Nitrogen Dioxide and Black Carbon Concentrations in Ljubljana

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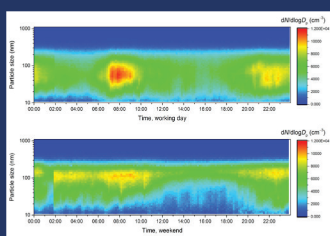

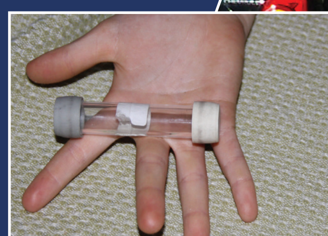

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Cartographers/Kartografi: Simon Koblar, Asta Gregorič, Tanja Koželj, Nejc Bobovnik

Photographers/Fotografi: Matej Ogrin, Katja Vintar Mally

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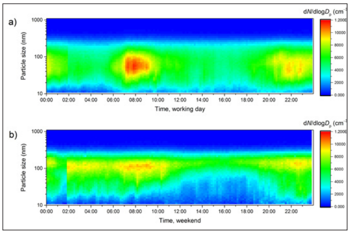

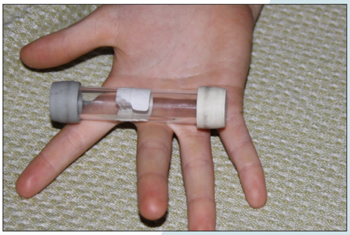

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1. Introduction

It would be difficult to conceive of modern society without transport. Among the different transport subsystems, road transport is by far the most predominant. Road transport in Slovenia has experienced phenomenal growth in the past two decades, as reflected in transit transport, a rapid increase in car ownership and therefore also in a growing volume of road traffic. A car is no longer a means of transport for an entire family, but increasingly a personal means of transport, with more and more families owning two or even three cars. The need for personal mobility has grown extremely rapidly, resulting mainly from lifestyle changes and social trends that continue to amplify this need. Day or weekend trips to destinations 100 or more kilometers distant have become routine in Slovenia, while the number of daily commuters to increasingly distant places of employment has also increased. The development of road infrastructure (the motorway network) and the hugely lopsided predominance of investments in this kind of infrastructure encourage road transport, as do remuneration policies that provide incentives for people to drive to work independent from the distance to work. Besides the widespread belief that owning a car in Slovenia is a "status symbol", we cannot deny that given the current status of public transport and corresponding transport policies, in many areas of Slovenia a car is the only thing that enables one to be competitive on the labor market and included equally in society. This is further exacerbated by the dispersed settlement pattern of Slovenia. Thus people who are unable to drive or buy a car (young people, the disabled, socially disadvantaged, etc.) as a rule find it more difficult to be included in social structures, since in a society that encourages mobility they do not have the same opportunities, and society (the state) does not provide access for them.

The development of tourism in Europe has also contributed to the rise in car traffic: every year we are witness to what have become traditional "migrations of peoples" – towards the Mediterranean coast in summer, and towards the Alps in winter. Slovenia in summer experiences pronounced flows of international tourist transit car traffic, as visitors mainly from Italy, Austria, Germany, the Netherlands, Poland, the Czech Republic, Slovakia and Hungary migrate en masse to the Croatian coast, while a not insignificant portion of the flow of traffic towards the Adriatic coast is also made up of Slovenes.

Besides car traffic, freight traffic also has a strong impact on roads and the environment, whether transit freight traffic resulting from the international flow of goods or local and regional freight traffic transporting services and goods between cities and towns within the country. In Slovenia, as well as more widely in Europe, the rapid growth of service activities, especially trade, has replaced the decline of industry and its relocation to other parts of the world. The liberalization of trade and the policies of a single market and the free flow of goods, people, and capital are fundamental principles underlying the functioning of the European Union. The failure to take into account the real costs of freight transport, in particular externalities, is quite significant—and with negative environmental and social impacts. Of all the methods of transporting freight, road transport is the most wasteful. Underestimation of the true costs has a strong impact on the economic rationale for this transport subsystem and consequently also on the growth of these kinds of transportation flows in all of Europe in recent decades up to the beginning of the economic crisis.

The impact of this growing traffic is also evident in the landscape, though we may not even notice all of the effects. The use of space for big parking lots, new and wider roads, ring roads around cities and large parking garages are just some of the more obvious signs. The pressure of road transport on space can also be seen in the increasingly greater volume of traffic in unpopulated areas, where the minimal infrastructure is inadequate to support the level of traffic during peak hours. Road noise has increased greatly due to the increase in traffic, and anti-noise road barriers have become urgently needed in many populated areas. In cities, addressing the problem of noise is even more difficult since the density of sources is considerably greater.

Along with noise, traffic-related air pollution is also a very serious problem. When traffic is minimal, the problem is relatively insignificant, although it also depends on the composition of the traffic, the age of vehicles and a few other factors. However, as traffic increases, the air quality near roads becomes increasingly problematic. If we also consider other factors reducing the self-cleaning capacity of the air near roads, such as building density and temperature inversions, the negative impact of traffic-related pollution is further amplified.

Traffic-related air pollution has not yet been assessed in view of the actual impact that it has. In recent years particulate matter has come under increasing attention as a problematic pollutant. Along with nitrogen oxides, volatile hydrocarbons and ozone, particulate matter represents a major problem for a number of institutions in meeting European air quality standards. The use of diffusive samplers is important for evaluating the spatial impacts of traffic-related pollution since it provides an insight into the spatial distribution of pollutants such as nitrogen dioxide, benzene, and ozone. Aethalometer measurements of black carbon have determined the contributions of its sources as well as the level of black carbon pollution, both very important pieces of information for adopting abatement measures for the reduction or elimination of particulate air pollution.

This book focuses on traffic-related air pollution and pollution from black carbon. It is in certain respects a continuation of the books "Traffic-related Nitrogen Dioxide Air Pollution in Ljubljana", published in 2008, and "Air Pollution in Ljubljana – Concentrations of Nitrogen Oxide, Ozone, Benzene and Black Carbon in 2013 and 2014", and thus concludes the trilogy by including a comparison of the results of measurements in 2005/2006 and 2013/2014. At the same time, it places the problem of air pollution in Ljubljana in a wider historical context by means of a brief historical overview of activities relating to protection of the air in the period after the Second World War. In the introductory part of the book there is an overview of the development of protection efforts in Slovenia after the Second World War, with descriptions of efforts to improve air quality in some Slovenian towns and other areas that for various reasons encountered very high concentrations of pollutants that would nowadays be almost unthinkable. This is followed by a review of the literature on pollution and protection of air quality in the field of traffic-related pollution, where some studies and published works are briefly presented. Although the problem of traffic-related air pollution in Slovenia became a focus of attention relatively late, since up until the beginning of the 1990s this aspect in comparison to pollution associated with heating (thermal power plants, heating plants, household stoves and furnaces) seemed more or less unimportant, considerable experience and knowledge have been gained in Slovenia over the last 25 years, and along with it a wealth of applicable literature. All of this will undoubtedly come in useful in efforts for the successful mitigation of traffic-related air pollution in Slovenian towns and the realization of sustainable mobility. This is followed by a survey and comparison of air pollution from nitrogen dioxide in Ljubljana, as a synthesis of studies from 2005/2006 and 2013/2014, enabling a survey of nitrogen dioxide pollution over a somewhat longer period of time. This is all the more important due to its close link with the traffic situation of Ljubljana. The remaining chapters of the book are devoted to air pollution from black carbon, which in the context of air pollution from particulate matter is becoming a very important part of not only traffic-related air pollution but also (once again) of pollution as a result of increasingly greater activation of individual household heating from biomass using outdated technologies. Burning of biomass in the form of wood during a time of increasingly expensive fossil fuels (heating oil, natural gas) has once again become widespread in Slovenia over the past decade, and is creating smoke and associated problems in residential areas.

In contrast to the two earlier books, this work is presented in English since the authors would like to present the problem of protecting air quality, its historical aspect as well as the current situation and challenges to a wider international audience. Ljubljana became the European Green Capital 2016 and we hope this book also serves as a mirror of successful efforts at improving air quality. This includes both earlier efforts from around Slovenia associated with individual household heating and with remote heating that today are regarded as very successful examples as well as present-day ones that are already showing positive trends in some places. However, the path to a successful solution is still a long, arduous, and a financially demanding one. This book has been supported by funding from the Slovenian Research Agency, the Scientific Research Institute of the Faculty of Arts, and the Aerosol d.o.o. company. Thanks to them, the authors are able to present this problem in a third publication, which due to the translation into English has represented a greater financial challenge.

2. The development of activities for protecting air quality in Slovenia and legislation

Due to its sheltered location at the lee side of the Alps, Slovenia is considered an unventilated region, and most of its towns are thus also in this position, with the exception of coastal cities (Ogrin et al., 2012). Ljubljana is also a poorly ventilated city, in which there are no regularly occurring strong winds, and this results in a lower self-cleaning capacity of the air. Due to its basin location, temperature inversions during times of clear weather are frequent and pronounced (Gams, 1972). Due to the concentration of industry and housing, air quality in Ljubljana worsened after the Second World War. According to the meteorologist Paradiž (1970), air quality in Ljubljana in the 1960s was among the worst in the world, and thus efforts were undertaken for its improvement. The main topic of issue no. 7 of the bulletin of the Slovenian meteorological society Vetrnica (2014), which was published in October 2014, was protection of the air from pollution. A number of experts who had done most in the development of this field contributed their part to an overview of activities on improving air quality. Missing was the contribution of the person who had begun the work on protecting air quality, Bojan Paradiž, who had unfortunately passed away. This section is primarily a summary of the articles that were published in that issue of Vetrnica.

After episodes of high concentrations of pollution in Donora (Pennsylvania, USA) in 1948 and in London in 1952, when the mortality rate increased drastically during days of very heavy air pollution, people in Slovenia also began to think about the quality of the air that city residents breathe. The first measurements of sulfur dioxide and smoke were carried out by regional Institutes of public health based on the British method, which was developed after the episode in London. Concentrations were so high that they at first doubted the accuracy of the measurements. When they carefully checked all the procedures, they realized that the air in Slovenian cities was among the most polluted in the world. This was found first for Ljubljana, Maribor and Celje, and somewhat later also for the Zasavje region. After these adverse findings, they began to investigate the underlying causes of the problem, which required undertaking systematic measurements, studies, and steps.

2.1 Monitoring of air quality in Slovenia

The first measurements of ambient air in Slovenia were conducted in the 1960s. These were measurements of the levels of acidic gases and smoke based on the standard British method. Among acidifying emissions, the most predominant was sulfur dioxide (SO_2), and thus the results of the measurements were shown as sulfur dioxide concentrations. A series of measurements lasting several months were performed as early as the first half of the 1960s, and regular measurements by the Hydrometeorological Institute (HMI) were begun in 1968. The number of measuring points then increased, such that by 1975 measurements had grown into a network that covered most major settlements in Slovenia. For some measuring points there exists a series of data from 1968-2002 and for others the series is shorter, but for at least 40 measuring points there is a series from 1975-2000. Altogether there are about 200 measuring points, including those with just a few months worth of measurements. All the data are collected in a computer archive. Analyses of water from precipitation and sediments and monthly indexes of air pollution were also conducted at a chemistry laboratory.

A 24-hour measuring interval was too long to determine the causes of excessive levels of pollutants, particularly around thermal power stations and industrial plants. Even before 1970, measurements in the vicinity of the Trbovlje thermal power station and the lead smelter in Žerjav were conducted using monitoring devices that continuously measured concentrations of sulfur dioxide. HMI purchased four monitoring devices of the Ultragas type from Wösthof in 1971 (Hrček, 1977) that also operated on the principle of electrical conductivity. Monitoring took place in cities and in the vicinity of thermal power stations. The monitoring occasionally showed levels of sulfur dioxide that were far too high relative to the limit values. In some locations in the vicinity of the Trbovlje thermal power station the measuring range of the device, which was set at 10 mg/m^3, was too small. By way of illustration – the currently valid hourly limit value of SO_2 is 350 $\mu g/m^3$ (0.350 mg/m^3). The highest levels were measured during the construction of the new stack at the station on the construction site of the new stack, which was above the operating old stack. The results of the measurements with Ultragas monitoring devices are stored in the archives of the Slovenian Environment Agency. Measurements did not take place at the same site for a long time and therefore these data have not been systematically processed.

In 1975 the Air Protection Act (Zakon o varstvu zraka, 1975) that had been adopted required that the public be informed of air pollution levels and alerted to excessive levels that could threaten human health. It also required that measures be taken to reduce pollution. These requirements led to collaboration between HMI and the Jožef Stefan Institute in the development and production of automatic meteorological-environmental stations. The stations had a built-in microcomputer that made it possible to carry out automatic monitoring and basic processing of data, and store them in a suitable form; in the beginning this was a magnetic tape. Soon thereafter the automatic stations were linked to a computer at HMI along telephone lines.

A step forward in monitoring was taken in 1983 with the purchase of a large number of automatic monitoring devices for measuring air pollution from Monitor Labs (ML). We called the system the Analytical Monitoring Alarm System, or AMAS for short. It was conceived of as a portable system of 10 automatic stations. The stations were placed in specially equipped kiosks to capture air, with air pollution monitors, meteorological sensors, and a computer for processing and storing data, but at the beginning without a connection to HMI. Data were stored on magnetic tapes that were then taken to a computer center where they could be read. The first measurements with all ten stations were conducted in Celje as part of the project "A model for improving air quality in an urbanized basin" in the period 1980-1983 (Raziskovalni project …, 1983). Simultaneous data from 10 measuring stations can provide a great deal of information. However, a problem arose because much of the data was missing and as a result data analyses were quite problematic. It turned out that automatic measurements without supervision, whether on site or through a remote connection, do not give good results. This kind of extensive measuring campaign was carried out later on in Ljubljana, while at other locations there were at most five stations.

The need for permanent stations became increasingly apparent. A network of stations in Ljubljana, Maribor, Celje, and three towns in Zasavje, where the air was most polluted, took shape. The majority of stations had monitors for sulfur dioxide, and monitors for ozone, nitrogen oxides, carbon monoxide and particulate matter were gradually added to some stations. In 1994 a mobile station in the form of a container trailer was purchased. It had a full set of monitors for measuring air quality, including hydrocarbon and meteorological sensors.

In 1989 the Šoštanj thermal power station built its own system of six measuring stations, and in 1992 the Trbovlje themal power station did likewise. Somewhat later, some urban municipalities and industrial plants set up their own monitoring of air quality. During this time HMI set up two measuring points for monitoring air pollution in areas that were not exposed to such pollution in order to monitor long range air pollution: at Iskrba, near Kočevska Reka, and on the mountain of Krvavec. Later a station for monitoring the transport of ozone from Italy was set up in Otlica on the Trnovski gozd plateau.

The monitoring system was upgraded with the help of EU funding (the PHARE program) in 2001. Measuring stations were modernized and two more were added, the Nova Gorica station and the Murska Sobota station in Rakičan. Later on, a measuring station was set up in Koper in cooperation with the Urban Municipality of Koper. At the time of this writing an additional improvement of the monitoring system is in preparation, with the purpose of coordinating monitoring stations and particular contaminants with an assessment of air quality.

In addition to permanent monitoring of air quality, there have also been several campaigns of occasional measurements in Slovenia. These measurements were conducted with the purpose of adding to measurements from the regular network for monitoring the pollution of ambient air. Measurements were conducted using detectors that take measurements according to reference methods a well as using other methods, for example diffusive samplers. The greatest number of measurements using reference methods were carried out in 2010 and 2011 around industrial plants, which in accordance with the Decree on the emission of substances into the atmosphere from stationary sources of pollution (Uredba o emisiji …, 2007) were obligated to prepare an assessment of existing and additional pollution of ambient air. There were nearly 30 such installations and they were required to take measurements for one year at two measuring stations. Measurements showed that the concentrations of particulate matter in particular were too high in places where there is no monitoring at permanent measuring stations. The main cause of the excessive concentrations of particulate matter was not emissions from industry or energy production, as indicated by the assessment of additional pollution by modeling emissions from installations, but mainly due to emissions from household heating sources as well as to some extent from traffic.

2.2 Legislative framework

Before 1975 we could compare the levels detected with the recommendations of the World Health Organization or the regulations of other countries. The Air Protection Act passed at that time and its related provisions stipulated a policy of protection of air quality, limit values for particular pollutants, and the responsibilities of government organs in this area. Municipalities that had problems with air pollution adopted ordinances on protection of the air. Based on these ordinances, measures for protecting air quality were adopted. These were predominantly public alerts advising local residents not to leave enclosed spaces, to heat just one space in their home and not to drive their cars unnecessarily and to use public transport instead. In the region of the municipality of Velenje, which at that time covered the territory of the present-day municipalities of Velenje, Šoštanj and Šmartno ob Paki, people were alerted by sirens when the limit values of sulfur dioxide were exceeded. In Ljubljana the mayor once restricted traffic and heating when sulfur dioxide concentrations reached alarming levels. Based on the Air Protection Act some municipalities adopted air quality protection programs. In Trbovlje, the most polluted town in Slovenia, due primarily to the use of domestic coal for heating, which anyone who worked at the coal mine or for companies that were associated with the coal mine could obtain for free in the amount of up to 3.5 tons of coal/year (called a *deputat* in Slovene), the *deputat* was abolished and part of the town heated from the newly built district heating plant.

After Slovenia became independent, the government passed the Environmental Protection Act (EPA) in 1993 (Zakon o varstvu okolja, 1993). This law superseded the Air Protection Act from 1975. The new law was very general and not sufficiently precise to cover all the specific aspects of the problem of protecting air quality. Based on the Environmental Protection Act the Decree on limit values, alert thresholds and critical immission values for substances into the atmosphere (Uredba o mejnih …, 1994) was adopted in 1994. This regulation stipulated the limit, alert, and critical values for contaminants in air, taken primarily from German legislation.

Slovenia already began moving closer to the European Union in the 1990s. Preparations were therefore begun for adopting EU legislation. New member states had to bring their national legislation in line with European legislation. Slovenia also did this, and during the negotiating process for EU membership this was thoroughly verified. As part of this process a host of decrees and regulations were adopted. Because the Environmental Protection Act was too general in nature we could not adopt European directives directly as written into our legal system but rather divided the provisions of the directives among various decrees and regulations.

The Decree on the emission of substances into the atmosphere from stationary sources of pollution should also be mentioned. This decree determines the method for obtaining the part of the environmental permit that applies to air quality and defines what the environmental protection permit must contain. The method for assessing the quality of ambient air and guidelines for the choice of the dispersal model for calculating the contribution of pollution from a specific source into its environment is also defined in this decree. There are a number of other regulations besides this one in Slovenian legislation regulating the discharge of waste gases into the atmosphere from various types of installations.

2.3 An integrated solution to the problem of major sources of pollution

In the period from 1970 to 1980, HMI carried out extensive research that was used as the basis for planning air quality protection measures at major sources of pollution and in major cities in consideration of local weather conditions, pollution, and existing pollution of the air (Trbovlje thermal power station, Šoštanj thermal power station, Krško nuclear power station, Žirovski vrh uranium mine, Ljubljana, Celje, the Mežica Valley, Maribor, Sarajevo, Trepča, Pljevlja). The common feature of all these places is that they lie in basins or valleys where temperature inversions occur frequently in the colder half of the year.

