# BLACK CARBON AIR POLLUTION – CASE STUDY OF LOŠKI POTOK

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**Abstract**
The paper presents a study of air pollution caused by black carbon (BC) and fine particulate matter (PM) carried out in the rural area of the municipality of Loški Potok in the winter season of 2017/2018. Measurements of pollutants were performed at two different locations, one at Retje, a village at the bottom of a karst depression, and the other on the top of the Tabor hill in settlement Hrib. The measurement results exposed the main sources of black carbon air pollution in this area: domestic heating with biomass (almost 80% of all black carbon emissions) and unfavorable meteorological conditions for dilution of pollutants during temperature inversions. Three times higher concentrations were measured at Retje during temperature inversions than in the days of mixed atmosphere. In the winter of 2017/18, the average concentrations in the Retje hollow were even higher than those of Ljubljana, which calls attention to the problem of polluted air in rural areas too.

**Key words:** local air pollution, carbonaceous particles, rural areas, hilly/mountainous relief, biomass combustion

## 1 INTRODUCTION

Particulate matter (PM) air pollution is related to the greatest health hazard for people, and black carbon (BC) is the most pronounced of the various types of particles (Health effects of ..., 2012; Health effects of ..., 2013). The most frequent of the recognized health effects are premature death, aggravated respiratory and cardiovascular diseases, functional changes in autonomic nervous system, changed blood pressure and pulmonary diseases (Bond et al., 2013; Health effects of …, 2013; Kranjec et al., 2016). Airborne particles have a significant impact on the climate too, as they affect the optical properties of the atmosphere and thus change the radiation balance of the Earth. Black carbon intensely absorbs solar radiation and is, next to carbon dioxide, the second most important cause of climate change (Bond et al., 2013; IPCC, 2013).

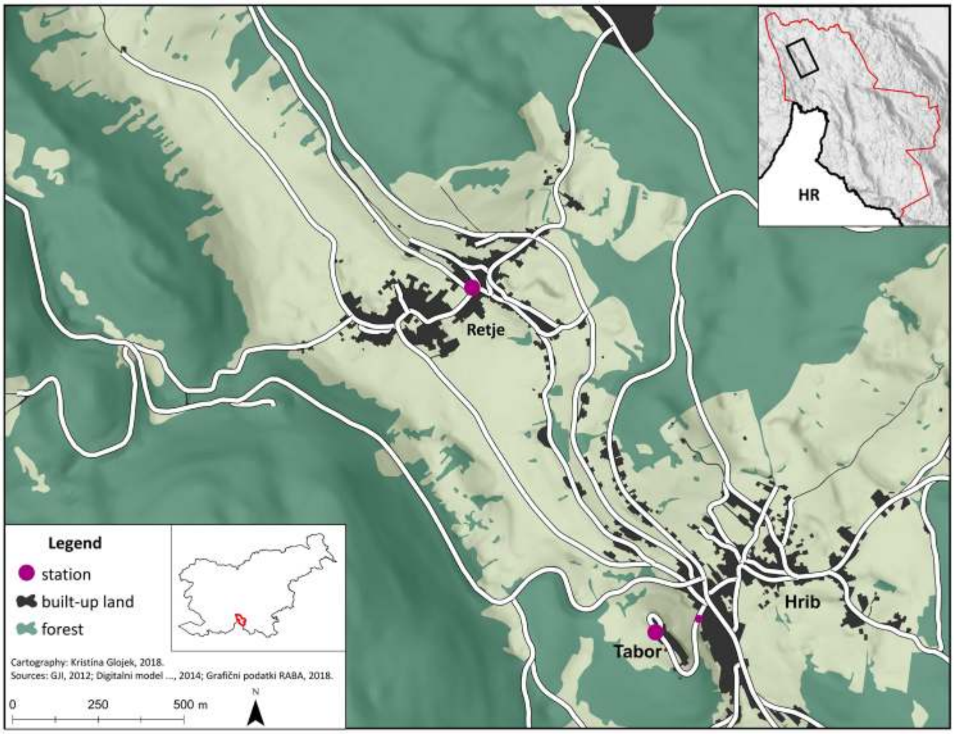
As to the area of impact and the level of observation, there is global, regional and local air pollution. Regional and local air pollution is strongly influenced by surface features and land use. The influence of surface is particularly pronounced in the areas with complex terrain, where the situation in the atmosphere and consequently the air pollution changes at very short distances. Most of Slovenian settlements are located in basins, valleys and karst depressions where specific meteorological situations often develop giving rise to spatial and temporal patterns of air pollution which differ from those in the broader area and in the planes (Rakovec, Žabkar, 2012; Petkovšek, 1979). In the cold half of the year in particular ground temperature inversions frequently and distinctly occur in depressed landforms (Ogrin, 2003), and give rise to a very stable air layer over the ground which heavily hinders or even blocks ventilation and vertical exchange of air with the upper layers of atmosphere.

