 140 m due to stronger wind at this altitude. Two more vertical profiles were made before: at 7:32 and 7:46 and data looked almost the same as profile at 7:56 (figure 4 left).

Vertical profile 2 hours later (10:13-10:21) is on the right of figure 4, where the inversion is just disappearing. Ground temperature inversion lasts till 20 m height. This inversion disappeared completely 20 minutes later (10:34, not shown) and since then we didn’t observe any inversion up to 300 m till 16:11, when we conducted the last flight.

During this day (January 18) medians of meteorological parameters at 4 m height were: WS 0.4 ms⁻¹ (S wind prevailed), T -3.9 °C, RH 92 %, GR 7 Wm⁻².

Comparison between these two vertical profiles (figure 4) is shown in the table 1. PM₁₀ concentration is decreasing as the temperature inversion is disappearing.
Figure 4. Temperature (T/°C) and relative humidity (RH/%) versus height (m), 18. 2. 2016, 7:56-8:04 (left), 10:13-10:21 (right), Kladno-Svermov

Table 1. Comparison of meteorological parameters measured by the ground station between two vertical profiles, Kladno-Svermov.

| Wind            | Wind            |
|-----------------|-----------------|
| 18th January 2016, 7:56-8:04 | 18th January 2016, 10:13-10:21 |
| 0.3 ms\(^{-1}\) | 0.7 ms\(^{-1}\) |
| Temperature    | Temperature    |
| -6.2 °C        | 1.4 °C         |
| Relative Humidity | Relative Humidity |
| 94 %           | 77 %           |
| Global Radiation | Global Radiation |
| 29 Wm\(^{-2}\) | 224 Wm\(^{-2}\) |
| PM\(_{10}\)     | PM\(_{10}\)     |
| 21 µgm\(^{-3}\) | 13 µgm\(^{-3}\) |
| Gaseous concentration | Gaseous concentration |
| SO\(_{2}\) 1.22 ppb, O\(_{3}\) 4.34 ppb, NO\(_{2}\) 17.8 ppb, CH\(_{4}\) 1.9 ppm | SO\(_{2}\) 3.52 ppb, O\(_{3}\) 14.7 ppb, NO\(_{2}\) 4.3 ppb, NO 3 ppb, CH\(_{4}\) 1.8 ppm |

Evening inversion on 12th January from 22:25 to 22:30 is at figure 5. PM\(_{10}\) concentration was 51 µgm\(^{-3}\) (over the health limit), T -5.4 °C, 0.9 ms\(^{-1}\) strong wind with SW direction, relative humidity 92 % and global radiation 7 Wm\(^{-2}\). Gaseous concentration during the profile were: SO\(_{2}\) 0.3 ppb, O\(_{3}\) 6.8 ppb, NO\(_{2}\) 10.7 ppb, NO 1.14 ppb and CH\(_{4}\) 2.8 ppm.

Temperature inversion layer occurs till approx. 60 m height which means people living under the edge of the valley are under the inversion cap and PM\(_{10}\) concentration measured by the station is relevant for them. Unfortunately, most of observed inversions were up to around 50 m height from the bottom of the valley.
Figure 5. Temperature (T/°C) and relative humidity (RH/%) versus height (m), 12. 2. 2016, 22:25-22:30, Kladno-Svermov

4. Conclusions
Tethered balloon T&RH measurements up to 300 m confirmed frequent formation of temperature inversions within planetary boundary layer in the locality of Svermov residential district. Inversions usually reached a height of 50 m from the bottom of the closed valley and we observed them mainly during mornings and nights. Daytime vertical profiles shown fast dynamic changes. Because the valley is just around 50 m deep, the lid over pot effect can occur, which means worse air pollutant dispersion. This can lead to smog and PM health limit exceedance. Within the microscale, temperature inversion can strongly influence local air quality. According to this study tethered balloon measurements has proved to be a good low-cost tool for completion comprehensive ground air quality measurements. Limitations are spacy balloon launch area and max 1.5 ms⁻¹ wind speed for balloon launch, however we can estimate well-mixed air in these situations.

Acknowledgment(s)
This work was supported by the project CENATOX under grant GAČR P503/12/G147.

References
[1] J. Hovorka, P. Pokorna, P. K. Hopke, K. Krumal, P. Mikuska and M. Pisova, “Wood combustion, a dominant source of winter aerosol in residential district in proximity to a large automobile factory in Central Europe,” Atmospheric Environment, vol. 113: pp. 98-107, 2015.
[2] J. Topinka, P. Rossner, A. Milcova, J. Schmuczerova, K. Pencikova, A. Rossnerova, A. Ambroz, J. Stolcpartova, J. Bendl, J. Hovorka, M. Machala, “Day-to-day variability of toxic events induced by organic compounds bound to size segregated atmospheric aerosol,” Environmental Pollution, vol. 202, pp. 135-145, 2015.
[3] IARC: Outdoor air pollution a leading environmental cause of cancer deaths, Press release
[4] J. M. Wallace, P. V. Hobbs, “Atmospheric Science, an Introductory Survey.” Academic, 1977.