Measurements of air quality have shown extremely high levels of sulfur dioxide and smoke in particular, in cities and near thermal power stations. The impact of this on vegetation could be seen primarily around the Trbovlje and Šoštanj thermal power stations and in the Mežica Valley. Some health studies have shown the strong impact of polluted air on the health of residents of the most heavily polluted places. Meteorologists suspected at that time that the main reason for such high pollution was the temperature inversion that occurs above basins and lowlands of central Slovenia where coal was used for heating and there was considerable pollution of the air from industry and tertiary activities. During this period emissions from transport contributed a lesser portion since the volume of road traffic was significantly lower than it is today. The inflow of air along the ground towards the city center due to heat islands also contributed to greater pollution in cities, as they found at that time in Ljubljana and Celje.

In the first half of the 1970s the most pressing problem was the air pollution in the vicinity of the Trbovlje thermal power station. In 1968 a new and more powerful block, with a stack height of 80 meters, began operations in Trbovlje alongside the old block with its 100-meter-high stack. The new stack was too low given the sulfur content of the coal used and the deep and narrow valley in which it was located. Because of its disadvantageous location on the floor of the valley and stacks that were too low, the Trbovlje power station caused such high concentrations of sulfur dioxide that the forests were damaged. The polluted air exacerbated forest degradation and erosive processes on the steep slopes of the Sava Valley, and rockfall became an increasingly common occurrence along the railway line, especially between the

Trbovlje and Zidani Most railway stations. Experts feared that the channel of the Sava River would be buried by a major landslide. For political reasons the closing down of the station and the coal mine associated with it was unthinkable. Smokestack gases needed to be placed above the temperature inversion or purified in the power station. In 1970 HMI adopted the very challenging task of preparing the foundations for cleanup measures at the Trbovlje thermal power station. Bojan Paradiž, who at that time directed air quality monitoring activities, suspected that the reason for the high levels of contaminants in Zasavje lay in the temperature inversion that prevented the vertical mixing of air. Radiosonde measurements showed that the temperature inversion could consist of several layers, with layers of air in between in which temperature dropped with increasing height. At ground level the radiosonde measuring points were too far apart by height to be able to show all the details of the vertical distribution of temperatures in the boundary layer of the atmosphere. The closest radiosonde measurements were in Zagreb (Croatia) and Udine (Italy), and these were only taken twice a day, which was useless for a detailed study of the temperature inversion in the interior of Slovenia. Field measurements of the vertical temperature profile were therefore undertaken. These measurements were first carried out along the slope above the Trbovlje power station using handheld electronic thermometers. Often field workers encountered a layer of such polluted air that they had to leave the site. Results of the measurements indicated that the vertical temperature gradient was strongly structured and that it changed over time. However, it was also observed that measurements along the slope were not the most suitable since local factors, in particular slope winds and vegetation growth of the terrain, had too strong an influence on the measurements.

The realization that measurements must be made in the free atmosphere required a new method of measurement. Bojan Paradiž and his colleagues at the Jožef Stefan Institute set about building equipment for measuring a vertical gradient of temperature. The system was composed of two sets of components: a hydrogen-filled balloon was attached to a string tied to a radio transmitter, and on the ground there was a radio receiver and an impulse meter (to measure the frequency of the measuring signal). A radio transmitter was used to carry a measuring signal from a thermistor on its carrying frequency: the resistance of the thermistor changed with temperature that caused the change of monitoring frequency. Some error arose in measuring height due to divergence from the vertical due to wind, but it was partially cancelled out by the stretching of the cord. The entire measuring process took between 30 and 60 minutes. Measurements were usually carried out every two hours and sometimes every hour.

Measurements of the vertical temperature gradient were always connected with other tasks. In most cases these were ordered by outside clients, and the revenue thereby generated was for the most part put back into the measuring equipment, in particular for measuring air quality. In this way they acquired, in addition to knowledge and experience in connection with the properties of the atmosphere, their own research equipment. This placed the HMI team in the top rank in then-Yugoslavia regarding knowledge and equipment for solving problems relating to protection of the air. HMI thus also carried out some measuring campaigns in Bosnia and Herzegovina, Montenegro, and Kosovo. Results from all these measurements expanded knowledge about the change in conditions in the boundary layer of the atmosphere from the emergence to the disintegration of a temperature inversion and in so doing contributed to a better understanding of events in cold air pools (Paradiž, 2004). During this time there was also little known at the international level about temperature inversions, and so it was necessary to rely primarily on one's own knowledge.

2.4 Measurements in Ljubljana

Two series of measurements were carried out in Ljubljana, first a set of test measurements to test the measuring equipment from 2-11 November 1972, and the following year measurements were taken from 8 November to 13 December in order to determine the height of the stack for the district heating plant in Šiška. Due to the use of hydrogen in the balloon, measuring in cities was halted out of safety concerns. The next location was in Stanežiče, near Ljubljana. Measurements were carried out due to the impending construction of a large housing community in Stanežiče for about 15,000 residents. Through a study of the weather conditions the manner of heating and the height and arrangement of buildings, location of industry, and regulation of traffic were to be determined. In particular, the local prevailing winds were to be taken into account. The Fužine neighborhood in Ljubljana was also treated in this way. There the high-rise apartment buildings were laid out in a north-south direction so that the light winds from Golovec Hill would enable ventilation of the neighborhood with clean air, while the stronger winds that were prevailingly east-west would be blocked by the buildings and reduce their intensity in the settlement. But the Stanežiče construction project remained nothing more than a big hole in the ground, since the community that had been planned there was never built.

Measurements of the vertical temperature gradient in Ljubljana showed that the temperature inversion occurred most often at a height between 150 and 250 m above the basin floor, but that there could also be several layers with a temperature inversion.

3. Review of literature and research on air pollution in Slovenia and Ljubljana

In the previous chapter we have already explained that air pollution in Slovenia up until the 1990s was related for the most part to processes in energy production and industry. Energy production gradually shifted over to a cleaner way of conversion through the replacement of energy sources, the installation of scrubbers and improved energy efficiency. As the industry was restructured, some plants ceased operations. Around the turn of the millennium awareness gradually grew that road transport was becoming the main source of pollution. Due to greater awareness of the problem of air pollution, knowledge in this area began to grow, based at first on foreign studies, then increasingly on research in Slovenia.

There are a number of Slovenian works on traffic-related air pollution, with most of them typically taking a problem-oriented approach. On the one hand are textbooks and material aimed at raising awareness, with an emphasis on a broader and more integrated view of air pollution from traffic, while on the other are case studies and research focused on particular regions and particular contaminants. The textbook "Air and Pollution. Part 1 Meteorology" (Petkovšek, Vrhovec, 2000) is intended for students at the College of Health; it contains an explanation of basic physics concepts and processes in air pollution, and meteorological processes that have a significant influence on pollution. A chapter of the textbook "Fundamentals of Meteorology for Natural Scientists and Technicians", written by Rakovec and Vrhovec (2000), is similarly devoted to air pollution, though it is lesser in scope. The work "Environmental Impacts of Traffic and Tourism in Slovenia" (2009) as part of the GeograFF monograph series is also partly devoted to the environmental impacts of traffic, including its impact on air quality.

Lukan (2002) engaged in research on traffic-related pollution, and in his master's thesis titled "The possible ways to reducing the tropospheric ozone relating to emissions from motor-vehicle traffic" showed among other things that it is not enough for the effective reduction of ozone concentrations to reduce the concentrations of its precursors: along with this, it is also important to achieve ratios of its precursors that are less favorable for the formation of ozone. Otherwise it can also happen that, despite the reduction of one of the precursors (for example nitrogen oxide – NO_x), the concentration of ozone actually increases, if the ratio between volatile organic compounds (VOC) and NO_x is more favorable for the formation of ozone.

Particulate matter was investigated by Bolte (2005) in her study "Traffic influence in air pollution with particulate matter". She provided important findings in the area of pollution from particulate matter for which the principal source is traffic. She also presented a method for calculating emissions and concentrations of particulate matter using the COPERT III emissions model and the Caline 4 dispersion model and in a selected case found considerable consistency between the measured results and those predicted by the model.

Studies on the possible impact of road transport on air quality given the construction of new roads were also performed in the framework of the Group for Evaluating Projects in the Environment (SEPO). The studies were conducted primarily by experts from the Meteorology Group at the Faculty of Mathematics and Physics at the University of Ljubljana. Rakovec et al. (1988, 1989) thus carried out a study titled "An investigation of the spread of air pollution in the Upper Sava Valley after the construction of the motorway from Hrušica to Žirovnica" and "A comparison of the amount of NO_x and CO in the air due to traffic from Hrušica to Vrba along the existing road and along the motorway".

An important study dealing with the environmental impact of traffic-related pollution was carried out in 2000 at the Hydrometeorological Institute of the Republic of Slovenia and published under the title "The Golovec Tunnel, measurements and assessment of pollution of the influence of traffic in the tunnel on nearby air pollution". The main conclusions of the authors of the study (Ciglar, Šprajcar, 2000) were that at that time the majority of pollutants at the tunnel portal were below permissible values and that only the concentrations of nitrogen oxides were strongly exceeded. Since traffic through the Golovec Tunnel has increased greatly since the time of the study, levels of directly emitted pollutants have also grown. The impact of tunnels on air quality at tunnel portals was also the subject of the master's thesis titled "Ecological aspects of road tunnels" (Likar, 1995), which used a dispersion model to investigate the spread of polluted air from the tunnel into the immediately surrounding environment.

The graduation thesis "Air pollution from motor vehicles" by Gardina (2000) also deserves mention in the field of traffic-related air pollution. This work provides an in-depth study of the negative impacts of traffic-related air pollution. Modeling of air pollution is described in the graduation thesis and resultant article by Žabkar (2000) titled "Study of SO_2 concentration variations in Zasavje with trajectories", which shows the influence of the Šoštanj thermal power station on sulfur dioxide concentrations near the Trbovlje thermal power station.

Traffic modeling was performed by Lukan (2006), who used the MLuS 02 model to calculate the concentrations of pollutants. There was a fairly good correspondence between the calculated and measured levels of pollutants. Some years earlier Zupančič (1997) described the quite pressing problem of lead pollution from road transport in the environment. She investigated the pollution of roadside soil from lead and found increased levels particularly in a ten-meter-wide roadside strip.

In 2003 the AIRPECO project took place in Slovenia. The project was headed by the Joint Research Centre of the European Commission (JRC), Ispra, and was carried out in Slovenia by the Slovenian Environment Agency. It involved measuring nitrogen dioxide, sulfur dioxide, ozone and benzene using diffusive samplers as well as measuring particulate matter. Crucial findings for nitrogen dioxide were that the annual limit value (40 $\mu g/m^3$) was exceeded especially along roads with heavy traffic and in the wintertime. Particularly in winter the annual limit value could also be exceeded in the city center. One-day measurements of tropospheric ozone on a summer day showed the influence of the prevailing southwest wind, which pushed air along with the ozone from Ljubljana to the northeast. Values usually exceeded 20 µg/m^3, locally also 30 µg/m^3. Interpretation of the one-day measurements is of merely an informative nature and we cannot compare it to the eight-hour limit value. The distribution of the concentration of benzene in ambient air showed that the highest concentrations were along main roads, which are an important source of benzene. Concentrations there could exceed the annual limit value of 5 µg/m^3. For the other parts of the city, or what is called the urban background, levels between 1.5 and 4 µg/m^3 were measured. Similarly as with benzene and nitrogen dioxide, particulate matter pollution was most critical in the winter, when it frequently exceeded the daily limit value of 50 µg/m^3. With regard to sulfur dioxide, the levels measured did not exceed limit values even in winter, and indicated a low level of pollution (Čemas, 2013, pp. 3–6).

As part of the PEOPLE project, which also came to Slovenia under the auspices of the JRC center in Ispra and was carried out in Slovenia by the Institute of Public Health of the Republic of Slovenia, people's exposure to benzene was determined as they drove to work and performed other errands. The greatest risk of exposure to individual one-day amounts of benzene was found in smokers, and levels were also high for users of cars and public transport, while bicyclists and pedestrians had the lowest levels (Čemas, 2013, p. 8).

That same year the SILAQ project also took place, whose purpose was to assess the level of air pollution from PM10 and PM2.5 particles and look for ways of reducing their concentrations. The Slovenian partner of the project was the Slovenian Environment Agency, which highlighted the following key findings of the project (Projekt SILAQ …, 2014):

- The biggest source of particulate matter are emissions from traffic, which confirms the assessment of many that road transport is a serious threat to health anywhere there is a high volume of traffic;
- The concentrations of particulate matter measured were highest at measuring points along a busy road (Ljubljana – Figovec, Domžale). Coarse particles predominated at these measuring points; they are caused by traffic through a mechanical effect and include particles from tires, which over time are abraded and worn, particles from brake pads, dust stirred up from the road, salt in winter, and similar;
- Concentrations of PM10 and PM2.5 particles were significantly higher in winter, with the sole exception of the measuring point Iskrba. This means that the air in winter is even more vulnerable to pollution, and people in cities more exposed to its effects, due to greater stability of the boundary layer and less mixing;
- Concentrations of PM10 and PM 2.5 were somewhat higher in summer at the measuring point in a rural environment – background (Iskrba);
- Particles are a large problem primarily in city centers, where the causes of pollution are traffic and industry. Based on the results of studies that have been conducted, particles have a negative impact on people's health since they penetrate deep into the lungs. Some fine particles are also carcinogenic, dependent on the chemical composition (heavy metals, organic compounds);

- The small number of measurements conducted in the winter and in the summer measuring periods is a problem since it would be easier to evaluate the results obtained if the series of measurements was longer. There is a lack of long-term monitoring in a dense spatial network in Slovenia that would provide more reliable data on air pollution from particulate matter.

In 2005 and 2006 the project "Traffic-related Air Pollution in Ljubljana within the Motorway Ring Road" was carried out, headed by the Department of Geography of the Faculty of Arts, University of Ljubljana, with the Slovenian Environment Agency as a partner. Using diffusive samplers, measurements of nitrogen dioxide, ozone (in summer), and benzene (in winter) were carried out in the densest network to date. Key findings of the research were that the air in street canyons is excessively polluted all year long, particularly in the most heavily populated street canyon of Slovenska Street, and that the air along arterial roads where there is not a concentration of pollutants due to building density exceeds the permissible level only in the area right along the road. For the first time transverse profiles of concentrations along roads were determined, and the impact of road pollution in relation to the distance from the road was assessed (Ogrin, D. et al., 2006; Ogrin, M., 2008). Based on these and other studies a monograph was published in 2008 in the just emerging GeograFF series of the Department of Geography of the Faculty of Arts University of Ljubljana. The title of the monograph, which was authored by Ogrin, is "Traffic-related Pollution of the Air from Nitrogen Dioxide in Ljubljana". Cerkvenik (2012) later, for 2009, estimated the share of emissions pollutants in Ljubljana and found among other things that 51.8% of particulate matter and 60.4% of BTX (benzene, toluene and xylene) came from traffic.

A continuation of the measurements that were carried out under the project "Traffic-related Air Pollution in Ljubljana within the Motorway ring Road" was one of the phases of the project Urban Heat Island (UHI), commissioned by the Urban Municipality of Ljubljana in partnership with the Anton Melik Geographical Institute SRC SASA; the Department of Geography at the Faculty of Arts University of Ljubljana in collaboration with the Slovenian Environment Agency was responsible for conducting studies of air quality. As part of this campaign authors used the same method as in the project "Traffic-related Air Pollution in Ljubljana within the Motorway Ring Road" to investigate in more detail air quality in Ljubljana within the city ring. Authors combined these findings with those of researchers from the Aerosol company and the Centre for Atmospheric Research at the University of Nova Gorica, which during roughly the same period were involved in measuring concentrations of black carbon in Ljubljana. All the findings were presented in a monograph by seven authors titled "Air Pollution in Ljubljana", published in 2014. Additional important works relating to traffic air pollution were published in 2015. In the PhD thesis "Contribution of traffic and biomass burning to air pollution discriminated with Aethalometer measurements of black carbon" (Ježek, 2015) and the accompanying publication (Ježek et al., 2015) BC, NOx and particle number traffic emissions were reported. In addition to the first on-road real world determination of diesel car emission factors, a comparison between ambient measurements of black carbon apportioned to traffic and biomass combustion and an emission model for the same region was carried out. The results show good agreement of the two approaches.

After 2000 the civil society movement for sustainable mobility also gathered strength in response to the pronounced dependence on cars in Slovenia and Ljubljana and the associated problems of the use of space, traffic jams, energy inefficiency and of course traffic-related pollution. In the framework of the Coalition for Sustainable Transportation Policy several nongovernmental organizations joined forces and were included in the processes of formulating transport policy at the national as well as city level. As part of this coalition, which is still active, a number of experts and decision makers provided their views at an informal level and influenced public awareness through the media. Thus in 2005 the conference "Road Transport and the Environment in the City of Ljubljana" was held in Ljubljana, and its proceedings published a year later under the same title (Cestni promet in okolje…, 2006). A number of challenges and problems affecting Ljubljana in the area of sustainable transportation policy were presented. These clearly showed the need for an integrated and sustainable system of transportation development in the capital city. Under the Civitas project (2005–2012) the Urban Municipality of Ljubljana set up a platform for science, exchange of perspectives and experience, and airing of views on transportation policy and planning.

The overall picture of air pollution in Ljubljana and Slovenia is also strongly supplemented by regular and occasional activities of the Slovenian Environment Agency in the area of air quality. Annual reports on air quality have been issued since the winter of 1989/1990, and assessments of air quality in Slovenia were also issued in 2003 and 2010. Specific studies identified the sources of PM10 particles in Ljubljana, Celje, Maribor, Nova Gorica, Trbovlje and Murska Sobota, and also looked at the influence of the advection of Saharan sand on the concentrations of particles in the air. Measurements in particular problematic regions, such as for example in the Upper Mežica Valley, the Zasavje region, and Lovran near Ankaran, are also carried out.

4. A brief description of Ljubljana

Since this book is intended for readers from English-speaking regions, in this chapter we describe the basic features of Ljubljana to give readers a better idea of the city and its activities. Ljubljana is the capital city of Slovenia and is located at the southern edge of the Ljubljana Basin. It has an elevation of about 290 m, and the whole of the Ljubljana Basin is surrounded by the high Kamnik Savinja Alps and the Karavanke to the north (with summits reaching over 2500 m), the Dinaric hills of Krim and Menišija to the south (reaching an elevation of about 1100 m), the Polhov Gradec Hills and the Škofja Loka Hills to the west (with the highest peaks reaching a bit more than 1000 m), and the Posavje Hills to the east, which surround the basin with peaks about 800 m high. There are also some passages at lower elevations through the surrounding hills, such as for example the passage by way of Turjak (el. ca. 500 m) into the Velike Lašče area or by way of Grosuplje into the Dolenjska lowlands (ca. 500 m) to the southeast, and through the Logatec plain (ca. 480 m) towards the Postojna Gate (611 m) at the southwestern edge of the basin or the passage by way of Jesenice (576 m) into the Upper Sava Valley to the northwest. To the northeast the Ljubljana Basin enters the Savinja Valley through the valley of Črni Graben and Trojane (594 m). The lowest but also narrowest passage of the Ljubljana Basin is through the Sava Valley to the east, where the basin at its eastern edge also reaches its lowest point of ca. 270 m. There, close to Zalog, the Sava near its confluence with the Ljubljanica and Kamniška Bistrica cuts a channel into the Posavje Hills and through a narrow valley continues along its path towards the Black Sea.