Unfavorable meteorological conditions for dilution and high emissions are also the source of excessive air pollution in Slovenia. According to diverse, complex terrain the official network of the Environmental Agency of the Repulic of Slovenia for air quality monitoring is rather scarce and covers mainly urban areas. On the other hand, we practically lack data on air pollution in rural areas which cover most of the territory of Slovenia (Prostorske tipologije ..., 2017) and where, according to the most recent data, approx. 50% of the total Slovenian population live (Prebivalstvo po ..., 2018). Studies on particulate matter air pollution from Slovenia (e.g. Ogrin et al., 2014; Ogrin et al., 2016; Ježek, 2015; Močnik, 2009; Šegula et al., 2010; Koleša, Šegula, Komar, 2012; Koleša, Šegula, Muri, 2011; Šegula et al., 2011; Drinovec, Ježek, Močnik, 2012; Jereb et al., 2018) have mainly dealt with the atmospheric issues in urban areas. Investigations hitherto have also been focused on transport pollution (e.g. Bolte, 2005, Cerkvenik, 2012, Projekt SILAQ ..., 2003), while the impact of biomass combustion has been neglected. But measurements and studies made so far show that biomass combustion is the major source of particulate matter concentration in the air in Slovenia (see the references above). Foreign researches in rural and urban areas (e.g. Puxbaum et al., 2006; Glasius et al., 2008; Caseiro et al., 2009; Wåhlin et al., 2010; Klenø Nøjgaard et al., 2012; Fuller et al., 2013, Herich et al., 2014; Denier van der Gon et al., 2015) have exposed the fact that even minor percentage of biomass-heated households significantly add to deterioration of air quality in a certain area. Because most of individual houses in Slovenia are heated with biomass, high concentrations of pollutants can also be expected in rural areas in the cold half of the year, in the populated relief depressions in particular. The current paper is meant to present air pollution from black carbon (BC) and fine particulate matter (PM) in the rural area of the karst hollow Retje in the municipality of Loški Potok. For this purpose, we carried out measurements with Aethalometer and Mobility Particle Size Spectrometer (MPSS) in 2017/18.

## 2 THE STUDIED AREA

The area selected for the study was the Retje hollow in the municipality of Loški Potok. This municipality lies in the southernmost part of Slovenia, at the border between Notranjska, Dolenjska and the Croatian Gorski Kotar.

*Figure 1: The studied area with two marked air-quality-measurement stations and a meteorological station of the Društvo za raziskovanje vremena in podnebja (Weather and Climate Research Society).*




It is a karst area with numerous depressions. The elevations range from 403 m to 1,254 m, with the average of 884 m. Owing to the rather high elevations, the average annual temperatures in a greater part of the municipality range from 6 °C to 8 °C. Throughout the year, the lowest temperatures can drop to or below the freezing point (Povprečne homogenizirane ..., 2018). Low temperatures in the area are due not only to the rather high elevation but mainly to favourable conditions for air cooling in karst depressions (the occurrence of temperature inversion), particularly in winter in calm and clear nights. Due to the position and similar elevation of karst fields (poljes) and depressions in the area, minimum temperatures are comparable to the officially measured minimum temperatures at Babno Polje in the neighbouring municipality, where the officially lowest air temperature in Slovenia (-34.5 °C) was recorded (Slovenski vremenski ..., 2018). The Retje hollow is slightly less than 3 km long, about 250 m wide in its narrowest section, and about 500 m in the central, i.e. the widest part. The elevation difference between its bottom and rim amounts to 100–200 m.

*Figure 2: View of Retje village with the church of St. Leonard on Tabor hill in the background in the morning (left) and at noon (right) (photo: K. Glojek).*

Forestry and wood industry represent an important economy branch in the area, and wood is the main source of energy for household heating (Predstavitev občine ... 2018; Glojek, 2018).

With 13.7 inhabitants/km$^2$ (Gostota naseljenosti ..., 2018), the municipality of Loški Potok belongs to the least populated municipalities in Slovenia. The two biggest settlements in the municipality are situated in the Retje hollow; the village of Retje with 380 inhabitants at the bottom of the hollow and part of the settlement Hrib with 379 inhabitants on the northeastern slopes of the hollow (Prebivalstvo po ..., 2018). There are no major industrial plants in the broader area, so industrial pollution of the atmosphere is not problematic. Transport volume is small or very small, except for the Sodražica-Hrib section with the average annual daily traffic of 1,330 vehicles; on the remaining sections the average of less than 100 vehicles per day is recorded (Povprečni letni ..., 2016).