The climate of Ljubljana according to Köppen's climate classification is moderate and humid with warm summers (Cfb). A more precise definition places the climate of Ljubljana in the moderate continental climate of Central Slovenia (Ogrin, 1996), with average annual temperatures of about 10 °C, average January temperatures just below 0 °C and average July temperatures of about 20 °C. The climate is relatively wet, with an annual precipitation of about 1300 mm distributed fairly evenly throughout the year.

Due to its basin location, Ljubljana is characterized by poor ventilation and the frequent occurrence of temperature inversions. Jernej (2000, p. 123) notes that in the center of the city surface based inversions predominate, comprising 50-55%, while 15 to 20% are elevated inversions. The thickness of the inversion is between 200 and 400 m. In winter elevated inversions are more common than in summer and appear in 27% of cases (Jernej, 2000, p. 123). A cold air lake is problematic for air quality especially during winter inversions lasting several days, when city emissions remain below the cap of the inversion and their concentrations increase. During a time of temperature inversion, local air circulation takes form in Ljubljana, separate from the circulation above the cold air lake. This circulation is dependent on relief and temperature differences, which are a consequence of the formation of the urban heat island. In this way slope winds are created along the edges of the basin and at the foot of the hills, a weak valley flow is created along the Sava Valley, and a flow of air from the edge of the city towards the center is created due to the effect of the urban heat island. In all cases these are weak winds, which affect the transfer of pollutants and heat within the urban heat island (Jernej, 2000, p. 124)

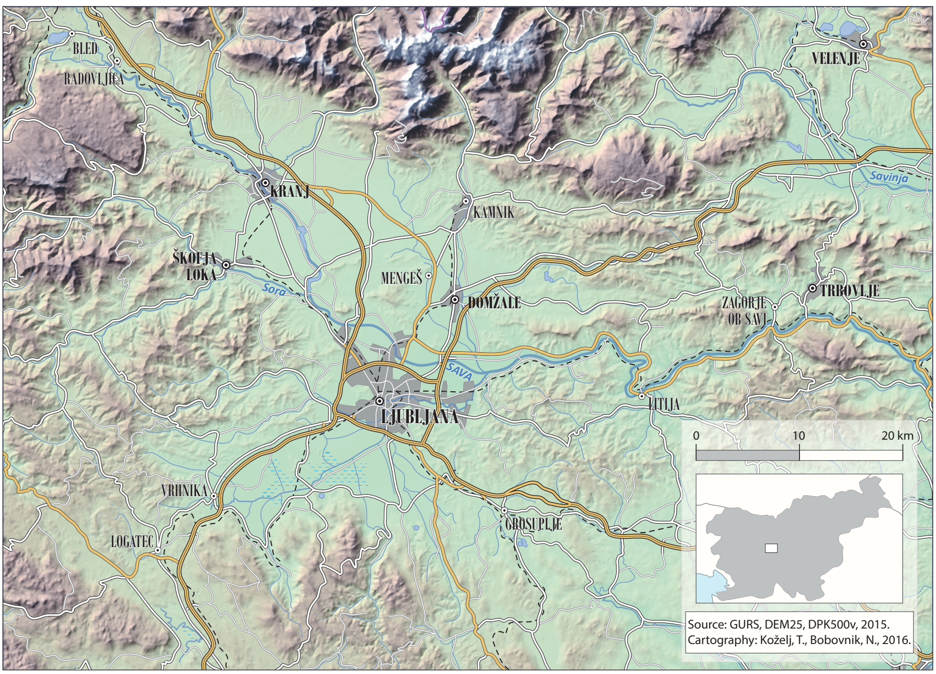
The location of Ljubljana represents an important regional traffic hub. As early as the time of the Roman Empire, there was a Roman fortress, Emona, at the site of present-day Ljubljana, which served to connect influences from the Apennine Peninsula to the Danube region (Pak, 2010), and its traffic role was further strengthened especially in the 16th century, when Kamnik lost its traffic role and the main route between Italy and Hungary passed through Ljubljana (Holz et al., 1995). A transportation milestone for Ljubljana was also the year 1847, when the first train of the Southern Railway, whose purpose was to connect Vienna with Trieste, which happened in 1857, arrived in the city. From that time on the traffic role of Ljubljana was enhanced by the city's increasingly important role in the province of Carniola. After the collapse of the Austro-Hungarian Monarchy, Ljubljana went from being a provincial center to taking on the role of the center of Slovenia and Slovenes in the newly created kingdom, and after the Second World War it became the capital of the republic in the framework of then Yugoslavia. In 1991, with the independence of Slovenia, it also became the capital of the newly created country. Especially from the end of the First World War, Ljubljana was also an important industrial center of Slovenia, and its central role with the adoption of administration functions of the republican center was further reinforced. After 1980, and especially after independence in 1991, Ljubljana strengthened its transportation and administrative role, while its industrial character began to weaken as a result of intensive deindustrialization and tertiarization.

Today the urban municipality of Ljubljana has a population of 287,000 (Prebivalstvo po …, 2016), and the strengthening of the traffic role due to the rapid growth of automobile use has led to even greater traffic-related impacts on the environment. Traffic flows around Ljubljana are also becoming more congested due to the fact that the Ljubljana ring road is at the same time one of the most important traffic axes of Slovenia. The volume of traffic on the Ljubljana ring road amounts to about 60,000 – 70,000 vehicles per day (Prometne obremenitve 2013, 2016). According to data from the Energy Balance of Ljubljana (Energetska bilanca in ocena …, 2016), traffic in the Urban Municipality of Ljubljana (UML) in 2014 was responsible for 60% of nitrogen oxide emissions, 33% of particulate matter, and 38% of greenhouse gases. The degree of motorization in the Central Slovenian statistical region, to which Ljubljana belongs, was 475 vehicles per 1000 residents in 2001, and 522 in 2014, which is close to the average for Slovenia, and 501 vehicles per 1000 residents for the urban municipality (Nekateri kazalniki transporta …, 2016; Prebivalstvo po …, 2016). The impact of traffic on Ljubljana can also be seen in the daily traffic jams along city arterials and the Ljubljana ring road during peak times. The relative proportions of modes of travel in Ljubljana have shifted strongly in an unsustainable direction. In 1986 the Ljubljana city bus service carried 160 million passengers, whereas in 2008 this number was only 84 million. In 1994 42% of people used a car to get around the UML, 21% travelled by bus, 10% by bike and 27% on foot. In 2011 the share of automobile travel had risen to 67%, and the share of people using the bus had dropped to 13%, the share of bicyclists remained the same and the share of pedestrians dropped to 10% (Anketa po gospodinjstvih …, 2003).

After 2000 Ljubljana became increasingly aware of the poor traffic situation and growing traffic impact, and discussions began with an increasingly vocal demand for a transition to a practice of sustainable mobility. The traffic situation of Ljubljana is also strongly dependent on traffic flows from other regions, since 106,000 jobs in Ljubljana are held by commuters from other municipalities, which causes strong pressure on arterials during peak times. At those times the share of commuters to work or school is as high as 68% of all car traffic, and it is clear that this group is the most important for reducing daily traffic volume (Predlog prometne politike…, 2012, p. 40, 42).

The network of bicycle paths has been improved, as has public bus transport, and the city center is being arranged in such a way so as to be more bike and pedestrian friendly. Parking places have been moved from the city center to parking garages and to the outskirts, and more and more areas in the city center are free of motorized traffic. Pedestrian zones are expanding, and squares that were previously used to park cars are regaining their traditional role – a place for interactions among city residents and city life. Since 2013 Slovenska Street, which up until then had been the main road through the center of the city, has also been closed to passenger car traffic, considerably relieving the center of traffic and improving the quality of the city experience. Today this once major road in the city center has become one of the largest peaceful places in the city, where only public transport is allowed. In recognition of these efforts towards a better urban environment, among which definitely belongs the gradual improvement of the city with respect to traffic, the European Commission has awarded Ljubljana the title of European Green Capital for 2016, an encouragement of these efforts as well as a commitment to continue them in future, in particular with regard to traffic regulation, since this is the area where Ljubljana still has a lot to do in order to catch up with the best European cities.

Figure 1: Ljubljana and its surroundings



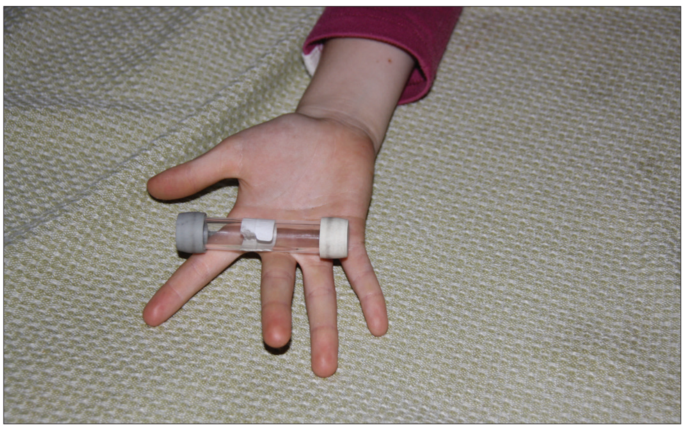
5. Investigation of air pollution from road transport using diffusive samplers

The use of diffusive samplers to provide spatial samples of pollution had already been shown by studies in 2006 and 2008 (Ogrin et al., 2006; Ogrin, 2008) to be a suitable method for determining air quality, and we therefore used them in a 2013/2014 study, thereby enabling easier comparability of results. In addition to assessing pollution from nitrogen dioxide we can also use this method to ascertain the level of pollution from ozone, sulfur dioxide, and benzene. The method is based on the transfer of the pollutant into the sampler by means of molecular diffusion.

Diffusive samplers measure the presence of certain substances in the air through passive sampling and are thus also called passive samplers. This means that we do not need pumps for the supply of air into the samplers: they are simply exposed to the air in ambient conditions. The level of sampling is monitored through the level of diffusion of the pollutant in the air within the sampler, as determined by Fick's law of diffusion, which explains the name of the sampler.

Figure 2:

Palmes diffusive sampler



(photo: M. Ogrin)

In our studies cited we used Palmes samplers (Figure 2), which have been in frequent use since 1976, when they were first tested and described (Palmes et al., 1976). They have a 7.1 cm long tube with an internal cross-sectional area of 0.71 cm^2 and a metal mesh at the closed end coated with a reagent that acts as a sorbent. At one end the tube is sealed and at the other end it is open during the time of measurement. Ambient air enters through this opening during the time of sampling, bringing with it pollutants. When the pollutant in the tube reaches the membrane and reacts with the reagent, a new substance is formed that remains on the membrane. Thus the concentration of the pollutant that is being measured is equal to zero in the immediate vicinity of the membrane, due to the reaction with the sorbent. A gradient of concentration is therefore always formed in the tube whenever the concentration of the measured pollutant of the entering air is greater than zero, and due to molecular diffusion this causes a flow of molecules towards the membrane with the reagent. At the end of the sampling the sampler is sealed, and the membranes are sent for chemical analysis, where the mass and hence also average concentration of the pollutant is determined by chemical analytical method.

Figure 3:

Palmes diffusive samplers in a shelter

(photo: K. Vintar Mally)

It is worth noting some of the important advantages of the method of measuring using diffusive samplers (Ogrin, Vintar Mally, 2013, p. 58):

- Flexibility and practicality. The samplers are simple and quick to set up and this can be performed by one person. The samplers and shelters are small, lightweight, and durable if cared for properly. Several hundred can be set up in one day, which greatly increases the quality of information on air pollution and enables a dense spatial grid of measurements.
- Low cost. This enables a greater extent of measurements and thus considerably more detailed spatial data on pollution, which can also form the basis for mapping pollution. Due to the low cost we can repeat measuring periods frequently and we can more easily tolerate losses of samplers due to vandalism.

On the other hand, we must also consider the disadvantages of carrying out measurements and interpreting results using this method (Ogrin, Vintar Mally, 2013, p. 59):

- Lower reliability, which is estimated at up to 30% (Cox, 2003; Bush et al., 2001); however, opinions regarding reliability are divided. According to the guarantee of the manufacturer of the samplers, Gradko International, which also carries out analyses, the accuracy of the results of the analytical method is ±8 %. Errors in any measuring period can be estimated and eliminated through parallel measurements at reference automatic stations, where we determine discrepancies between the results of measurements with samplers and with automatic measuring devices during the time of measurement. Assuming that the external conditions of the sampler at the reference station were sufficiently similar to others in the vicinity, we can use the relationship between the reference value and the value of the sampler as a factor of correction for the other measured values.

- Results obtained using this method provide information only on average pollution and not on maximum, hourly, multi-hourly, or daily values on which legally determined limit values are based. The method is also not suitable for monitoring air quality in real time since the results are available only after a time lag, after the final chemical analysis of the samplers, which can last from several days to several weeks.
- Measuring with Palmes diffusive samplers is less suitable for shorter periods; it must last for at least a few days and preferably for one to three weeks. Where concentrations of pollutants are low, we tend to have a longer measuring period so that the quantity of mass of the pollutant collected in the membrane is greater than the threshold for detection in the analytical method.

Samplers are usually placed in special shelters (Figure 3), which reduces turbulence in the area surrounding the sampler and consequently also inside it. Any entry of turbulence into the tube can influence the diffusion and spoil the quality of the results. The shelters were mounted on streetlights, traffic signs, traffic lights, the roof gutters of buildings and similar places. Samplers along roads were placed at a height of about three meters from the ground, usually 0.5–3.0 m from the edge of the road, exceptionally even more. Measuring points were usually located along roads, in parks, along streets in residential neighborhoods, and in pedestrian zones. Measuring points along roads were set up in pairs on either side of the road (i.e. the measuring point consists of two measuring spots). This enabled us to avoid the influence of wind on the distribution of pollution, since polluted air from the road was always detected by samplers on at least one side of the road regardless of wind direction. We used the arithmetic mean of the results from both measuring spots as the representative value. Measurements of

Figure 4:

Street canyon along Slovenska Street

(photo: M. Ogrin)

nitrogen dioxide were performed using a set of three samplers in one shelter; the value used for the concentration at each measuring spot was the arithmetic mean of the two most similar values, with the third being eliminated.

5.1. Types of urban space

Urban space is highly heterogeneous, containing a combination of numerous factors that can change over a short distance. In the same way the density, distribution, and types of pollution sources can be highly differentiated, which results in air pollution that differs depending on the particular part of the city. Land use in cities also changes over a short distance: over a relatively small area we can find factories, shops, squares, parks, various institutions and of course many streets. In order to determine changes in the level of air pollution within the city it is therefore essential to set up a dense grid of measuring points in different types of urban space. In Ljubljana, measuring points were determined with respect to three predefined types of urban space.

- **Urban background.** For measuring points in the urban background, it is the case that sources do not affect the flow of concentrations directly but rather with a lag. Daily fluctuations in pollutants are significantly lower than along roads, where there are fluctuations in the degree of traffic congestion, and the average concentrations are lower. These points are in areas of residential neighborhoods, parks, gardens and similar places, and are usually more distant from major roads and other sources that would directly affect the path of concentrations. Pollution of these areas is an especially important problem since people spend time in them more frequently and for longer periods, spending their free time there, and such areas are generally regarded by people as more peaceful and less polluted.

(photo: K. Vintar Mally)

Figure 5:

Urban background measuring point on Murgle Pod hrasti

- **Street canyons.** Street canyons are a particular spatial category. They are crowded, densely built up or walled areas, usually in town centers, where arterial roads converge in squares and large parking areas, or lead to a major road that runs through the city center. Traffic is often congested and slow-moving along street canyons. Although they usually have a lower volume of traffic than arterials at the outskirts of the town or ring roads, they are nonetheless quite busy. Since the self-cleaning capacity of the air in street canyons is severely diminished, the concentrations of primary pollutants are greater. Pedestrians are often to be found in the narrow spaces along street canyons, at bus stops or pedestrian areas, and bus and car passengers should also not be overlooked.
- **Measuring points in open space along roads.** We also took measurements along arterial and other roads outside street canyons in order to gain an insight into the air quality and its degree of pollution from nitrogen dioxide along roads where pollutants are not concentrated due to topography but pollution is instead dependent on the volume of traffic and the speed of vehicles along them.

Figure 6:

At the intersection of Linhartova and Vojkova streets, building density is sufficiently low and set back from main roads that pollutants from traffic are quickly diluted. This measuring point is categorized as the type open space along roads.

(photo: K. Vintar Mally)

Measurements of nitrogen dioxide took place in three-week measuring campaigns, in the summer and winter. The first study took place in the 2005/2006 season, from 25 August to 14 September 2005 and from 24 January to 7 February 2006. The second study was conducted in the 2013/2014 season. Summer measurements were taken from 26 August to 16 September 2013 and winter ones from 15 January to 6 February 2014. Measurements were conducted in all the pre-defined types of urban space.

5.2 Estimates of annual pollution from nitrogen dioxide in Ljubljana

We performed an estimate of the annual pollution of the air from nitrogen dioxide for all the measuring points where summer and winter measuring took place, as a synthesis of the summer and winter measuring campaigns. The estimate was based on the calculation of concentrations based on annual concentrations measured by automatic measuring equipment of the Slovenian Environment Agency (ARSO). The estimate of the average annual value relies on periods of 12 consecutive months that include both measuring campaigns. We calculated the estimate based on the following method. For both measuring campaigns we calculated the relationship between the automatic measuring station of ARSO and all the other measuring points where we measured with diffusive samplers. The values of the concentrations from the samplers that were compared were already normalized for the measuring point (this means that the normalized measurement of the sampler at the ARSO measuring point had the same value as the automatic measuring station), and also corrected, meaning that blind values were subtracted. In this way for each measuring point we determined the ratio of concentrations of nitrogen dioxide between the two measuring campaigns with respect to the ARSO measuring point.

The estimate of annual pollution is based on the assumption that the relationship between the ARSO measuring point and the other measuring points is maintained throughout the year. This is not necessarily the case, and we therefore used the summer and winter relationship. It turned out that the relationships are not maintained over the course of the year and significant differences can appear. On the one hand this justifies our assumption that it is necessary to make use of both factors, while on the other hand the fact that summer and winter factors are entirely different also indicates that the estimate of annual pollution is only an estimate, and that deviations are quite possible. Relationships can even differ to the point that they are greater than 1 at one time and less than 1 at another, which does not indicate a stable pattern of pollution, for example, that in some place over the year there is more polluted air than at the ARSO measuring point or vice versa. An additional difficulty in our case was also the fact that the ARSO measuring point was moved.

The common factor was calculated from both factors, taking into account the length of a particular measuring campaign:

$Fi_{cf}=0.5 * Fi_{sum} + 0.5 * Fi_{win}$

in which:

Fi_{cf} is the common factor for the i-th measuring point,

Fi_{sum} is the summer factor for the i-th measuring point,

Fi_{win} is the winter factor for the i-th measuring point.

The estimate of the average annual pollution for each measuring point was calculated as follows:

$Ki_{annual}= Fi_{cf} * K_{ARSO\ annual}$,

in which Ki_{annual} is the annual concentration of nitrogen dioxide for the i-th measuring point and

$K_{ARSO\ annual}$ is the average annual concentration of nitrogen dioxide at the ARSO measuring point.