## 3 MEASUREMENT METHODS AND METEOROLOGICAL DATA

Two measuring points were set up in the studied area, one at the bottom of the hollow in the village of Retje (715 m), the other at the top of Tabor hill (815 m) which separates the Retje hollow from the neighbouring Travnik hollow and is part of the settlement Hrib. The former measuring station was named Retje and the latter Tabor. The main features, settings and the measurement period of measuring instruments, whose data are presented in the paper, are described in Table 1.

*Table 1: Description of measuring instruments with their main features, settings and measuring periods at the measurement stations Retje and Tabor.*

| Instrument | Model | Station | Period | Measurement principle | Sensitivity and detection | Other properties | Output of the instrument |
|---|---|---|---|---|---|---|---|
| Aethalo meter | AE-33, Magee Scientific | Retje, Tabor | 24 Oct. 2017—28 May 2018 | Attenuation | Flow rate: 5 l/min<br>Time resolution: 1 min<br>Detection limit: 30 ng | Measurements at 7 wavelengths; σ: 7,7 $m^2/g$ (Drinovec et al., 2015) | Absorption coefficient, calculated BC mass concentrations ($ng/m^3$) |
| Mobility Particle Size Spectro meter | TROPOS Reference MPSS No. 1 with TSI CPC 3772 | Retje | 30 Nov. 2017—11 March 2018 | Electrical mobility | Flow rate: 1,0:5,0 l/min (CPC: electrometer)<br>Time resolution: 5 min<br>Detection limit: size range: 20—800 nm particle concentrations: less than $10^6$ #/$cm^3$ (Wiedensholer et al., 2012) | Parts of the instrument: DMA TSI 3081, buthanol CPC, bipolar charger, vacum pump<br>Source: Kr. 85 | Particle number size distribution (20–800 nm), particle number concentrations (#/$cm^3$) |
| | TSI MPSS with TSI CPC 3785 | Tabor | 30 Nov. 2017—11 March 2018 | | Flow rate: 1,0:5,0 l/min (CPC: electrometer)<br>Time resolution: 5 min<br>Detection limit: 20—600 nm particle concentrations: less than $10^6$ #/$cm^3$ (Wiedensholer et al., 2012) | DMA TSI 3081, Water CPC<br>Source: x-ray | Particle number size distribution (20–600 nm), particle number concentrations (#/$cm^3$) |
| Total Condensa-tion Partice Counter | TSI TCPC, *model 3772* | Retje | 30 Nov. 2017—23 Jan. 2018 | Condensation | Flow rate: 1 l/min<br>Time resolution: 5 min<br>Detection limit: less than $10^4$ #/$cm^3$ | Buthanol CPS<br>Source: Kr. 85 | Particle number concentrations (#/$cm^3$) |
| Meteoro logical sensor | TPR 159, AMES | Retje, Tabor | 24 Oct. 2017—28 May 2018 | Sensor | Time resolution: 1 min<br>Detection limit: ± 0,15 °C; ± 2 % RH; ± 1 mbar | Temperature sensor: Pt100<br>RH sensor: semiconductor, capacitive<br>pressure sensor: piezoelectrical | Temperature, relative air humidity (RH), air pressure |

*Legend:*
*σ - mass absorption cross-section*
*#/$cm^3$ - unit, number of particles per $cm^3$ of air*
*DMA - Differential Mobility Analyzer*
*CPC - Condensation Particle Counter*
*TCPC - Total Condensation Particle Counter*

Measurements of BC concentrations and meteorological measurements in the area of Retje and Hrib started on October 25, 2017, and measurements of number concentrations and other measurements of PM in the air on November 30, 2017. Measurements of BC (Aethalometer AE33) were carried out until May 28, 2018, and measurements of number concentrations (TROPOS MPSS with CPC 3772 and TSSI MPSS 3 with CPC 3782) until March 11, 2018.

## 3.1 Determination of black carbon sources

Measurements of attenuation with Aethalometer AE33 are done at seven wavelengths (λ) (370 nm, 470 nm, 520 nm, 590 nm, 660 nm, 880 nm and 950 nm), which allows characterization of particulate absorption within the range from ultraviolet to infrared. The spectral dependence of absorption can be generally described with the power law: $b_{ab} = 1 / \lambda^{\alpha}$, where α stays for Ångström exponent (Moosmüller et al., 2011). The latter renders it possible to distinguish between wood smoke and diesel engine exhaust.

Diesel exhaust contains a high percentage of BC and as long as it is fresh its Ångström exponent is close to 1 (even absorption of light through the entire visible wavelength spectrum) (Schnaiter et al., 2003). Smoke produced by biomass (wood) combustion besides BC also contains organics that strongly absorb in the blue and ultraviolet (UV) part of the light spectrum which increases Ångström exponent. For wood smoke or smoke resulting from biomass combustion, the Ångström exponent is expected to be higher than about 1.7 (Favez et al., 2009; Sandradewi et al., 2008a; Sandradewi et al., 2008b; Saleh et al., 2013; Zotter et al., 2017).

The Ångström exponent was calculated for the interval of wavelengths between 470 nm ($\lambda_1$) and 950 nm ($\lambda_2$), since the contrast between the particles of different sources is the largest within this range (Zotter et al., 2017). The calculation we used was based on the methodology described in Sandradewi et al. (2008a). The final contribution of biomass combustion and transport to black carbon concentrations was estimated by means of the so-called Aethalometer model (Sandradewi et al., 2008a), which presumes that the total concentration of black carbon is the result of these two sources. In correspondence to source-specific Ångström exponents provided in intense measurement campaigns in the Swiss Alpine valleys (Sandradewi et al., 2008a), in Ljubljana and in other Slovenian and Austrian cities (Ogrin et al., 2014; Drinovec et al. 2011; et al., 2012; Drinovec et al., 2013; Jereb et al., 2018), Ångström exponent 1 for traffic and 2 for biomass combustion was selected for the rural area. Distribution of values of the Ångström exponent calculated from the measurements shows that the selected pair of exponents is suitable for the studied rural area too. In any case, further results of the research will be important for the determination of the uncertainty of Ångström exponent selected values for the Slovenian rural setting.

## 3.2 Meteorological data at the time of the measurements

In addition to particle measurements, measurements of some meteorological parameters – temperature (T), air pressure (p) and relative humidity (RH) – were made at both measuring sites (Retje, Tabor). Data on temperature, wind, relative humidity and precipitation were also obtained from the meteorological station near the kindergarten in the settlement Hrib; the station, named Hrib, is owned by the Society for Weather and Climate Research.

We used meteorological data to provide a general description of meteorological conditions and asses the occurrence of temperature inversion. When the temperature at the Retje measuring station (red line in Figure 3) was lower than that at the measuring station on the Tabor hill (yellow line in Figure 3), the phenomenon was defined as temperature inversion; but when the temperature at the bottom at Retje was higher than that on Tabor hill, it was treated as a less stable atmosphere, which usually allows the mixing of pollutants. In determining the periods of temperature inversion we also used other meteorological parameters (relative air humidity, wind, and precipitation), field observation (fog, smoke rising) and additional slope measurements of temperature profile in the Retje hollow (Ogrin, 2016, 2017; mobile measurements).

*Table 2: Periods of stable atmosphere – temperature inversion and mixed atmosphere in the winter of 2017/18.*

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| December | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | |
| January | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | |
| February | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | | | | | |

*Legend:*

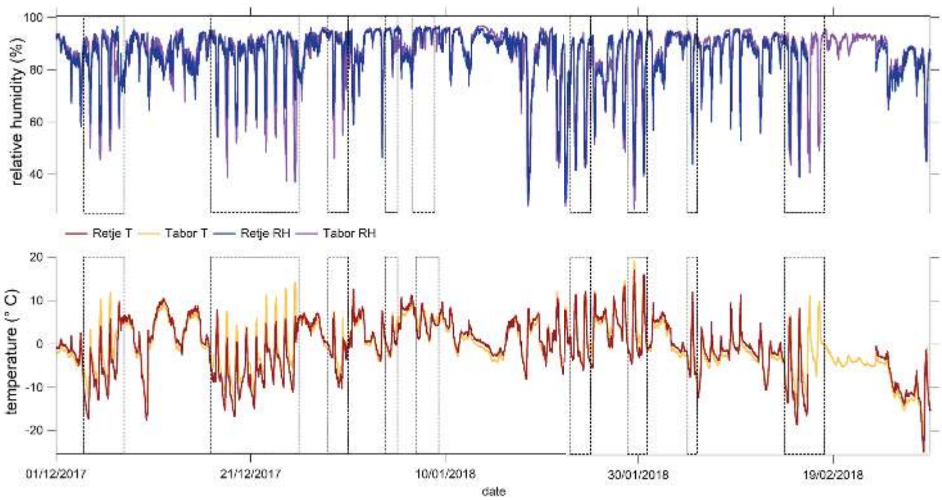
*day with temperature inversion*

*day with mixed atmosphere*

Table 2 lists individual days of stable and mixed atmosphere in the winter, also marked with a dotted line in Figure 3. Classified as days with temperature inversion were the days when temperature inversion occurred both in the morning and in the evening, and classified as periods of mixed atmosphere were the days without temperature inversion occurrence, when the air was intensely mixed throughout the day (temperature decreases with increasing height).