6. Results of nitrogen dioxide measurements using diffusive samplers in Ljubljana in 2005/2006 and 2013/2014

In the 2005/2006 season we carried out measurements at a total of 69 measuring spots (Table 1 and Figure 7) and in the 2013/2014 season at 110 measuring spots (Table 2 and Figure 8).

Table 1: Measuring spots for nitrogen dioxide in the summer and winter measuring campaigns 2005/2006 in Ljubljana

No.	Measuring spot
1	ARSO
2	Slovenska Street (Figovec) – west
3	Slovenska Street (Figovec) – east
4	Moste: Rojčeva Street
5	Rožna dolina: Rutarjeva Street
6	Vič: Biotechnical Faculty
7	Rudnik: Jurčkova Street
8	Šiška: Andreaševa Street
9	Šiška: Smrekarjeva Street
10	Bežigrad: Ptujska Street
11	Trg OF (Bus station) – south
12	Trg OF (Bus station) – north
13	Celovška Street (Union Brewery – north
14	Celovška Street (Union Brewery) – south
15	Celovška Street (Šiška Cinema) – north
16	Celovška Street (Šiška Cinema) – south
17	Poljanska Street (Peglezen) – north
18	Poljanska Street (Peglezen) – south
19	Dunajska Street underpass – east
20	Dunajska Street underpass – west
21	Northern ring road (Dunajska Street) – north
22	Northern ring road (Dunajska Street) – south
23	Krekov trg (Tunnel below the castle) – east
24	Krekov trg (Tunnel below the castle) – west
25	Slovenska Street (Bavarski dvor) – east

No.	Measuring spot
26	Slovenska Street (Bavarski dvor) – west
27	Slovenska Street (A Banka) – east
28	Slovenska Street (A Banka) – west
29	Slovenska Street (Šestica) – east
30	Slovenska Street (Šestica) – west
31	Slovenska Street (Nama) – east
32	Slovenska Street (Nama) – west
33	Slovenska Street (Kazina) – east
34	Slovenska Street (Kazina) – west
35	Slovenska Street (Congress Square) – west
36	Slovenska Street (Congress Square) – east
37	Slovenska Street (Drama) – west
38	Slovenska Street (Drama) – east
39	Slovenska Street (Faculty of Arts) – west
40	Slovenska Street (Faculty of Arts) – east
41	Šmartinska Street (Kajuhova Street) – north
42	Šmartinska Street (Kajuhova Street) – south
43	Tržaška Street (Tbilisijska Street – Dolgi most) – north
44	Tržaška Street (Tbilisijska Street – Dolgi most) – south
45	Zaloška Street (Hospital) – north
46	Zaloška Street (Hospital) – south
47	Zaloška Street (Fužine) – north
48	Zaloška Street (Fužine) – south
49	Tivoli
50	Gosposvetska Street (Kersnikova Street) – north
51	Gosposvetska Street (Kersnikova Street) – south
52	Gosposvetska Street (Vošnjakova Street) – north
53	Gosposvetska Street (Vošnjakova Street) – south
54	Dalmatinova Street (Metalka) – north
55	Dalmatinova Street (Metalka) – south
56	Dalmatinova Street (Miklošičev Park) – north
57	Dalmatinova Street (Miklošičev Park) – south
58	Dalmatinova Street (Mala Street – Miklošičeva Street) – north
59	Dalmatinova Street (Mala Street – Miklošičeva Street) – south
60	Aškerčeva Street (Faculty of Arts) – north
61	Aškerčeva Street (Faculty of Arts) – south
62	Aškerčeva Street (Snežniška Street) – north
63	Aškerčeva Street (Snežniška Street) – south
64	Aškerčeva Street (Trg MDB) – north
65	Aškerčeva Street (Trg MDB) – south
66	Southern ring road (Barje rest area) – north
67	Southern ring road (Barje rest area) – south
68	Drenikova Street underpass – north
69	Drenikova Street underpass – south

Figure 7: Measuring spots for nitrogen dioxide in the summer and winter measuring campaigns 2005/2006 in Ljubljana

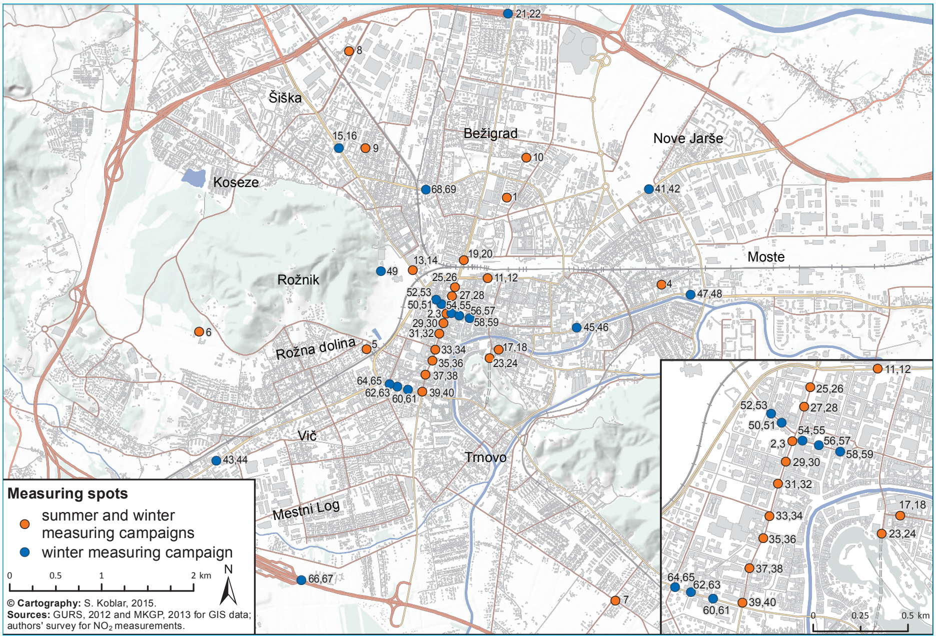


Table 2: Measuring spots for nitrogen dioxide in the summer and winter measuring campaigns 2013/2014 in Ljubljana

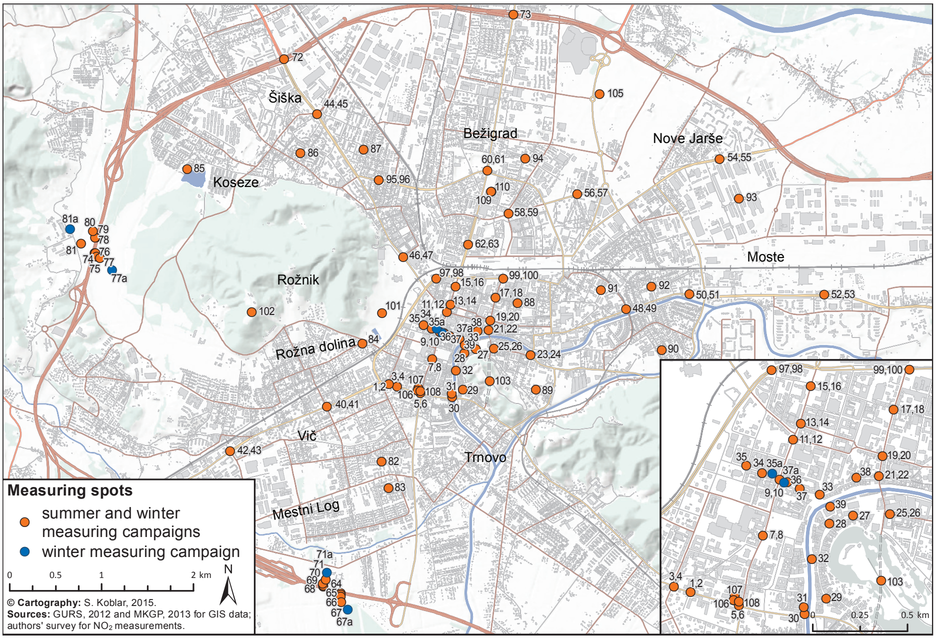
No.	Measuring spot
1	Aškerčeva Street (Snežniška Street) – north
2	Aškerčeva Street (Snežniška Street) – south
3	Aškerčeva Street (Trg MDB) – north
4	Aškerčeva Street (Trg MDB) – south
5	Aškerčeva Street (Faculty of Arts) – south
6	Aškerčeva Street (Faculty of Arts) – north
7	Slovenska Street (Congress Square) – east
8	Slovenska Street (Congress Square) – west
9	Slovenska Street (Nama) – east
10	Slovenska Street (Nama) – west
11	Slovenska Street (Figovec) – east
12	Slovenska Street (Figovec) – west
13	Slovenska Street (A Banka) – east
14	Slovenska Street (A Banka) – west
15	Slovenska Street (Bavarski dvor) – east
16	Slovenska Street (Bavarski dvor) – west
17	Resljeva Street (Slomškova Street) – east
18	Resljeva Street (Slomškova Street) – west
19	Resljeva Street (Komenskega Street) – east
20	Resljeva Street (Komenskega Street) – west

No.	Measuring spot
21	Resljeva Street (Trubarjeva Street) – east
22	Resljeva Street (Trubarjeva Street) – west
23	Poljanski Embankment – east
24	Poljanski Embankment – west
25	Poljanska Street (Peglezen) – north
26	Poljanska Street (Peglezen) – south
27	Ciril-Metodov trg
28	Mestni trg
29	Stari trg
30	Zoisova Street (Breg)
31	Breg
32	Cobblers' Bridge
33	Triple Bridge
34	Cankarjeva Street R1
35	Cankarjeva Street R2
35a	Cankarjeva Street R3
36	Čopova Street R1
37	Čopova Street R2
37a	Čopova Street R3
38	Trubarjeva Street (Prečna Street)
39	Adamič-Lundrovo Embankment
40	Tržaška Street (Jadranska Street) – north
41	Tržaška Street (Jadranska Street) – south
42	Tržaška Street (Tbilisijska Street) – north
43	Tržaška Street (Tbilisijska Street) – south
44	Celovška Street (Slovenija avto) – east
45	Celovška Street (Slovenija avto) – west
46	Celovška Street (Tivoli) – east
47	Celovška Street (Tivoli) – west
48	Zaloška Street (Grablovičeva Street) – north
49	Zaloška Street (Grablovičeva Street) – south
50	Zaloška Street (Ulica bratov Rozmanov) – north
51	Zaloška Street (Ulica bratov Rozmanov) – south
52	Zaloška Street (petrol station) – north
53	Zaloška Street (petrol station) – south
54	Šmartinska Street (BTC petrol station) – north
55	Šmartinska Street (BTC petrol station) – south
56	Linhartova Street (Fabianijeva Street) – north
57	Linhartova Street (Fabianijeva Street) – south
58	Linhartova Street (Vojkova Street) – north
59	Linhartova Street (Vojkova Street) – south
60	Dunajska Street (Stadium) – east
61	Dunajska Street (Stadium) – west
62	Dunajska Street (Exhibition and Convention Center) – east
63	Dunajska Street (Exhibition and Convention Center) – west
64	Barje profile – south 1
65	Barje profile – south 2
66	Barje profile – south 3

No.	Measuring spot
67	Barje profile – south 4
67a	Barje profile – south 5
68	Barje profile – north 1
69	Barje profile – north 2
70	Barje profile – north 3
71	Barje profile – north 4
71a	Barje profile – north 5
72	Celovška Street overpass
73	Dunajska Street overpass
74	Vič profile – east 1
75	Vič profile – east 2
76	Vič profile – east 3
77	Vič profile – east 4
77a	Vič profile – east 5
78	Vič profile – west 1
79	Vič profile – west 2
80	Vič profile – west 3
81	Vič profile – west 4
81a	Vič profile – west 5
82	Kolezija: Koseskega Street
83	Murgle: Pod hrasti
84	Rožna dolina: Rutarjeva Street
85	Koseze Pond
86	Šiška: Tugomerjeva Street
87	Šiška: Smrekarjeva Street
88	Tabor: Slomškova Street
89	Poljane: Zemljemerska Street
90	Kodeljevo: Jan Hus Street
91	Vodmat: Potrčeva Street
92	Moste: Rojčeva Street
93	BTC parking lot
94	Bežigrad: Ptujska Street
95	Drenikova Street (Aljaževa Street) – north
96	Drenikova Street (Aljaževa Street) – south
97	Tivolska Street – north
98	Tivolska Street – south
99	Trg OF (Bus station) – north
100	Trg OF (Bus station) – south
101	Tivoli (Jakopič Promenade)
102	Rožnik
103	Ljubljana Castle
105	Gramozna jama
106	Faculty of Arts, 2nd Floor, Aškerčeva Street
107	Faculty of Arts, top of building, Aškerčeva Street
108	Faculty of Arts atrium, north
109	ARSO 1*
110	ARSO 2*

** Two sets of samplers at the same measuring spot.*

Figure 8: Measuring spots for nitrogen dioxide in the summer and winter measuring campaigns 2013/2014 in Ljubljana



6.1 Measurements of nitrogen dioxide in the urban background

In the 2005/2006 season we carried out measurements at a total of nine different measuring points in the urban background (though only in winter in Tivoli Park) and in the 2013/14 season at 28 measuring points.

Table 3: Concentrations of nitrogen dioxide in the urban background in Ljubljana in summer 2005 (from 25 August to 14 September 2005) and in winter 2006 (from 24 January to 7 February 2006)

Measuring point	**Concentration (μg/m³)**	
	Summer 2005	**Winter 2006**
Tivoli	/	54
Rožna dolina: Rutarjeva Street	30	52
ARSO	21	51
Rudnik: Jurčkova Street	28	43
Vič: Biotehnical Faculty	19	42
Šiška: Smrekarjeva Street	26	33
Moste: Rojčeva Street	32	30
Šiška: Andreaševa Street	31	29
Bežigrad: Ptujska Street	28	28

In the summer measuring campaign in 2005 the average concentration at these points was 27 μg/m³, with a range from 19 μg/m³ at the Biotechnical Faculty to 32 μg/m³ at Rojčeva Street in Moste. Winter concentrations were considerably higher: the average winter measurement at the same eight locations was 39 μg/m³. The highest concentration was measured at the measuring point in Tivoli Park, which was unexpected considering that this is a park area. Very similar concentrations were also measured at the measuring points Rutarjeva Street (Rožna dolina) and ARSO (52 and 51 μg/m³). The range for all the concentrations measured was between 54 and 28 μg/m³, with an average value of 40 μg/m³. The lowest winter values were measured at the measuring points Bežigrad – Ptujska Street (28 μg/m³) and Šiška – Andreaševa Street (29 μg/m³).

Table 4: Concentrations of nitrogen dioxide in the urban background in Ljubljana in summer 2013 (from 26 August to 16 September 2013) and winter 2014 (from 15 January to 6 February 2014)

Measuring point	**Concentration (μg/m³)**	
	Summer 2013	**Winter 2014**
Cankarjeva Street R1	36	48
Breg	27	45
Cankarjeva Street R3	31	43
Cobblers Bridge	24	42
Stari trg	26	41
BTC parking lot	26	40
Bežigrad: Ptujska Street	22	38
Mestni trg	24	38
Tabor: Slomškova Street	29	38
Triple Bridge	25	38
Ciril-Metodov trg	26	37
Trubarjeva Street (Prečna Street)	25	37
Faculty of Arts atrium, north	24	37
Adamič-Lundrovo Embankment	21	36
Šiška: Smrekarjeva Street	25	36
Rožna dolina: Rutarjeva Street	23	35
Vodmat: Potrčeva Street	25	34
Šiška: Tugomerjeva Street	19	34
Moste: Rojčeva Street	24	33
Gramozna jama	22	33
ARSO 1	22	32
ARSO 2	23	32
Tivoli (Jakopič Promenade)	17	32
Kolezija: Koseskega Street	21	31
Poljane: Zemljemerska Street	23	31
Murgle: Pod hrasti	21	29
Ljubljana Castle	19	27
Kodeljevo: Jan Hus Street	19	25
Rožnik	15	24
Koseze Pond	16	23

In the 2013/2014 season the nitrogen dioxide concentrations for the summer measuring campaign measured ranged from 15 to 36 μg/m^3 (Table 4), well below the annual limit value of 40 μg/m^3. The highest concentrations were measured in the urban background of the city center, where they generally reached from 24 to 36 μg/m^3. In this respect, it is interesting that these areas include both those where cars are prohibited as well as areas where they are allowed. Concentrations lower than 24 μg/m^3 were measured in some residential neighborhoods outside the city center or at the edge of the city (Murgle – Pod hrasti Street, Kolezija – Koseskega Street, Bežigrad – Ptujska Street, Šiška – Tugomerjeva Street, Kodeljevo – Jan Hus Street), as well as in Poljane – Zemljemerska Street, which are still within the city center. Among the measuring points with lower levels of pollution were also locations without any houses, such as Rožnik Hill, Tivoli Park, and Ljubljana Castle, which is good news for the many users of these areas.

In the winter measuring campaign of the 2013/2014 season, measurements in the urban background showed considerably higher values, in some places even exceeding the annual limit value for nitrogen dioxide (40 μg/m^3). From a total of 30 measuring points, concentrations reached or exceeded 40 μg/m^3 in six of them, and in 25 of them it reached or exceeded 30 μg/m^3. Nowhere was it lower than 23 μg/m^3. High concentrations in pedestrian areas in the city center arouse concern: they exceed 35 μg/m^3, and at the measuring points in Poljane, Tivoli and Kolezija they exceed 30 μg/m^3. As in the summer measuring campaign of 2013, the lowest concentrations were measured at Koseze Pond, Kodeljevo, Rožnik, and Ljubljana Castle, where the concentrations of nitrogen dioxide were below 30 μg/m^3. The last two measuring points indicate low concentrations in somewhat higher layers of air and the retention of polluted air near the ground.

Table 5: Comparison of nitrogen dioxide concentrations in the urban background in Ljubljana at common measuring points in the 2005/2006 and 2013/2014 seasons.

Measuring point	**Concentration (μg/m^3)**			
	Summer 2005	**Winter 2006**	**Summer 2013**	**Winter 2014**
Bežigrad: Ptujska Street	28	28	22	38
Šiška: Smrekarjeva Street	26	33	25	36
Rožna dolina: Rutarjeva Street	30	52	23	35
Moste: Rojčeva Street	32	30	24	33
ARSO 1	21	51	22	32
Average	27	39	23	35

A comparison of nitrogen dioxide concentrations at the same measuring points was possible in only five cases. Summer concentrations in 2005 were higher on average by 4 μg/m^3, or by 17%, with respect to 2013, with concentrations in all cases with the exception of the ARSO measuring point showing higher values in 2005, though to differing extents, from almost identical concentrations (ARSO 1 and Šiška – Smrekarjeva Street) to noticeable differences at the measuring points Moste – Rojčeva

Street, Bežigrad – Ptujska Street and Rožna dolina – Rutarjeva Street. In winter conditions during the time of measurement the air in 2006 was more polluted with nitrogen dioxide. The difference on average was 4 μg/m^3 or 11%. This difference is mainly a result of much greater pollution during the time of winter measurements in 2006 at the measuring points Rožna dolina – Rutarjeva Street and ARSO. Although the location of the latter was moved in 2014 with respect to 2006 by about 650 m to the area of the Agricultural Institute, we estimate that this did not have a significant influence on the concentrations at this measuring point. At the other measuring points the differences were small or the concentration in 2006 was even noticeably lower, as occurred in Bežigrad on Ptujska Street. In our view the reasons for the generally lower summer and winter concentrations in the 2013/2014 season are to be found in the greater atmospheric dynamics. In the summer of 2013 windiness was somewhat greater than in 2005, and the conditions during the time of the winter measuring campaigns were quite different, with the weather in 2006 being quite wintry with significantly lower temperatures and more frequent temperature inversions. During winter measurements in 2006 the average air temperature in Ljubljana was -3.5 °C, while in 2014 it was 2.6 °C. There was virtually no precipitation in the winter of 2006 (only 0.4 mm), whereas 207 mm of precipitation fell during the period of winter measurements in 2014 and only five of those days were dry. Considering such large differences in the meteorological conditions, the differences in the concentrations measured are relatively small.