The wintertime was characterized by variable weather with only a few longer periods of stable weather between December and March. Air temperature during the winter measurements ranged between –24.7 °C (Retje, 28 Februar 2018) and about 14 °C (29 January 2018). The average temperature at the measuring station near the kindergarten at Hrib (775 m) was 0.5 °C, at Retje (715 m) –0.7 °C and on Tabor (815 m) –0.3 °C. There are conspicuous differences in temperatures between the measuring sites on the top of Tabor and at Retje close to the bottom of the hollow, especially the differences in minimum temperatures during the occurrence of temperature inversion.

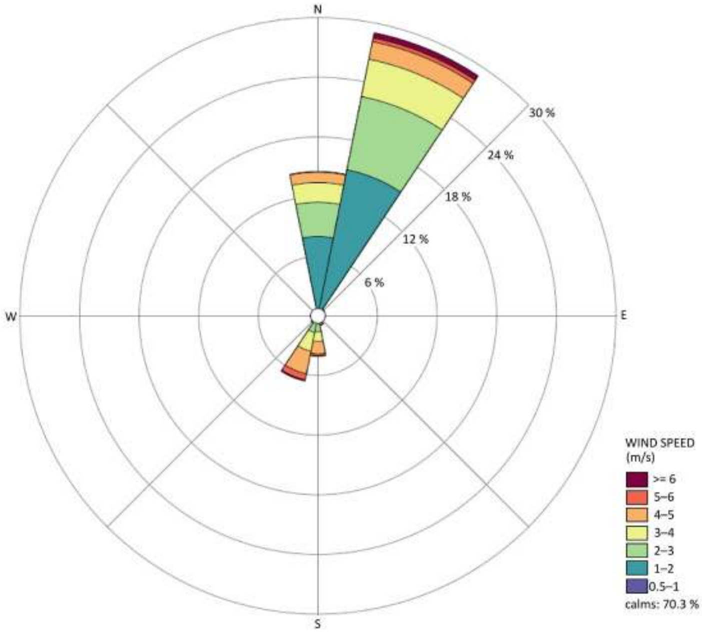
*Figure 3: Air temperature (T) (°C) and relative humidity (RH) (%) at the station at Retje (715 m) and on Tabor (815 m) during winter measurements (from 1 December 2017 to 1 March 2018). The dotted line indicates selected days with temperature inversion.*




Most of temperature inversions occurred in December when they were also the most pronounced (the highest temperature gradients). They were the least numerous and the least intense (the lowest temperature gradients) in January, which was also by far the warmest month in the winter of 2017/18 (on average at Hrib +2,7 °C, at Retje +2,2 °C and on Tabor +2.1 °C.). The deviation from the long-term average of the 1981–2010 period at Babno Polje and at Nova vas on the Bloke plateau, which are the two official meteorological stations most closely comparable to the studied area, was 4.7 °C and 4.8 °C (Data archive ..., 2018, Povprečne homogenizirane ..., 2018). February was the coldest winter month (on average at Hrib –3.6 °C, Retje –2.9 °C and Tabor also –2.9 °C) and the coldest were its last days; due to frequent precipitation the conditions were not favourable for the development of temperature inversion. In the course of the three months the amount of precipitation exceeded the long-term average of the above-stated period (Povprečne homogenizirane ..., 2018). Snow covered the ground most of December and February, while it melted in January due to the warming.

Despite the relatively dynamic weather in the 2017/18 winter period, the average wind speed at the location of Hrib was only 0.97 m/s. We expect, that due to topography preventing effective ventilation wind speeds were even lower in the very basin, but we lack wind data from the bottom. Windless periods were the most frequent (70% of the measurement period), while the remainder of 30% was windy, with wind speeds between 0.5 m/s and 6 m/s. Prevailing were the winds from the northern quadrant (north-northeast wind, north wind) which occur during anticyclone-type of weather and during the passing of a cold front. Prior to the passing of the cold front, south and southwest winds blow in the area, often reaching the highest speeds between 4 m/s and 5 m/s. From 11 to 14 December, a strong south-west wind was blowing that caused windthrows.

*Figure 4: Wind speed frequency distribution (%) as to directions in the winter measurement period (from 1 December 2017 to 1 March 2018) at the Hrib weather station.*




*Data source: Data archive Društvo ..., 2017, 2018.*

# 4 CONCENTRATIONS AND SOURCES OF BLACK CARBON AND FINE PARTICULATE MATTER, WITH DISCUSSION

Concentrations at Tabor were generally much lower than concentrations at Retje and ranged from a few hundred ng/m$^3$ to about 20 µg/m$^3$ of BC, and from a few thousand to 20,000–30,000 #/cm$^3$ of fine PM during the periods of greater emissions or during the periods of rather stable weather conditions.