Table 6: Estimate of average annual concentrations of nitrogen dioxide in Ljubljana in the urban background from 1 July 2005 to 1 July 2006

Measuring point	**Concentration (μg/m^3)**
Rožna dolina: Rutarjeva Street	34
Moste: Rojčeva Street	31
Rudnik: Jurčkova Street	30
Šiška: Andreaševa Street	30
ARSO	28
Bežigrad: Ptujska Street	27
Šiška: Smrekarjeva Street	27
Vič: Biotehnical Faculty	23

In the 2005/2006 season the average summer concentrations of nitrogen dioxide in the urban background showed a fairly uniform level of pollution, with seven measuring points showing values within 7 μg/m^3 of one another (27–34 μg/m^3). Only the least polluted measuring point of Vič – Biotehnical Faculty had a concentration that was 4 μg/m^3 lower. All the values were within the permissible limit of pollution.

Table 7: Estimate of average annual concentrations of nitrogen dioxide in Ljubljana in the urban background from 1 February 2013 to 1 February 2014

Measuring point	Concentration (μg/m³)
Cankarjeva Street R2*	44
Cankarjeva Street R1*	38
Breg	37
Tabor: Slomškova Street	35
Stari trg	35
BTC parking lot	34
Cobblers' Bridge	34
Faculty of Arts atrium, north	33
Ciril-Metodov trg	33
Triple Bridge	32
Trubarjeva Street (Prečna Street)	32
Mestni trg	32
Šiška: Smrekarjeva Street	31
Bežigrad: Ptujska Street	31
Vodmat: Potrčeva Street	31
Rožna dolina: Rutarjeva Street	30
Moste: Rojčeva Street	30
Adamič-Lundrovo Embankment	29
Gramozna jama	28
Poljane: Zemljemerska Street	28
ARSO	28
Kolezija: Koseskega Street	27
Šiška: Tugomerjeva Street	27
Murgle: Pod hrasti	26
Tivoli (Jakopič Promenade)	25
Ljubljana Castle	24
Kodeljevo: Jan Hus Street	23
Koseze Pond	20
Rožnik	20

**The measuring point from the profile is exceptionally taken into account for comparison for the purpose of the completeness of the analysis since the location meets the criteria of urban background.*

It is also true of the urban background to a certain extent that the estimate of annual air pollution from nitrogen dioxide is dependent on the location, which means that the level of pollution in the urban background is not the same everywhere. Values in the 2013/2014 season ranged from 20 to 44 μg/m³, which results from the internal heterogeneity of this spatial type. The highest concentrations, which are close to or exceed the annual limit value, were measured along Cankarjeva Street between Slovenska Street and Beethovnova Street, where the influence of Slovenska Street can be seen. Relatively high concentrations were also found in the pedestrian area in the center of Ljubljana, where they were from 29 to 37 μg/m³, while in the residential neighborhoods outside the city center they were from 23 to 31 µg/m^3. The exception was only the measuring point on Slomškova Street in the Tabor neighborhood, where the average annual concentration is 35 µg/m^3. The lowest estimates of annual concentrations, from 20 to 25 µg/m^3, are on Rožnik Hill, by Koseze Pond, at Ljubljana Castle, in Tivoli (Jakopič Promenade) and in Kodeljevo on Jan Hus Street. Except for the last measuring point mentioned, which belongs to a residential neighborhood, all the other measuring points are located in parks or at the edge of a settled area, which indicates a noticeable reduction in nitrogen dioxide concentrations in green areas of the urban background as compared to built-up areas.

Table 8: Comparison of the estimate of average annual nitrogen dioxide concentration in Ljubljana in the urban background at common measuring points in the 2005/2006 and 2013/2014 seasons

Measuring point	**Concentration (µg/m^3)**	
	2005/2006 season*	**2013/2014 season***
Bežigrad: Ptujska Street	27	31
Šiška: Smrekarjeva Street	27	31
Rožna dolina: Rutarjeva Street	34	30
Moste: Rojčeva Street	31	30
ARSO 1	28	28
Average	29	30

** The 2005/2006 season refers to the period from 1 July 2005 to 1 July 2006, and the 2013/2014 season refers to the period from 1 February 2013 to 1 February 2014.*

A comparison of the estimate of average annual pollution from nitrogen dioxide at common measuring points in the urban background does not show a significant difference. In the 2005/2006 season the average annual concentration for all measuring points was 29 µg/m^3, and in the 2013/2014 season it was 30 µg/m^3. In the case of the modest number of common measuring points that were included in both measuring campaigns, we thus cannot conclude that there are significant differences in air quality between the two years at the all-year level, even though the summer as well as winter comparison does indicate this to a certain extent. But this was a result of greater weather dynamics during the time of measurement.

6.2 Measurements of nitrogen dioxide in open space along roads

Table 9: Concentrations of nitrogen dioxide in open space along roads in Ljubljana in summer 2005 (from 25 August to 14 September 2005) and winter 2006 (from 24 January to 7 February 2006)

Measuring point	Concentration (µg/m³)	
	Summer 2005	Winter 2006
Celovška Street (Union Brewery)	66	59
Drenikova Street underpass	/	69
Southern ring road (Barje rest area)	/	66
Dalmatinova Street (Metalka)	/	65
Trg OF (Bus station)	59	64
Tržaška Street (Tbilisijska Street – Dolgi Most)	/	64
Northern ring road (Dunajska Street)	/	61
Šmartinska Street (Kajuhova Street)	/	54
Krekov trg (Tunnel below the castle)	57	53
Zaloška Street (Fužine)	/	52
Dalmatinova Street (Mala Street – Miklošičeva Street)	/	50
Zaloška Street (Hospital)	/	50
Dalmatinova Street (Miklošičev Park)	/	47
Dunajska Street underpass*	46	43
Celovška Street (Šiška Cinema)	/	39

**The winter location was at the underpass below the railway, the summer one was at the intersection with Linhartova Street.*

In the 2005 summer measuring campaign we took measurements at four measuring points, and in winter 2006 at 15 points. The highest concentrations of nitrogen dioxide in summer were measured at the measuring point along Celovška Street (66 µg/m³), while the lowest were along Dunajska Street (46 µg/m³). In winter the highest concentration of nitrogen dioxide was measured on Drenikova Street, 69 µg/m³. A comparison of summer and winter concentrations at the same locations shows that summer concentrations on average were somewhat higher (by 2 µg/m³), which is surprising. The difference is not large, but even so we would expect an increase in concentrations in winter. The results (Table 9) confirm predictions that the concentrations along roads without high-density building are lower than those along street canyons despite an equal or greater volume of traffic. Values in both summer and winter in the 2005/2006 season were for the most part above the limit value (40 µg/m³). In the summer measuring campaign the concentration amounted to less than 50 µg/m³ only at Dunajska Street at the intersections with Linhartova Street; in winter it was lower than 50 µg/m³, in addition to this location (moved to the underpass below the railway), also on Dalmatinova Street near Miklošičev Park and at Celovška Street by Šiška Cinema.

Table 10: Concentrations of nitrogen oxide in Ljubljana in open space along roads in summer 2013 (from 26 August to 16 September 2013) and winter 2014 (from 15 January to 6 February 2014)

Measuring point	**Concentration (µg/m³)**	
	Summer 2013	**Winter 2014**
Celovška Street overpass	64	81
Dunajska Street overpass	62	78
Vič 1 profile *	61	69
Barje 1 profile *	61	67
Trg OF (Bus station)	54	67
Dunajska Street (Exhibition and Convention Center)	51	65
Dunajska Street (Stadium)	53	65
Tivolska Street	47	61
Celovška Street (Slovenija avto)	57	61
Tržaška Street (Jadranska Street)	46	57
Tržaška Street (Tbilisijska Street)	48	55
Zaloška Street (Grablovičeva Street)	40	50
Zoisova Street (Breg)	45	48
Drenikova Street (Aljaževa Street)	42	47
Šmartinska cesta (BTC petrol station)	38	46
Linhartova Street (Fabianijeva Street)	33	44
Linhartova Street (Vojkova Street)	32	44
Zaloška Street (Ulica Bratov Rozman)	40	43
Zaloška Street (petrol station)	36	41
Poljanski Embankment	29	38

**The profile measuring point was exceptionally taken into account for the purposes of completeness of the analysis due to its location that meets the criteria for open space along roads.*

We carried out measurements at 21 measuring points in open space along roads in the 2013/2014 season, but since we lack summer data for Celovška Street (Tivoli) we do not cite this point/spot. In the table we take into account the two measuring points in a transverse profile directly along the ring road (i.e. Vič 1 profile and Barje 1 profile). We measured high concentrations in the summer measuring campaign at some measuring points along the arterials Celovška Street and Dunajska Street, where in the case of the points at the former Slovenija avto company, by Plečnik Stadium, and the Exhibition and Convention Center concentrations exceeded 50 µg/m³. From a total of 20 measuring points there were five during the summer measuring campaign that had a concentration of nitrogen dioxide lower than 40 µg/m³, while Tržaška Street, Tivolska Street, Zoisova Street and Drenikova Street were significantly polluted, and the measuring point at Trg Osvobodilne fronte by the main bus station was especially so. Šmartinska Street and Zaloška Street had concentrations lower than 40 µg/m³, and by far the least polluted air in the summer season was found at Poljanski Embankment at the beginning of Rozmanova Street, which may indicate cleaning of the air along the corridor of the Ljubljanica River. In this group of measuring points we selected two so-called hot spots, the measuring points along the arterial above the ring road: one along Celovška Street and the other along Dunajska Street. Both showed the highest concentrations in this group; however, they are still lower than the highest concentration in the street canyon at the Nama department store.

If we compare summer concentrations from 2013 with winter ones from 2014 we see that the winter levels are noticeably higher, on average by 9 µg/m^3. Summer levels were already above the limit value, except in five cases, and the situation in winter is considerably worse. Only one measuring point (by Poljanska Street on Poljanski Embankment at the intersection with Rozmanova Street) had a concentration of nitrogen dioxide that measured below 40 µg/m^3, and only seven others were lower than 50 µg/m^3. Three points had concentrations between 50 and 60 µg/m^3, and the other nine were even higher. Both hot spots, as we call the points on the overpasses above the ring road (Celovška Street overpass and Dunajska Street overpass), understandably showed the highest concentrations. These values in the winter measuring campaign exceeded the annual limit values by close to 100%. The remaining measuring points were along arterials or roads of lower importance along which non-motorized traffic also travels, hence pedestrians and cyclists are also exposed to these levels along with drivers and passengers.

Table 11: Comparison of nitrogen dioxide concentrations in Ljubljana in open space along roads at the only common measuring point in the 2005/2006 and 2013/2014 seasons

Measuring point	**Concentration (µg/m^3)**			
	Summer 2005	**Winter 2006**	**Summer 2013**	**Winter 2014**
Trg OF (Bus station)	59	64	54	67

Only one measuring point was present for all measuring campaigns in both studies. This was the measuring point at Trg Osvobodilne fronte by the main bus station, which shows a similar level of air pollution in both summers and winters, with a concentration of nitrogen dioxide in summer 2013 slightly lower than in summer 2005, and in winter 2014 somewhat higher than in winter 2006.

Table 12: Estimate of the average annual concentration of nitrogen dioxide in Ljubljana in open space along roads from 1 July 2005 to 1 July 2006

Measuring point	**Concentration (µg/m^3)**
Celovška Street (Union Brewery)	62
Trg OF (Bus station)	58
Krekov trg (Tunnel below the castle)	54
Dunajska Street underpass*	44

**The winter location was at the underpass below the railway and the summer location was at the intersection with Linhartova Street.*

The estimate of the average annual concentration of nitrogen dioxide at measuring points in open space along roads from 1 July 2005 to 1 July 2006 shows that the level of concentrations was similar and ranged from 44 µg/m^3 to 62 µg/m^3. The most polluted air among these measuring points was found along Celovška Street by the Union Brewery and the least polluted was along Dunajska Street, where the location of the measurement during the summer measurements and the winter ones was changed by about 300 meters (from the intersection with Linhartova Street to the underpass below the railway). The average level of pollution was 55 µg/m^3, all points exceeded the limit value of 40 µg/m^3 that is in force today, whereas during the time of measurement the limit value was still 48 µg/m^3 and thus the measuring point along Dunajska Street was below the limit value.

Table 13: Estimate of average annual concentration of nitrogen dioxide in Ljubljana in open space along roads from 1 February 2013 to 1 February 2014

Measuring point	Concentration (µg/m^3)
Celovška Street overpass	76
Barje profile – north 1*	76
Dunajska Street overpass	73
Vič profile – west 1*	71
Vič profile – east 1*	68
Barje profile – south 1*	64
Trg OF (Bus station)	64
Celovška Street (Slovenija avto)	63
Dunajska Street (Stadium)	62
Dunajska Street (Exhibition and Convention Center)	61
Tivolska Street	57
Tržaška Street (Jadranska Street)	54
Tržaška Street (Tbilisijska Street)	54
Zoisova Street (Breg)	50
Celovška Street (Tivoli) – west	49
Drenikova Street (Aljaževa Street)	47
Zaloška Street (Grablovičeva Street)	47
Šmartinska Street (BTC petrol station)	45
Zaloška Street (Ulica bratov Rozmanov)	44
Zaloška Street (petrol station)	41
Linhartova Street (Vojkova Street)	40
Linhartova Street (Fabianijeva Street)	40
Poljanski Embankment	35

** The profile measuring point was exceptionally taken into account for the purposes of completeness of the analysis due to its location that meets the criteria for open space along roads.*

The top six places in terms of average annual pollution from nitrogen dioxide in the 2013/2014 season are composed of the two measuring points above the ring road and four measuring points along the ring road. At these locations the estimated average concentration of nitrogen dioxide is from 64 to 76 µg/m³, which is 60 to 90% above the permissible threshold. Of course this is a specific type of urban space or a space along roads, which ordinarily is not intended for any other function and so people do not spend extended periods of time there while walking or cycling along the overpass above Celovška Street or Dunajska Street. An overview of the other measuring points shows that the differences are still relatively large. Along Celovška, Tržaška and Dunajska streets concentrations are quite high and for the most part exceed 50 µg/m³ (from 49 to 64 µg/m³), while along Zaloška and Šmartinska streets, which are also arterials, concentrations are from 41 to 47 µg/m³, which indicates a lower level of pollution but still exceeds the reference value of 40 µg/m³. Along connecting streets the air is quite polluted along Tivolska Street (57 µg/m³), and less polluted, though still too much, along Drenikova Street, while the estimated annual concentrations of nitrogen dioxide along Linhartova Street are right at the boundary of permissible annual values. These values are noticeably lower than those in street canyons but the situation is of concern due to the bike lanes and sidewalks along the arterials. In some cases the infrastructure is removed from the road by about 10 m, which is much better than in the cases where it runs right along the road. In future it would be necessary, from the standpoint of air quality, to locate bicycle infrastructure somewhat more distant from arterials where this is possible, and in the medium term it would make sense to reduce the number of motor vehicles that enter the city and increase the share of public transport, since each fewer car means not only less pollution from road transport for the city but also reduced pressure on parking spaces, less use of space for parking, less noise and greater traffic safety. It is encouraging that cars are being built with more advanced engines with increasingly cleaner combustion and emissions technologies, and electric cars are also on the horizon, which will also contribute to lower emissions of pollutants.

Table 14: Comparison of the estimates of average annual concentrations of nitrogen dioxide in Ljubljana at the only common measuring point in open space along roads in the 2005/2006 and 2013/2014 seasons

Measuring point	Concentration (µg/m³)	
	2005/2006 season*	**2013/2014 season***
Trg OF (Bus station)	58	64

**The 2005/2006 season refers to the period from 1 July 2005 to 1 July 2006 and the 2013/2014 season refers to the period from 1 February 2013 to 1 February 2014.*

Because of the differing locations of measurements in the 2005/2006 and 2013/2014 seasons a comparison of the average annual concentration of nitrogen dioxide is possible only for the measuring point at Trg Osvobodilne fronte at the main bus station. It turns out the concentrations in both seasons were about 60 µg/m³, which is higher than the permissible value. Given that this is the area of the main bus station in Ljubljana, which is also the largest station in Slovenia, and that a heavily traveled city road also runs directly past it, a high concentration of transport pollutants is expected. At the same time, due to the presence of a large number of passengers and users of this space, it is also worrying.

6.3 Measurements of nitrogen dioxide in street canyons

Measuring points in street canyons are those that on average show the highest concentrations of nitrogen dioxide, since the small amount of space that is available means that emissions concentrate there, and the air quality is further worsened by poor ventilation. We performed measurements at ten measuring points in street canyons in the summer measuring campaign of 2005, and added another five new ones to those in the winter measuring campaign in 2006.

Table 15: Concentrations of nitrogen dioxide in Ljubljana in street canyons in summer 2005 (from 25 August to 14 September 2005) and in winter 2006 (from 24 January to 7 February 2006)

Measuring point	**Concentration** (µg/m³)	
	Summer	**Winter**
Poljanska Street (Peglezen)**	80	103
Slovenska Street (Bavarski dvor)	70	87
Slovenska Street (A Banka)	79	85
Slovenska Street (Nama)	83	83
Slovenska Street (Šestica)	64	70
Slovenska Street (Drama)	68	66
Gosposvetska Street (Vošnjakova Street)	/	62
Slovenska Street (Kazina)	65	61
Slovenska Street (Faculty of Arts)	62	61
Gosposvetska Street (Kersnikova Street)	/	60
Slovenska Street (Congress Square)	52	59
Slovenska Street (Figovec)	54	58
Aškerčeva Street (Faculty of Arts)*	/	53
Aškerčeva Street (Trg MDB)	/	53
Aškerčeva Street (Snežniška Street)	/	52

** The measuring point on Aškerčeva Street by the Faculty of Arts in the 2013/2014 season was located 150 m west of the point with the same name in the 2005/2006 season.*

***The measuring point on Poljanska Street in the 2013/2014 season was located 75 m west of the point with the same name in the 2005/2006 season.*

The most polluted air in street canyons was found during the summer measuring campaign in 2005 by the Nama department store (83 µg/m^3) and the least polluted was at Congress Square (52 µg/m^3). It is interesting that despite the considerably lower volume of traffic of Poljanska Street, the concentration of nitrogen dioxide on its most closed portion reached 80 µg/m^3, ranking this measuring point in second place according to level of pollution. The average level of pollution of measuring points in street canyons was 67 µg/m^3, which exceeded the annual limit of permitted levels with acceptable risk for 2006, which was 48 µg/m^3, and also exceeds the currently valid limit value of 40 µg/m^3. In winter measurements the greatest pollution was found at the measuring point on Poljanska Street, which even exceeded 100 μg/m³. In second place was Bavarski dvor, in third place the measuring point by A Banka and in only fourth place was the measuring point by Nama (all on Slovenska Street), where the concentration of nitrogen dioxide was the same as in summer. On average winter concentrations were 5 μg/m³, or 7 percent, higher.