In Retje, the village in the karst depression, much higer concentrations of BC and fine PM were measured, often reaching very high values, during shorter spells can exceed 70 µg/m$^3$ of BC and 60,000 #/cm$^3$ of PM. Big differences in concentrations between the two measuring sites are due to their locations. The station at Retje is located close to the bottom of the depression in the vicinity of a larger number of emission sources, while the station at Tabor is located on the top of the hill where fewer emission sources can be found in its immediate vicinity and ventilation is better.

*Figure 5: Time scale of minute concentrations (µg/m³) of BC from 25 October 2017 to 19 April 2018.*

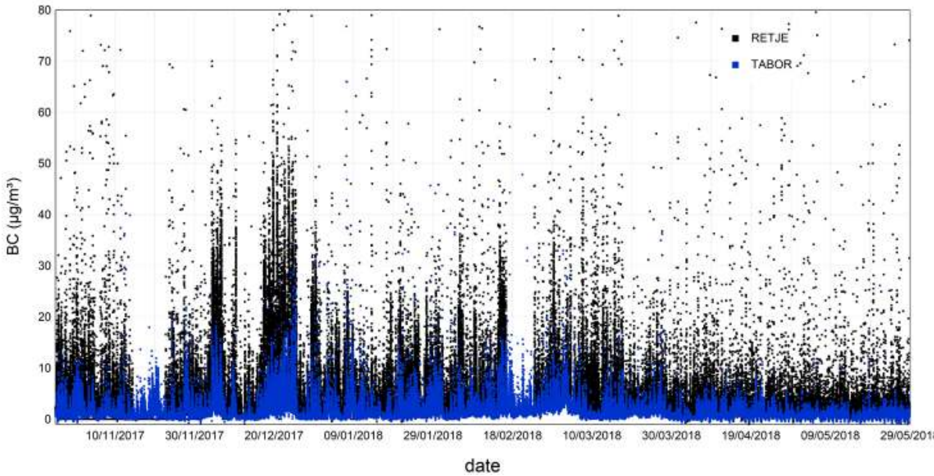
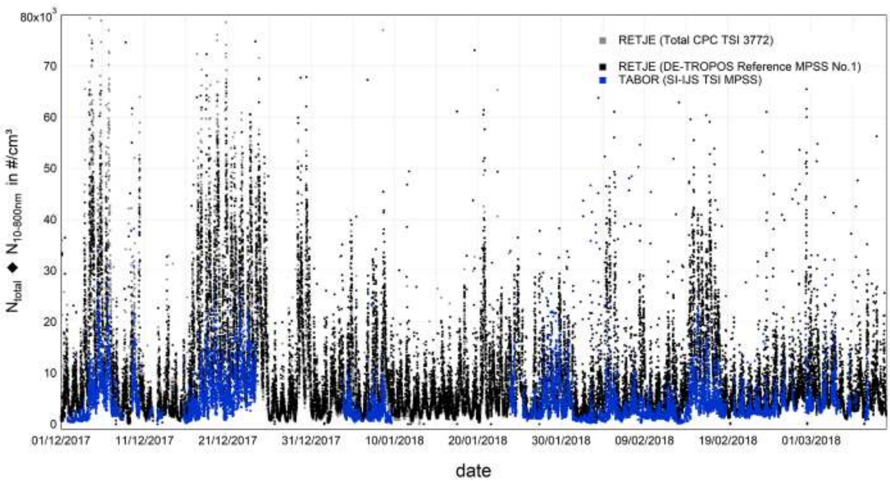



*Figure 6: Time scale of number concentrations (number of particles per cm³ of air – #/cm³) of fine PM (10–800 nm) from 1 December 2017 to 10 March 2018.*




Concentrations of black carbon are the highest in winter and they decrease in spring. With higher temperatures the need for heating is lesser and concurrently the mixing of atmosphere also intensifies at higher temperatures and stronger insolation. During the winter measurement period, from 1 December 2017 to 1 March 2018, the median of BC mass concentrations at Retje was 2.4 µg/m³ and of fine PM number concentrations

6,300 #/cm$^3$. On the top of Tabor hill, the median of BC mass concentrations was 0.9 µg/m$^3$ in winter, and of fine PM number concentrations 2,500 #/cm$^3$. Average concentrations (arithmetic mean) are higher from the stated medians due to uneven distribution with occasional spikes of very high concentrations.

According to the calculation presented in the Chapter 3.1 the source of pollution from biomass combustion was greater than or equal to 50% in all seasons. The heating season in the area is long and extends into the spring. The share in pollution from local biomass combustion at Retje is even greater than that at Tabor. In the winter of 2017/18, it amounted to 79% at Retje and 62% at Tabor of total BC concentrations. Due to its position in a depression, Retje stays longer in shadow, which results in a bigger need for heating. Contribution of biomass combustion was lower during the days of mixed atmosphere than during the days with temperature inversion, which is probably due to higher temperatures during the advection in comparison with more stable days (certain days with temperature inversion), and thus due to lesser needs for heating.