At all measuring points the concentrations detected were too high with respect to the annual limit of 40 μg/m³ currently in force as well as too high for the limit of 48 μg/m³ in force at that time, which is a clear indicator of air quality in these areas during the time of monitoring.

Table 16: Concentrations of nitrogen dioxide in Ljubljana in street canyons in summer 2013 (from 26 August to 16 September 2013) and winter 2014 (from 15 January to 6 February 2014)

Measuring point	**Concentration (μg/m³)**	
	Summer 2013	**Winter 2014**
Slovenska Street (A Banka) – east	60	67
Slovenska Street (Bavarski dvor)	60	65
Slovenska Street (Nama)	72	65
Resljeva Street (Komenskega Street)	56	61
Aškerčeva Street (Faculty of Arts)*	52	59
Aškerčeva Street (Trg MDB)	50	56
Aškerčeva Street (Snežniška Street)	44	56
Slovenska Street (Congress Square)	47	55
Poljanska Street (Peglezen)**	49	51
Slovenska Street (Figovec)	51	50
Resljeva Street (Trubarjeva Street)	38	48
Resljeva Street (Slomškova Street)	39	45
Faculty of Arts, 2nd floor, Aškerčeva Street	42	41
Faculty of Arts, top of building, Aškerčeva Street	38	31

** The measuring point on Aškerčeva Street by the Faculty of Arts in the 2013/2014 season was located 150 m west of the point with the same name in the 2005/2006 season.*

***The measuring point on Poljanska Street in the 2013/2014 season was located 75 m west of the point with the same name in the 2005/2006 season.*

In the summer measuring campaign in 2013, measurements in the street canyon of Slovenska Street showed the highest concentrations, where the markedly highest concentration was at the measuring point by the Ljubljana post office and the Nama department store. Other measuring points in the same canyon also showed high values (A Banka – east, Bavarski dvor, Faculty of Arts, Figovec) – from a total of six points only the measuring point at Congress Square had less than 50 μg/m³, but here it is not a true street canyon since on one side it opens up into a square and park. Otherwise, concentrations in this canyon reached between 51 and 72 μg/m³. It is worth noting that the value at A Banka is composed only of a measurement on the east side of the street since the samplers along with their shelter were stolen on the western side. We can thus see that the concentrations of nitrogen dioxide on Slovenska Street everywhere exceeded the annual limit value, which is a warning sign.

The Aškerčeva street canyon showed somewhat lower concentrations, but still high, about 50 μg/m^3. On Aškerčeva Street we also took measurements at two locations higher than ground level, on the second floor and at the top of the Faculty of Arts building, approximately 11 m and 24 m above the ground on the street side of the building. At a height of 11 m the concentration was 42 μg/m^3, and at a height of 24 m it was 38 μg/m^3, which indicates that within the canyon there is not much dilution of the air, but that with increasing height above the ground the concentration in this instance was gradually reduced. Here we should also mention the measurement on the inner side of the Faculty of Arts building at a height of 11 m in the atrium, which is separated from the street canyon by a large, high building. This measuring point was classified as being in the urban background and the concentration of nitrogen dioxide during the summer measuring campaign was only 24 μg/m^3, which is noticeably lower and justifies the classification of this measuring point in the category mentioned. At the same time, it is a good example of how pollution is substantially reduced even over a short distance if there are large obstacles in between.

In the summer and winter campaign of the 2013/2014 season two of three locations on Resljeva Street in Ljubljana showed the lowest levels of nitrogen dioxide air pollution in this type of urban space and in summer it even dropped a bit below 40 μg/m^3, which ranks it among less polluted street canyons, but in one place (the intersection with Komenskega Street) the air was quite polluted (56 and 61 μg/m^3).

Winter measurements in 2014 in street canyons showed relatively high concentrations, which were never lower than 45 μg/m^3 at ground level. Concentrations were also high in the street canyon of Slovenska Street from Figovec to Aškerčeva Street, which during the time of measurement was closed to passenger car traffic along a large portion (from Figovec to the intersection with Šubičeva Street) and open only to public transport and deliveries. It is necessary to consider that the values in the urban background were noticeably higher in the winter period than in the summer period, which is also reflected in the pollution of air in street canyons. The street canyon of Slovenska Street had concentrations ranging from 67 μg/m^3 at A Banka to 50 μg/m^3 at Figovec. The street canyon of Aškerčeva Street had concentrations of nitrogen dioxide somewhat lower than the highest ones in the street canyon of Slovenska Street, but still from 56 to 59 μg/m^3. In this street canyon we also took measurements at two higher locations, on the building of the Faculty of Arts at a height of 11 m and 26 m above the street. At 11 meters the concentrations had already dropped to 41 μg/m^3 and at 26 meters high to 31 μg/m^3. In the protected atrium on the other side of the building of the Faculty of Arts the concentration at 11 m height was still 37 μg/m^3, which confirms the high values of the background. In the street canyon of Resljeva Street the values measured were from 45 to 61 μg/m^3, which is similar to the street canyon of Aškerčeva Street. Taking into account all the above, pollution of the air from nitrogen dioxide in street canyons during the winter measuring campaign of 2014 was from 45 to 67 μg/m^3 at ground level, and of 12 measuring points at ground level only two had a concentration lower than 50 μg/m^3.

Table 17: Comparison of nitrogen dioxide concentrations in Ljubljana in street canyons at common measuring points in the 2005/2006 and 2013/2014 seasons

Measuring point	Concentrations (µg/m³)			
	Summer 2005	Winter 2006	Summer 2013	Winter 2014
Slovenska Street (A Banka) – east	79	92	60	67
Slovenska Street (Bavarski dvor)	70	87	60	65
Slovenska Street (Nama)	83	83	72	65
Aškerčeva Street* (Faculty of Arts)	/	53	52	59
Aškerčeva Street (Trg MDB)	/	53	50	56
Aškerčeva Street (Snežniška Street)	/	52	44	56
Slovenska Street (Congress Square)	52	59	47	55
Poljanska Street (Peglezen)**	80	103	49	51
Slovenska Street (Figovec)	54	58	51	50
Average***	70	71	57	58

** The measuring point on Aškerčeva Street by the Faculty of Arts in the 2013/2014 season was located 150 m west of the point with the same name in the 2005/2006 season.*

***The measuring point on Poljanska Street in the 2013/2014 season was located 75 m west of the point with the same name in the 2005/2006 season.*

****The average for the categories Summer 2005 and Summer 2013 was calculated based on only the six measuring points that were represented in both measuring campaigns.*

Table 18: Estimate of average annual concentrations of nitrogen dioxide in Ljubljana in street canyons from 1 July 2005 to 1 July 2006

Measuring point	Concentration (µg/m³)
Poljanska Street (Peglezen)	83
Slovenska Street (Nama)	80
Slovenska Street (A Banka)	78
Slovenska Street (Bavarski dvor)	72
Slovenska Street (Drama)	65
Slovenska Street (Kazina)	62
Slovenska Street (Šestica)	63
Slovenska Street (Faculty of Arts)	60
Slovenska Street (Figovec)	53
Slovenska Street (Congress Square)	51

A comparison of the concentrations in the 2005/2006 and 2013/2014 seasons shows a better quality of air for street canyons in the 2013/2014 measuring campaigns. In the summer and winter measuring campaigns of 2013/2014 the average concentration of nitrogen dioxide at the same measuring points was 13 µg/m³ lower than in the 2005/2006 season. In the case of the summer measurements, the concentrations of nitrogen dioxide were lower in 2013 than in 2005 at all measuring points, while in the case of winter measurements the concentrations in the street canyon of Aškerčeva Street in the winter of 2014 were slightly higher. The difference at the measuring point on Poljanska Street is striking: it was the most polluted in the 2005/2006 season and considerably less so in the 2013/2014 season, showing in the summer measurements even less than 50% of the concentration from 2005. But here it must be noted that the location of the measuring point was moved by 75 m, to the intersection with Kopitarjeva Street, where the space is considerably more open and ventilated, thus the measurements are not directly comparable.

Regardless of the expected higher concentrations in winter and somewhat lower concentrations in summer, the finding for the average annual concentration is also important since it represents the average value of pollution that can also be present during the times in between, when the concentrations are between the winter and summer values. In summer many people are on vacation and so there is less traffic, and the air is more unstable due to the strong solar radiation. In winter it is necessary to take into account that traffic emissions are somewhat greater due to greater consumption of fuel since engines take longer to warm up and the air is more stable. As expected, the estimate of the average summer concentration in the street canyons of Slovenska Street and Poljanska Street from 1 July 2005 to 1 July 2006 indicates a very high level of air pollution, well above the limit values of both that in force at the time of measurement (48 $\mu g/m^3$) as well as that in force today (40 $\mu g/m^3$), in which the closed space and hence reduced self-cleaning capacity of the air is more significant than the traffic impact. The pollution of the air at Congress Square shows this well: the level of pollution there is significantly lower than at the measuring point Nama, only 270 m distant, whereas the volume of traffic along this section is similar.

Table 19: Estimate of average annual concentrations of nitrogen dioxide in Ljubljana in street canyons from 1 February 2013 to 1 February 2014

Measuring point	**Concentration ($\mu g/m^3$)**
Slovenska Street (Nama)	74
Slovenska Street (A Banka) – east	67
Slovenska Street (Bavarski dvor)	66
Aškerčeva Street (Faculty of Arts)	58
Aškerčeva Street (Trg MDB)	56
Resljeva Street (Komenskega Street)	56
Slovenska Street (Figovec)	54
Slovenska Street (Congress Square)	54
Poljanska Street (Peglezen)	53
Faculty of Arts, 2nd floor, Aškerčeva Street	52
Resljeva Street (Trubarjeva Street)	51
Resljeva Street (Slomškova Street)	44
Aškerčeva Street (Snežniška Street)	42
Faculty of Arts, top of building, Aškerčeva Street	40

At the annual level from 1 February 2013 to 1 February 2014 concentrations at all measuring points were higher than 40 $\mu g/m^3$, with the exception of the top of the

Faculty of Arts building, where even at a height of about 25 m it still amounted to 40 μg/m^3. The highest concentration was measured at the bus stop by the Nama department store and the main post office. In summer traffic there was still heavy, while from fall onwards passenger car traffic was prohibited but delivery vehicles and public transport were still running.

Table 20: Comparison of the estimates of average annual concentrations of nitrogen dioxide in Ljubljana in street canyons at common measuring points in the 2005/2006 and 2013/2014 seasons

Measuring point	**Concentration (μg/m^3)**	
	2005/2006 season	**2013/2014 season**
Poljanska Street (Peglezen)	83	53
Slovenska Street (Nama)	80	74
Slovenska Street (A Banka) – east	77	67
Slovenska Street (Bavarski dvor)	72	66
Slovenska Street (Figovec)	53	54
Slovenska Street (Congress Square)	51	54

** The 2005/2006 season refers to the period from 1 July 2005 to 1 July 2006, and the 2013/2014 season refers to the period from 1 February 2013 to 1 February 2014.*

The estimate of the average annual concentration for the 2013/2014 season was lower than that for the 2005/2006 season on Poljanska Street and on Slovenska Street at Nama, Bavarski dvor, and A Banka (this measuring point is only about 150 m distant from Bavarski dvor). As already noted, a direct comparison on Poljanska Street is not possible since the measuring point in the 2013/2014 season was moved 75 m relative to that of 2005/2006, to the intersection with Kopitarjeva Street, where the microlocation is considerably better ventilated. The location of measurements in 2005/2006 was in the most closed in part of the street canyon of Poljanska Street, which shows the very high importance of microlocation. On the other hand, the estimate of the average annual concentration at two measuring points of Slovenska Street at Figovec and at Congress Square indicates a similar or somewhat lower concentration of nitrogen dioxide in the first season investigated.

We can conclude that at the annual level the average estimated concentrations of nitrogen dioxide in the 2013/2004 season for all types of measuring points were not significantly different from those in the 2005/2006 season. Although concentrations in the measuring campaigns of the 2013/2014 season were lower, the weather and greater mixing of the air played a major contributing role in this. This is also seen in the calculation of the annual level. Even the partial closure of Slovenska Street to passenger car traffic, which had already come into force during the winter 2014 measuring campaign, did not contribute significantly to an improvement of the situation. Concentrations of nitrogen dioxide were thus still too high in many places along street canyons, which requires further measures for calming traffic in the city center, with an important role as well for the introduction of cleaner technologies in public transport and encouraging commuters in and to Ljubljana to make the greatest possible use of public transport or non-motorized forms of mobility such as biking or walking.

Figure 9: Nitrogen dioxide air pollution in Ljubljana during the summer measuring campaign 2005

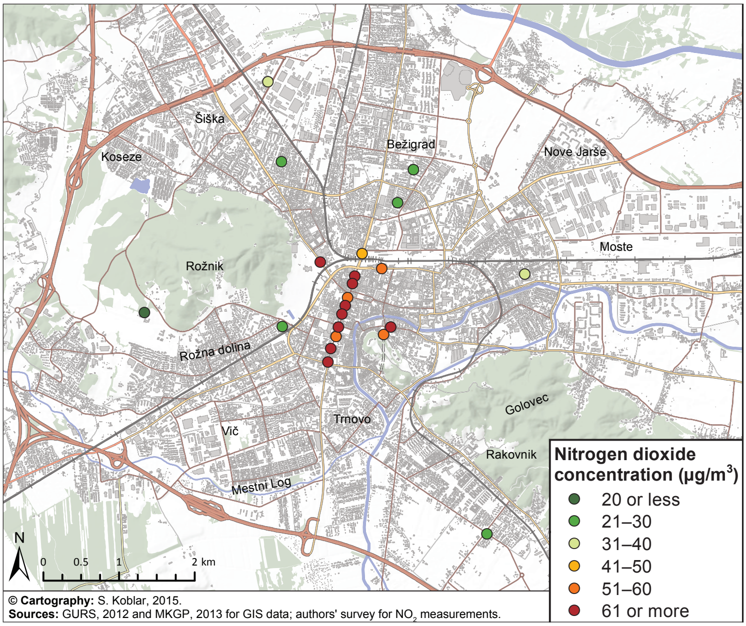


Figure 10: Nitrogen dioxide air pollution in Ljubljana during the summer measuring campaign 2013

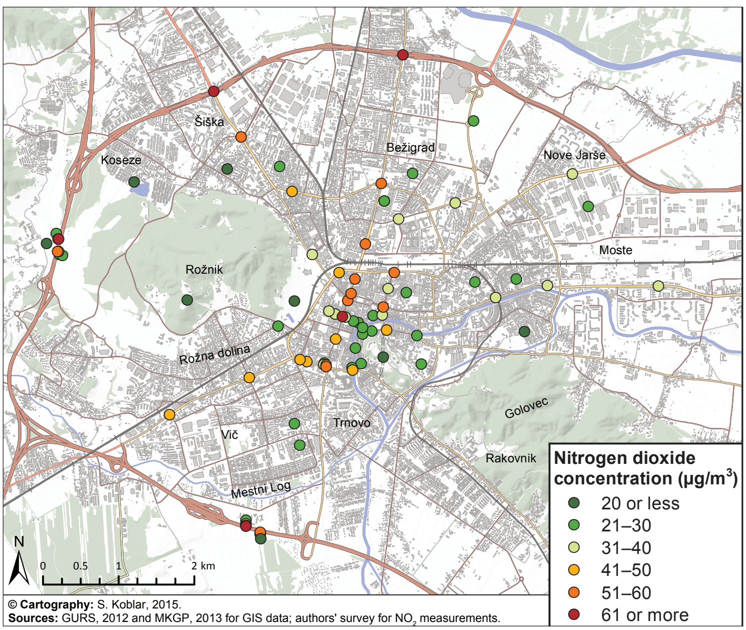


Figure 11: Nitrogen dioxide air pollution in Ljubljana during the winter measuring campaign 2006

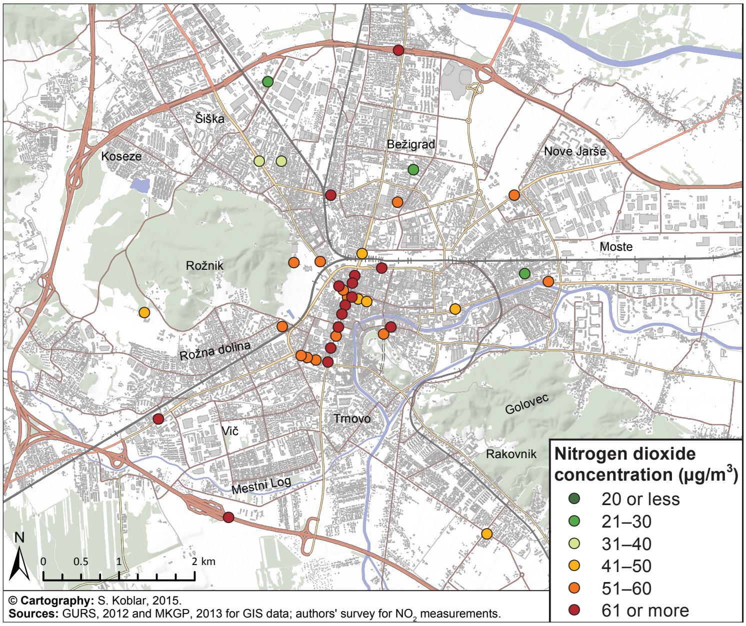


Figure 12: Nitrogen dioxide air pollution in Ljubljana during the winter measuring campaign 2014

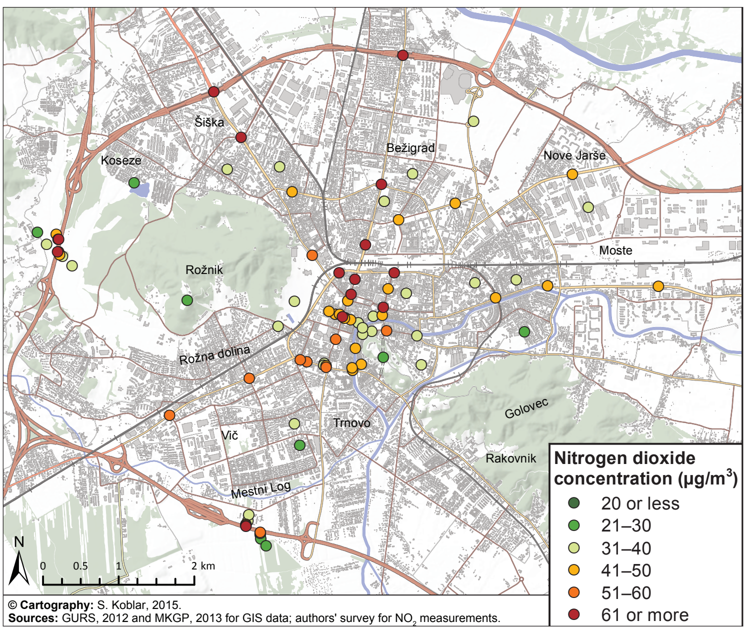


Figure 13: Estimate of average annual concentration of nitrogen dioxide in Ljubljana from 1 July 2005 to 1 July 2006

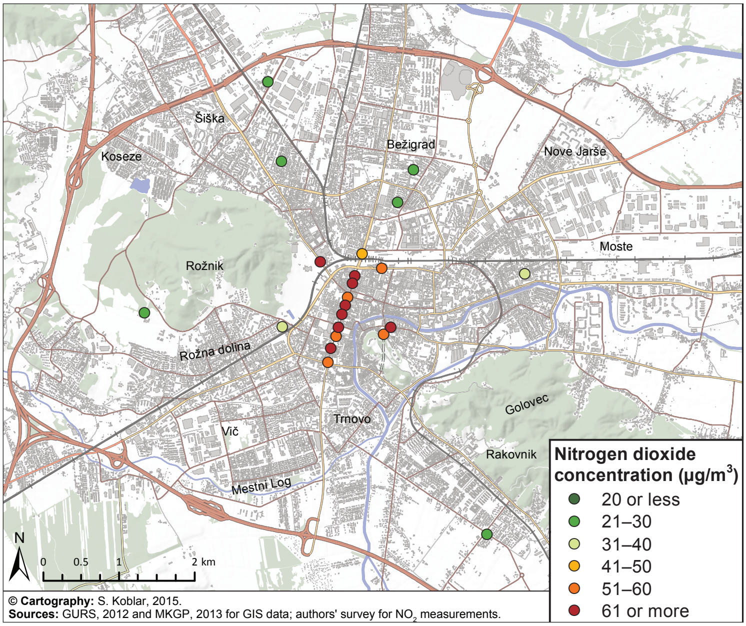
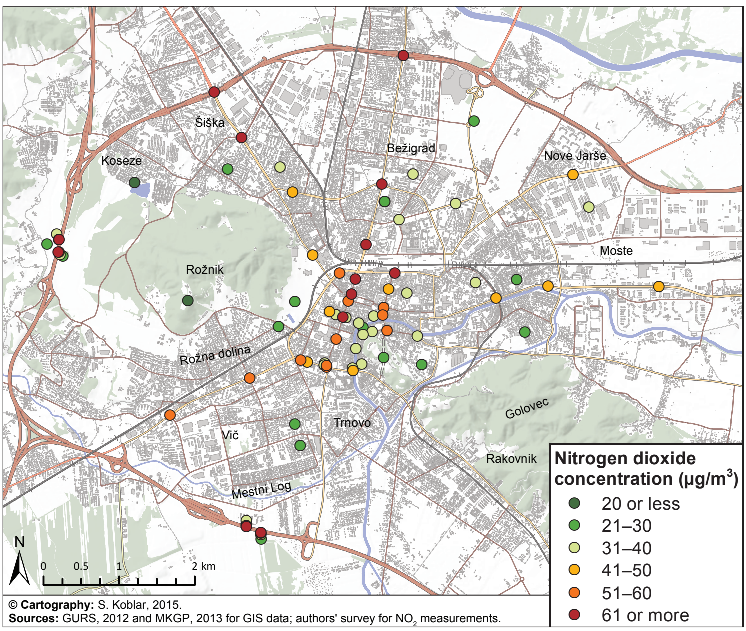


Figure 14: Estimate of average annual concentration of nitrogen dioxide in Ljubljana from 1 February 2013 to 1 February 2014



7. Aerosolized black carbon concentrations and source contributions in Ljubljana between 2012-2015

7.1 Introduction to black carbon and its sources

Aerosolized black carbon (*BC*) is a product of incomplete combustion of carbonaceous fuels, present in the atmosphere in the form of particulate matter with a large optical absorption cross-section across the visible light spectrum (Petzold et al., 2013). Black carbon is a good indicator of primary emissions and it is often used as an indicator for the efficiency of abatement measures, geared toward specific sources, such as traffic (Titos et al., 2015). Black carbon is related to undesirable health outcomes (WHO, 2012) and is the second most important climate forcing agent (Bond et al., 2013). Black carbon can be emitted by local sources, or transported regionally. The determination of sources relies on the different optical properties of carbonaceous aerosols from different sources (Sandradewi et al., 2008a).

Atmospheric conditions play an important role in controlling concentration and time evolution of atmospheric pollutants. Anthropogenic air pollutants are generally emitted from the surface and constrained in the lowest part of the troposphere - the so-called planetary boundary layer (PBL) (Hayden et al., 1997; McGrath-Spangler et al., 2015; Quan et al., 2013). Air pollutants emitted at the surface are diluted in the planetary boundary layer due to turbulent vertical mixing, thus low planetary boundary layer depths result in high concentrations of local pollutants near the surface. Therefore, the information on atmospheric stability is very important for accurate interpretation of air quality data.

Several measurement campaigns have been carried out during the last few years in Ljubljana, Slovenia, in order to evaluate air pollution within the city, the contribution of different emission sources, and source specific heterogeneity of black carbon in the city center as well as in the broader Ljubljana basin. The influence of recent abatement strategies on air quality in the Ljubljana city center was studied, taking into account also meteorological conditions, which partly govern time evolution of all air pollutants.

Black carbon concentration was measured with Aethalometers at different locations in Ljubljana city center and at urban and suburban background sites. Additionally, measurements of particle number size distribution of particles smaller than 1 μm (PM1) were carried out during the summer 2014 campaign. The monitoring network covered the area of the city center, as well as the urban and suburban background, making it possible to distinguish the contributions of regional and local air pollution and sources within the Ljubljana basin.

7.2 Methods

7.2.1 Aethalometer

Continuous measurements of black carbon concentration were conducted using Aethalometers, which were installed at 7 different measurement sites depending on the purpose of each measurement campaign (Table 22).

The Aethalometer samples air with a flow rate of several liters per minute. The sampled air passes through a fiber filter on which aerosols are collected. The light sources above the filter tape illuminate the tape and the sample collected on it and the detectors below the tape measure light attenuation due to the sample deposition. Black carbon concentrations are calculated from light attenuation at the wavelength 880 nm. Attenuation is measured relative to the reference measurement of light transmission through the unloaded part of the same filter where there is no air flow. Attenuation is defined as the logarithm of the ratio of the intensities of light under the reference part of the filter and the part of the filter with the deposited sample.

The gradual accumulation of light absorbing carbonaceous aerosols causes a gradual decline in the optical transmission of light and an increase in attenuation. The flow of air through the filter is measured by a mass flow sensor, which also serves as the measurement needed to stabilize the air pump. The Aethalometer stores data for each sampling period. From measurements of light transmission the Aethalometer determines the corresponding increase in attenuation. This is then converted into black carbon mass concentrations, expressed in nanograms per cubic meter (ng m^{-3}), using the known black carbon mass absorption cross-section. When the filter becomes heavily loaded, so that the light intensity measured under the filter falls below a specified value, the filter tape advances and the measurement recommences on the new part of the tape. At this time, the Aethalometer performs quality control and assurance self-tests.

The Aethalometer AE33 (Magee Scientific / Aerosol d.o.o.) (Drinovec et al., 2015) was used in these campaigns. Aethalometers were set to 5 lpm inlet flow and 1 minute time resolution. Light sources in this type of instrument are light emitting diodes with central wavelengths at 370 nm, 470 nm, 520 nm, 590 nm, 660 nm, 880 nm and 950 nm. Measurements in such a wide spectrum of light enable us to characterize the absorption of aerosols in the range from the ultraviolet to the infrared part of the spectrum.

The Ångström exponent describes the variation of the aerosol absorption coefficient with the wavelength of light. For completely black spherical aerosols the Mie calculation shows that the absorption coefficient b is inversely proportional to the wavelength λ: $b = A / \lambda$. The equation can be generalized to: $b = A / \lambda^{\alpha}$, and the Ångström exponent α for the completely black aerosols is thus 1. Aerosols absorbing more strongly at lower wavelengths feature a higher value of the Angström exponent.

Diesel exhaust is composed of black carbon in a significant part. As long as it is fresh, its Ångström exponent is close to 1 (Schnaiter et al., 2003). Wood smoke contains aerosolized substances that strongly absorb in the blue and ultraviolet (UV) part of the light spectrum and may not absorb in the infrared (IR) parts of the spectrum. The high aerosol absorption at low wavelengths leads to high Ångström exponent values (Sandradewi et al., 2008a). For wood smoke or smoke resulting from the combustion of biomass, we expect an Ångström exponent of around 2 (Favez et al., 2009; Sandradewi et al., 2008a; Sandradewi et al., 2008b).

Because the Ångström exponent is specific to sources, we can use it as a parameter to distinguish between wood smoke and diesel exhaust aerosols. The source apportionment of aerosol black carbon was performed using a model by Sandradewi et al. (2008b), using the wavelength pair 470 and 950 nm.

7.2.2 Scanning mobility particle sizer – SMPS

Continuous particle size distributions in the particle size range up to 1 µm were measured during the summer 2014 campaign at two sites. Two SMPS instruments were installed for this purpose: SMPS+C Series 5.400 with long DMA unit (Grimm Aerosol Technik) at the KIS measurement site (Figure 15) and an SMPS with a DMA (TSI, Model 3080) connected to a water-based Condensation Particle Counter (TSI, Model 3785 UWCPC) at the Brezovica measurement site (site D in Figure 15). The SMPS instrument works on the principle of particle separation on the bases of their electrical mobility, which depends on the particle size and electrical charge: the smaller the particle and the higher its electrical charge, the higher its mobility. Particle separation takes place in a differential mobility analyzer (DMA), from where particles enter the condensation particle counter unit (CPC). In the CPC, particles are firstly enlarged by condensation of butanol or water around them, which enables optical detection with a laser beam. Particle size distribution in the whole range of sizes was measured at subsequent 7 and 5 minute intervals at the KIS and Brezovica sites, respectively. A coaxial diffusion dryer filled with silica gel was used to decrease humidity and remove water droplets. Before ambient measurements, both SMPS instruments were compared in our laboratory.

7.2.3 Meteorological parameters

The meteorological parameters during the measurement campaigns in Ljubljana (sites A, B, C, D) were obtained from the database of the Slovenian Environment Agency (ARSO) for the Bežigrad meteorological station. For measurements at the background Brezovica site meteorological data were provided by the on-site meteorological station operated by the company AMES d.o.o.. Additional data, which were associated with the Barje measurements (sites F1 and F2), were obtained from an environmental measurement system located at the waste disposal site Barje (Snaga d.o.o.).

Data on air temperature (*T*), air pressure (*p*), relative humidity (*RH*), precipitation (h_p), wind speed and direction, as well as intensity of solar radiation (global and diffuse) in 30-minute intervals were combined with black carbon data and processed on a 30-minute time scale.

The planetary boundary layer is the lowest part of the atmosphere, and its behavior is directly influenced by its contact with a planetary surface. The height of the planetary boundary layer depends on the intensity of the processes within the atmosphere, which are mainly governed by solar radiation. Planetary boundary layer height can be lower than 100 m in very stable conditions, while with strong convection it may exceed 3 km. At night and in the cool season (more stable atmosphere) the planetary boundary layer tends to be thinner, while during the day and in the warm season (higher temperature differences and strong convection) it tends be thicker. The structure of the boundary layer alters during the day (Quan et al., 2013).

The Pasquill atmospheric stability classification divides the stability of the planetary boundary layer into seven classes from A (very unstable) to G (very stable), depending on the wind speed, solar radiation and cloud cover (Pasquill, 1961). Table 21 shows meteorological conditions that determine the Pasquill stability class.

Table 21: Meteorological conditions that determine the Pasquill stability class

	Daytime solar radiation			**Nighttime condition**	
Surface wind speed (m s^{-1})	**Strong**	**Moderate**	**Slight**	**Thin overcast or > 4/8 low cloud**	**<= 4/8 cloudiness**
< 2	A	A-B	B	E	F-G
2-3	A-B	B	C	E	F-G
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Archived modeled datasets obtained from the website of the Air Resources Laboratory (NOAA, National Oceanic and Atmospheric Administration) contain information on the stability and thickness of the planetary boundary layer. Archival datasets (GDAS, Global Data assimilation Archive Information System) of meteorological parameters with a spatial resolution of 1° and temporal resolution of 3 hours are available.

Collected data contain the following information:

- PSQ - Pasquill Stability Class (Table 21): A - very unstable, B - moderately unstable, C - slightly unstable, D - neutral, E - slightly stable, F - moderately stable, G - very stable) ,
- Z_i - thickness of the planetary boundary layer,
- the vertical mixing coefficient.

7.3 Measurements of black carbon concentration

7.3.1 Spatial heterogeneity of black carbon concentration

Measurement campaigns for black carbon monitoring lasted for selected periods from winter 2012/13 until summer 2015 (Table 23). Measurement sites, along with their characteristics, are listed in Table 22. Locations were categorized based on the criteria for air quality monitoring as proposed by the European Environment Agency (EEA, 1999), considering type of zone (urban, suburban or rural) and type of site (traffic, industrial or background).

Table 22: List of measurement sites

Site	Short name	Address	Type of measurement site	Description	Instrumentation
A	Vošnjakova	Vošnjakova Street 9	Urban traffic	Environmental measurement system UML	AE33
B	Post Office	Slovenska Street 32	Urban traffic		AE33
C	KIS	Hacquetova Street 17	Urban background	Environmental measurement system ARSO	AE33 SMPS (Grimm)
D	Vojkova	Vojkova Street 1b	Urban traffic	Environmental measurement system ARSO	AE33
E	Brezovica	Na Lazih 30, Brezovica	Suburban background	AMES d.o.o.	AE33 SMPS (TSI)
F1	Barje	Cesta dveh cesarjev	Traffic, highway	Close to the motorway	AE33
F2				150 m away from the motorway	AE33

The locations of the measurement sites are presented in Figure 15. The Slovenian Environment Agency (ARSO) site was chosen as the urban background site, which was located at Vojkova Street (D) or at Hacquetova Street (C) near the Agricultural Institute of Slovenia in different campaigns. Traffic sites were chosen in the city center at Slovenska Street (B) near the Post Office and at the bypass – Vošnjakova Street (A). A low emission zone was introduced in September 2013 at Slovenska Street in order to reduce local air pollution in the city center (Titos et al., 2015). In winter 2014 two additional instruments were installed near the southern ring road of Ljubljana (Barje F1 and F2) in order to study the range of influence of local traffic sources on black carbon concentration. A suburban background location was added in summer 2014 to the west of Ljubljana (Brezovica, E).

Figure 15: Locations of measurement sites; a) overview and b) Ljubljana city center c)