*Table 3: Median (MED), arithmetic mean (AS) and standard deviation (SD) of black carbon (BC) mass concentrations, expressed in absolute values; share in pollution from biomass combustion ($BC_{IB}$), expressed as percentage of total BC concentration and number concentrations of fine PM ($NC_{10\text{-}800nm}$). The values are shown for the winter period (from 1 December 2017 to 1 March 2018) for both measuring sites, separately for the periods with temperature inversion and the periods of mixed atmosphere.*

| Sation | Period | BC (µg/m$^3$) | | | $BC_{IB}$ (µg/m$^3$) | | | $BC_{PR}$ (µg/m$^3$) | | | $BC_{IB}$ (%) | | $NC_{10–800nm}$ (#/cm$^3$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | MED | AS | SD | MED | AS | SD | MED | AS | SD | MED | AS | MED | AS | SD |
| RETJE | Winter 2017/18 | 2.4 | 5.2 | 7.4 | 1.8 | 4.2 | 6.3 | 0.3 | 1.0 | 3.0 | 79 | 81 | 6,300 | 10,200 | 19,300 |
| | Temp. inversion | 5.6 | 8.1 | 8.3 | 4.9 | 7.1 | 7.3 | 0.4 | 1.1 | 3.0 | 86 | 87 | 12,600 | 15,500 | 12,400 |
| | Mixed atm. | 1.6 | 2.7 | 4.6 | 1.1 | 1.7 | 2.2 | 0.4 | 1.0 | 3.4 | 67 | 73 | 4,500 | 6,300 | 2,900 |
| TABOR | Winter 2017/18 | 0.9 | 1.7 | 2.3 | 0.5 | 1.2 | 1.9 | 0.3 | 0.5 | 0.9 | 62 | 65 | 2,500 | 4,000 | 4,200 |
| | Temp. inversion | 1.8 | 2.8 | 3.0 | 1.3 | 2.5 | 2.1 | 0.4 | 0.7 | 1.1 | 70 | 71 | 4,300 | 5,600 | 4,500 |
| | Mixed atm. | 0.9 | 1.2 | 1.3 | 0.5 | 0.7 | 0.9 | 0.3 | 0.5 | 0.7 | 54 | 59 | 1,800 | 2,300 | 2,900 |

*Legend:*
*BC – black carbon*
*$BC_{BB}$ – black carbon from biomass burning*
*$BC_{TR}$ – black carbon from transport*
*$NC_{10–800nm}$ – number concentrations of 10–800 nm particles*

There are significant differences in the concentration of pollutants with regard to meteorological conditions. Significantly higher concentrations were measured in the days with temperature inversion when on average the increase in concentrations was 3-times higher at Retje and 2-times higher at Tabor in comparison with the days of mixed atmosphere.

Due to temperature inversion all pollutants (gases and particles) remain within the limited layer in the basin, which prevents the concentrations from spreading into the higher layers of the atmosphere. During the stable atmosphere at the ground (selected days with temperature inversion) the median at Retje was 5.6 μg/m$^3$ of BC and 12,600 #/cm$^3$ of fine PM. On selected days with temperature inversion on Tabor hill the median of BC mass concentrations was 1.8 μg/m$^3$ and 4,300 #/cm$^3$ of fine PM. Concentrations of pollutants on Tabor during temperature inversion are very similar to those at Retje during mixed atmosphere. On selected days of mixed atmosphere, the median at Retje was 1.6 μg/m$^3$ of BC and 4.500 #/cm$^3$ of fine PM. At the same time at Tabor the median was 0.9 μg/m$^3$ of BC and 1,800 #/cm$^3$ of fine PM. Depending on the height of the inversion layer, the top of Tabor hill can be within the temperature inversion or above it. For that reason, also in the spells of stable weather (development of temperature inversion) the differences in concentrations at the Tabor station were considerable (standard deviation was 4,500 #/cm$^3$).

If mean values of BC mass concentrations and the ultrafine and fine particle number concentrations measured in Loški Potok are compared to mean values of the concentrations measured in Ljubljana in the same period (median: 2.4 μg/m$^3$ of BC and 6,800 #/cm$^3$ of ultrafine and fine PM; arithmetic mean: 3.5 ± 3.3 μg/m$^3$ of BC and 8,000 ± 4,900 #/cm$^3$ of fine PM) (Aerosol d.o.o., 2018; Nacionalni laboratorij …, 2018), we can see that both BC mass concentrations and the fine particle number concentrations at Retje were higher on average, while mean concentrations at Tabor were lower than those in Ljubljana. The average of particle number concentrations at Retje in the winter of 2017/18 is comparable to average winter concentrations in major North- and Central-European cities, such as Helsinki, Stockholm, Augsburg (on average from 10,000 to 20,000 #/cm$^3$) (Aalto et al., 2012; Borsös et al., 2012). Average concentrations at Tabor are comparable to the values of the rural background measurement stations (Birmili et al., 2016), which are specific for being away from major emission sources by 10 to 50 km (Larssen, Sluyter, Helmis, 1999; Putaud et al., 2010).

# 5 CONCLUSION

The levels of pollutant concentrations in the studied area are decisively influenced by the intensity of local emissions and position in the relief depression where temperature inversion occurs. During the inversion a lake of cold air forms at the bottom of the hollow; cold air is heavier and denser than the upper warmer air, so they do not mix. This results in the accumulation of pollutants within the lake of cold air and thus increased air pollution in the holllow. In Retje village, particle number concentrations and BC mass concentrations often reach extremely high values which, during spells of stable atmosphere with high emissions, can exceed 60,000 #/cm$^3$ of fine PM and 70 μg/m$^3$ of BC. However, despite intense local emissons the concentrations of pollutants sharply decline during the time of mixed atmosphere. In days with temperature inversion, BC mass concentration and number concentrations of fine PM at Retje are on average more than 3 times higher than in the periods of mixed atmosphere, and 2 times higher at Tabor. This is due to the rather unpolluted surroundings of the studied area with low population density and longer distance from other major emission sources. The reason for the poor quality of air in the Retje basin therefore lies exclusively in local emissions, since at the time of good ventilation concentrations of fine PM and BC do not nearly reach those at temperature inversion occurrence.

Intensive changing in the concentration of pollutants through time is due to both human activities and the thickness of inversion layer. This layer is only a few tens of metres thick in the Retje basin and quickly breaks up in stronger winds or under intense insolation. A few longer spells of stable weather conditions when the basin atmosphere remained unmixed for several days were recorded only in December and February.

Local biomass burning is the main source of PM emissions in the area; in winter, it contributes 79% to the concentration of BC at Retje and 62% at Tabor. The results of measurements at Loški Potok in the 2017/18 season showed that concentrations of fine PM and BC in mountainous rural areas in the cold half of the year are comparable to those stated in literature for Central European cities. In the winter of 2017/18 concentrations of PM and BC in the Retje basin were on average even higher than those in Ljubljana, but the frequency of changes is greater and the range of concentrations of pollutants is much wider in the studied area. Due to the much smaller volume of the Retje basin in comparison to that of Ljubljana, concentrations of PM in the former rise fast to a very high level when the emission sources are active. However, these concentrations also decrease faster than those in Ljubljana because the shallow inversion layer in the Retje basin breaks up faster. In addition, the surroundings of this area are sparsely populated, with only few sources of emissions, and when the basin atmosphere is intensely mixed with the surrounding air, the concentrations are very low. Due to the distribution of emission sources and position of the Retje village in the basin, the villagers are most highly exposed to high concentrations of PM and BC in the cold half of the year.

Similar conditions can be expected in other similar hilly and mountainous rural areas in Slovenia and Europe which are located in terrain depressions with frequent temperature inversions and where biomass is an important source of household heating. Since PM concentrations in the air in Slovenia mostly result from local biomass burning in individual households, the problem of air pollution will have to be dealt with in its entirety. This is particularly true of rural areas where measures such as district heating are more difficult to realize and they are less effective than in cities. Reduction of household emissions in rural areas can be achieved by replacing old combustion plants (stoves and boilers) with newer combustion plants with more efficient combustion, installation of secondary emission reduction technologies (catalysts, electrostatic filters), or with change of heat supply technology (installing heat pumps), improving the efficiency of burning (optimum use of existing combustion plants, correct preparation, selection and use of appropriate fuel) and heating habits of the population through appropriate awareness raising and trainings and the use of common boiler rooms for several buildings. In the Alpine valley Vorau, Austrian Styria, such measures proved to be successful in reducing the emissions of individual households (Klauser et al., 2017). In addition to the above-mentioned measures, concurrent energy rehabilitation of buildings (thermal insulation, replacement of old windows with energy efficient windows) is also urgent in order to reduce emissions. Such measures are promoted in Slovenia by the Eko sklad [Eco Fund] which was established with the aim to promote environmental investments (Eko sklad, 2018).

It should be emphasized that the measures must involve all households, as all the sources in the area add to PM concentrations. Even a small percentage of a high emission heating systems can have an important impact on the air quality in the entire basin. The research in Loški Potok showed that local sources and topography are the most important factors influencing local air quality. It also indicates that we can expect similar air quality conditions in other populated karst depressions.

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