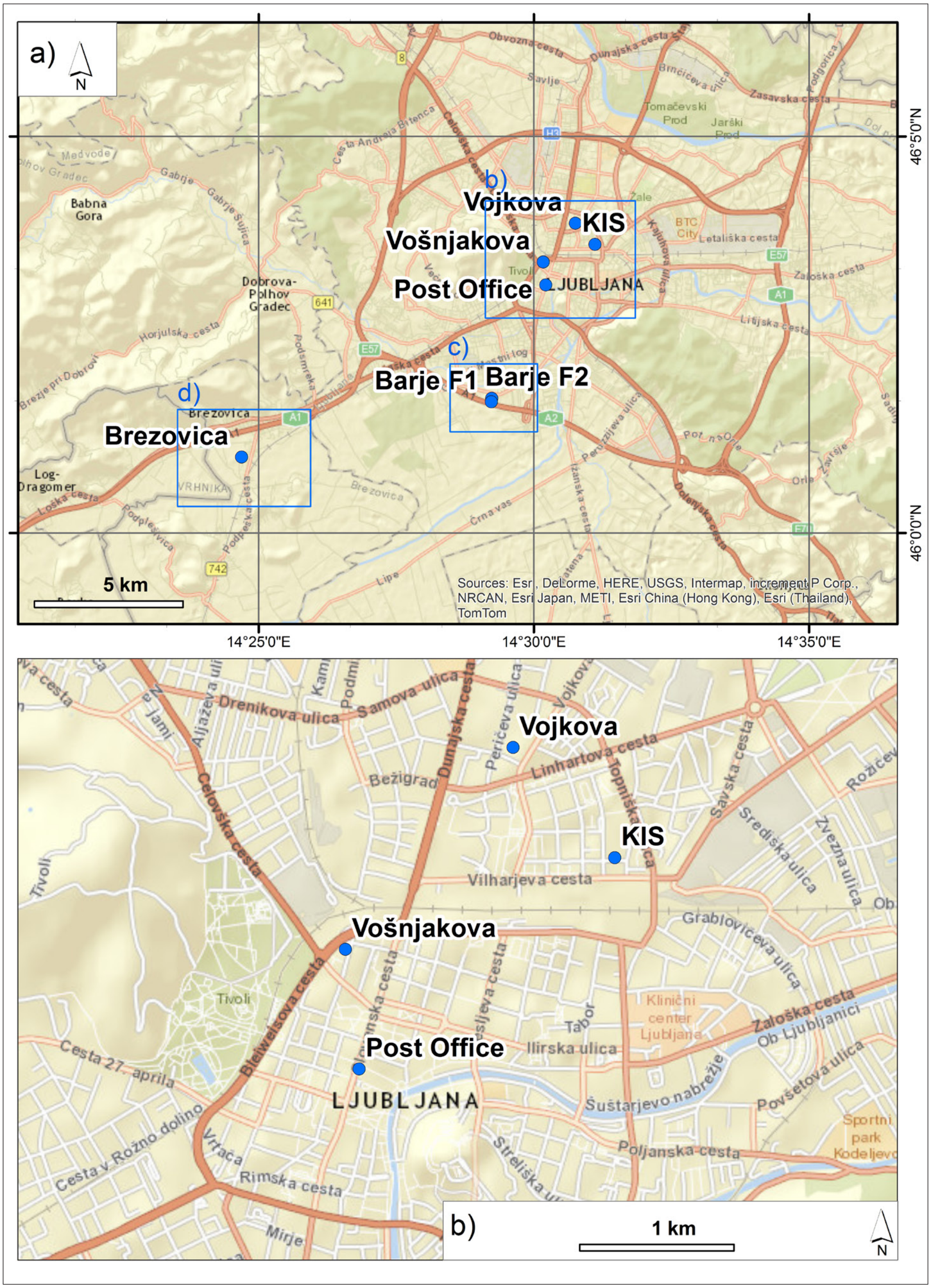
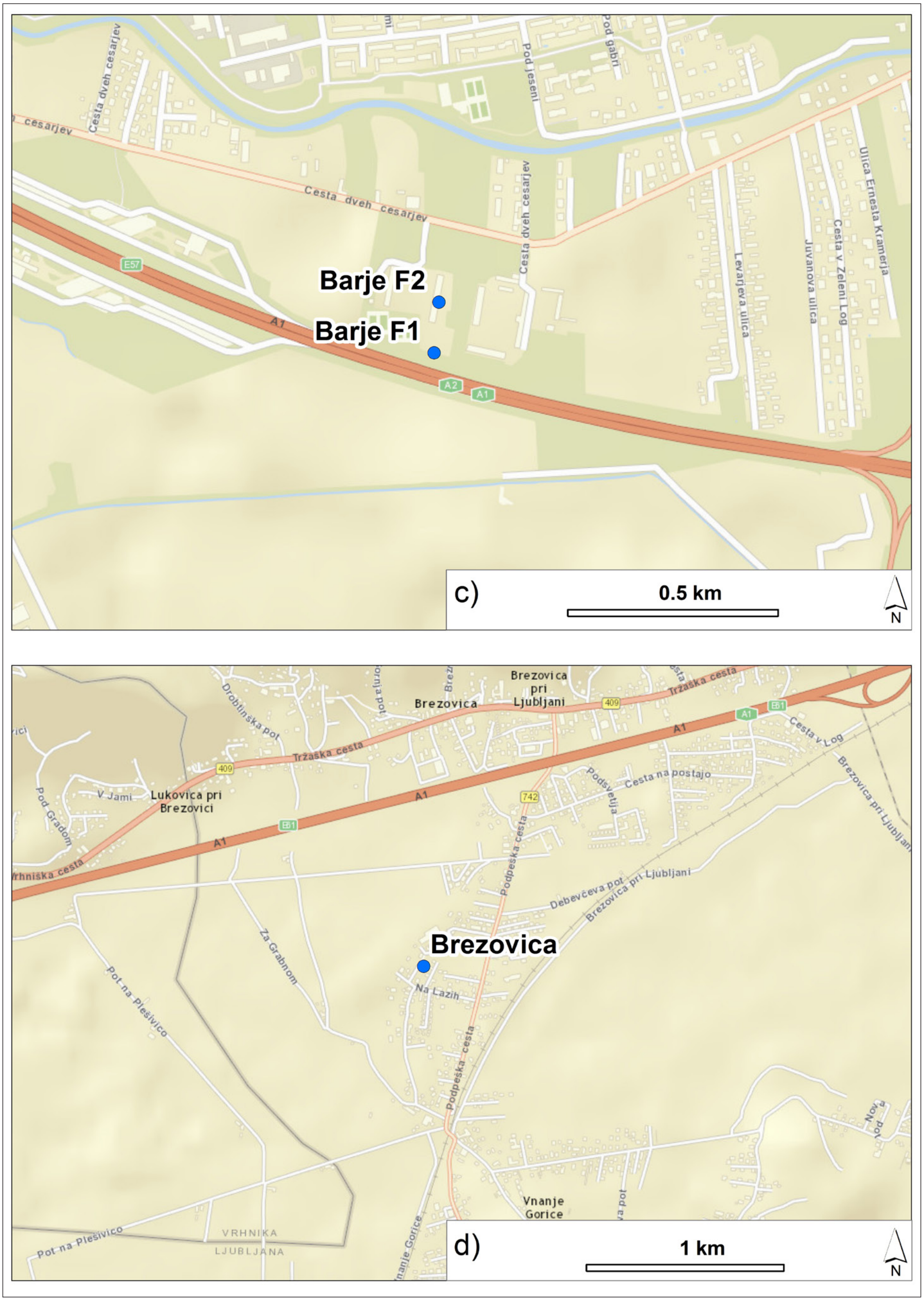
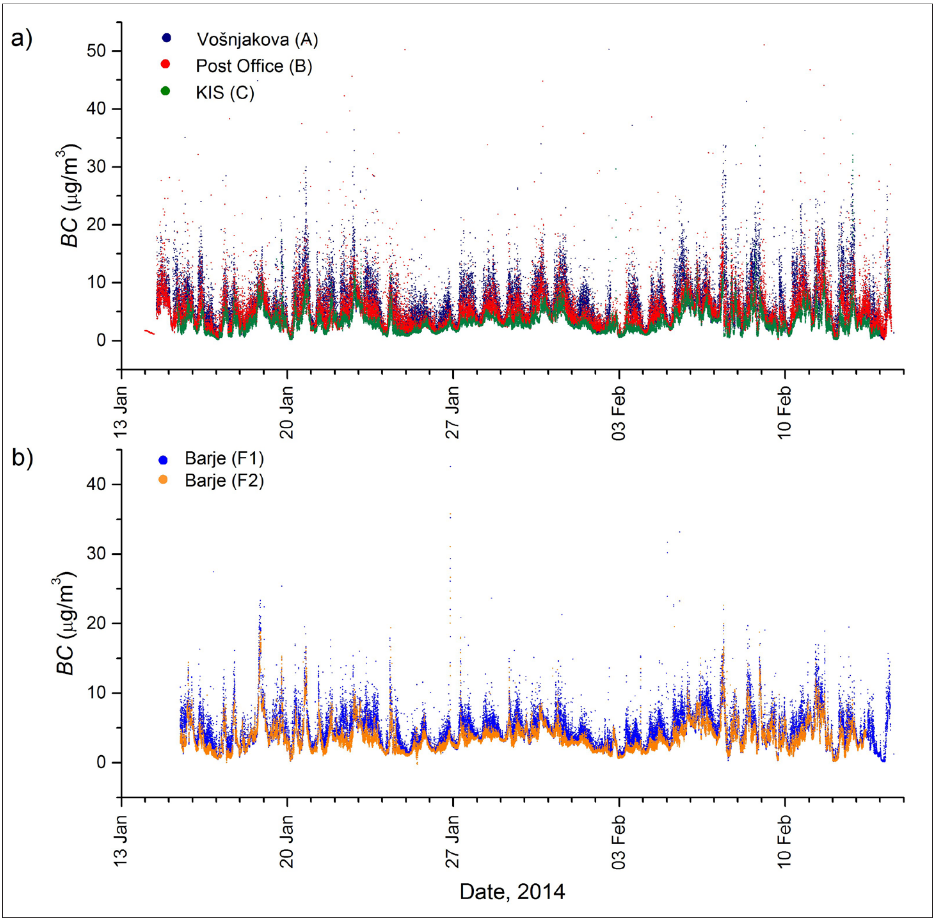


Figure 16: Locations of measurement sites; c) Barje sites near the highway and d) Brezovica



Each of these campaigns resulted in a dataset of black carbon concentration with a one-minute time resolution. The winter 2013/14 campaign is presented in Figure 17. Measurement sites located near busy roads, such as Vošnjakova, Post Office and Barje-F1, are characterized by higher daily black carbon variation due to the proximal traffic source of black carbon, whereas KIS and Barje-F2 represent urban background (Table 24, Figure 17). These data are evaluated to give average black carbon concentration, diurnal plots, black carbon sources, and take into account the meteorology. This analysis allows us to investigate pollution sources and other parameters influencing local air quality.

Figure 17: Time series of black carbon concentration (BC) for the period between 14 January and 15 February 2014 for a) Vošnjakova (A), Post Office (B) and KIS (C) and b) Barje near the highway (F1) and Barje-F2 measurement sites

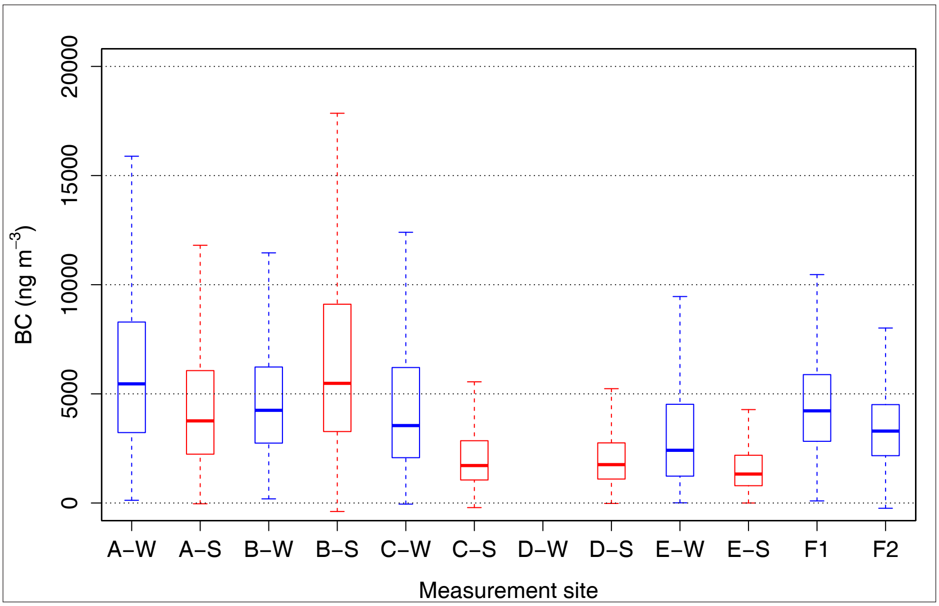


An overview of measured black carbon concentrations at different types of measurement sites is presented in Figure 18 for winter and summer season separately, whereas mean and standard deviation for each measurement campaign are summarized in Table 23.

Significant differences in black carbon concentrations can be observed for different types of measurement sites (Table 23). Urban traffic sites (Vošnjakova, Post Office, Barje F1) show the highest black carbon concentrations caused by local traffic emissions during the whole year, following by urban and suburban background sites (KIS, Vojkova, Brezovica and Barje F2).

Low seasonal variation is observed at urban traffic sites, since they are mostly under the influence of local traffic emissions (Vošnjakova and Post Office sites). Background sites (KIS, Vojkova, Brezovica) on the other hand, are subjected to larger seasonal variations, governed by favorable summer meteorological conditions and, on the other hand, emissions from biomass burning in the winter period.

Figure 18: Summary of black carbon concentrations at each measurement site during summer (S, red) and winter period (W, blue) presented by box plots: median (bold line in the box), first quartile (lowest edge of the box), third quartile (upper edge of the box) and 5% and 95% confidence interval (whiskers). Blue boxes – winter values, red boxes – summer values; (A – Vošnjakova, B – Post Office, C – KIS, D – Vojkova, E – Brezovica, F1, F2 – Barje); B-S – different traffic regime without restrictions in effect during B-W*



The only location showing higher black carbon concentrations in summer than in winter in Figure 18 is location B, near the Post Office in the city center, reflecting the measures introduced by the municipality of Ljubljana in late summer 2013 to reduce air pollution in the Ljubljana city center. Lower winter concentrations at the Post Office were measured in the following winter, after the introduction of the low emission zone at Slovenska Street, where traffic was restricted and only public buses and taxis were allowed to enter this street segment. Since the part of Slovenska Street near the Post Office is a typical street canyon, the highest black carbon concentration of 8.0 ± 6.8 µg m^{-3} was measured there in summer 2013, in the period before the introduction of the low emission zone. After that, black carbon concentration decreased to 5.0 ± 4.4 µg m^{-3}, lower than concentrations measured in the same period at the bypass road at Vošnjakova Street (site A). Considering as a reference black carbon measurements at the background site at Vojkova Street (D), traffic restriction measures resulted in 72% lower local contribution to black carbon concentrations (Drinovec et al., 2013; Titos et al., 2015). At the same time, traffic restrictions in the city center did not influence black carbon concentration at the bypass road (Vošnjakova).

As expected for background sites, the site at KIS (C) shows lowest urban black carbon concentrations, with summer values of 2.1 ± 1.5 µg m^{-3} and winter black carbon concentrations 3.9 ± 3.5 µg m^{-3} and 3.5 ± 2.2 µg m^{-3} for consecutive winters 2012/13 and 2013/14. Even lower black carbon concentrations were observed at the suburban background site (Brezovica, E), where summer concentrations with mean values 1.6 ± 1.1 µg m^{-3} and 1.4 ± 1.1 µg m^{-3} were measured in summer 2014 and summer 2015, respectively. On the other hand, winter concentrations of 3.2 ± 2.5 µg m^{-3} are comparable to black carbon concentrations at the urban background site.

7.3.2 Long-term trends of black carbon concentration are necessary

The whole database of black carbon measurements in Ljubljana can reveal long-term seasonal and yearly trends, which depend on meteorological conditions as well as on anthropogenic influences. We obtained an approximately 10% reduction of black carbon for two consecutive winters at sites Vošnjakova (A) (6.8 ± 5.1 -> 6.2 ± 3.2 µg m^{-3}) and C (3.9 ± 3.5 -> 3.5 ± 2.1 µg m^{-3}) but the difference was not significant. We observed similar nonsignificant decrease in black carbon for two consecutive summers at site Brezovice (E). The main difference was observed at site Post Office (B), where traffic reduction measures resulted in a 38% decrease in measured black carbon (72% decrease in local contribution) (Drinovec et al., 2013; Titos et al., 2015). Because of large daily variations in measured black carbon and the influence of weather, more measurements are needed to determine a statistically significant long-term trend.

7.4 Identification of black carbon sources

7.4.1 Spatial heterogeneity of black carbon sources

Concentrations of aerosol species and gaseous pollutants (NO_x, SO_2, NH_3, CO, ozone) within the planetary boundary layer are controlled by the balance between emission sources of primary aerosols and gases, production of secondary aerosols, chemical reactions of precursor gases under solar radiation and the rate of dilution by mixing within the planetary boundary layer and also with tropospheric air. The balance therefore varies seasonally and daily (with a characteristic diurnal cycle), as well as within the week due to different emission patterns on workdays and weekends. Temporal variation of concentration (and thus its standard deviation) is usually higher at locations with higher concentration due to the proximity and variation of source activity, whereas during the day dilution is governed by air mixing within the planetary

Table 23: Mean and standard deviation of black carbon concentration during measurement campaigns at measurement sites in and around Ljubljana (A – Vošnjakova, B – Post Office, C – KIS, D – Vojkova, E – Brezovica, F1, F2 – Barje).

Measurement period		Urban traffic		Urban background		Suburban back-ground	Highway	
		Vošnjakova (A)	Post Office (B)	KIS (C)	Vojkova (D)	Brezovica (E)	Barje F1	Barje F2
		BC (μg m^{-3})	*BC* (μg m^{-3})	*BC* (μg m^{-3})	*BC* (μg m^{-3})	*BC* (μg m^{-3})	*BC* (μg m^{-3})	*BC* (μg m^{-3})
Winter 2012/13	26 Nov 2012 – 5 Dec 2012	6.8 ± 5.1	/	3.9 ± 3.5	/	/	/	/
Summer 2013[a]	24 Aug 2013 – 21 Sep 2013	4.5 ± 3.6	8.0 ± 6.8	/	2.0 ± 1.3	/	/	/
Summer 2013[b]	21 Sep 2013 – 23 Oct 2013	5.5 ± 3.8	5.0 ± 4.4	/	3.0 ± 2.2	/	/	/
Winter 2013/14	14 Jan 2014 – 14 Feb 2014	6.2 ± 3.8	4.8 ± 3.2	3.5 ± 2.2	/	/	4.6 ± 2.6	3.6 ± 2.1
Summer 2014	6 Aug 2014 – 15 Sep 2014	/	/	2.1 ± 1.5	/	1.6 ± 1.1	/	/
Winter 2014/15	8 Jan 2015 – 28 Feb 2015	/	/	/	/	3.2 ± 2.5	/	/
Summer 2015	1 Jun 2015 – 16 Jun 2015	/	/	/	/	1.4 ± 1.1	/	/

a *before the closure of Slovenska Street around site B*

b *after the closure of Slovenska Street around site B* boundary layer and other meteorological processes (Backman et al., 2012; Sahu et al., 2011; Tiwari et al., 2013).

Measurement of aerosol optical absorption by the Aethalometer enables the determination of the Ångström exponent (α), which describes the dependence of the aerosol absorption coefficient on the wavelength of light (Moosmüller et al., 2011). Because biomass (wood) combustion generates aerosols, which absorb strongly at lower wavelengths, we can use the Ångström exponent as a source specific parameter and it can be used for source apportionment of black carbon. Discrimination of fossil fuel and wood burning emissions was carried out using the two-component model (Sandradewi et al., 2008b). Below we present the source apportionment results of winter 2013/14 campaign data.

Analysis of black carbon concentration generated by traffic (BC_{TR}) shows great variability among the measurement sites (Table 24). KIS (C) and Barje (F2) locations show an urban background value of 2.5 µg m^{-3}. We can see that close to the road the traffic contribution to black carbon is higher due to the local sources – for Vošnjakova (A) as high as 5.2 µg m^{-3}. For the Barje sites we can see that the highway contribution diminishes over 150 meters. This suggests that traffic is a highly heterogeneous source causing big differences in local air quality on a small scale.

Table 24: Averages for the winter 2013/14 campaign. Black carbon concentration – BC, contribution from traffic (BC_{TR}) and contribution from biomass burning (BC_{BB}), as absolute and relative values for measurement sites in and around Ljubljana

Measurement site	BC (µg m^{-3})	BC_{TR} (µg m^{-3})	BC_{BB} (µg m^{-3})	BC_{TR}/BC (%)	BC_{BB}/BC (%)
Vošnjakova (A)	6.2 ± 3.8	5.2 ± 3.7	1.0 ± 0.6	84	16
Post Office (B)	4.8 ± 3.2	3.7 ± 2.8	1.1 ± 0.7	77	23
Barje (F1)	4.6 ± 2.6	3.5 ± 2.2	1.1 ± 0.7	76	24
Barje (F2)	3.6 ± 2.1	2.4 ± 1.6	1.2 ± 0.8	68	32
KIS (C)	3.5 ± 2.2	2.6 ± 1.9	0.9 ± 0.6	73	27

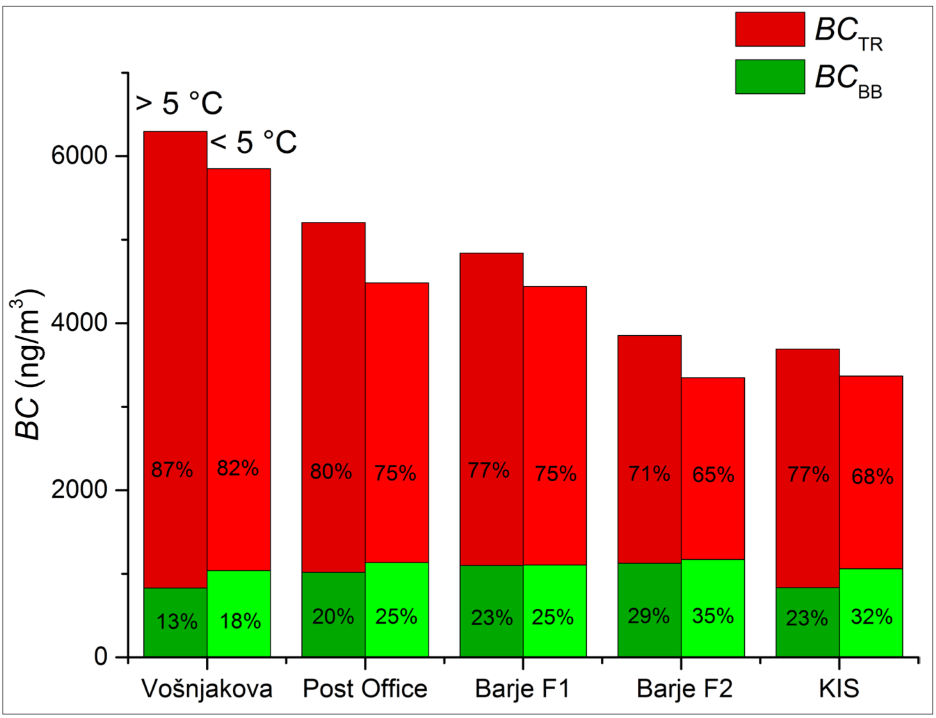
Contribution of biomass burning (BC_{BB}) is spatially distributed more homogeneously across a wider area of Ljubljana and reached around 1 µg m^{-3} during the measurement campaign. Higher contributions to black carbon from biomass burning were measured at the outskirts of the city (up to 32% of the total black carbon concentration), while lower contributions of biomass burning (16 and 23% at Vošnjakova and Post Office, respectively) were found in the city center.

The proportions of the contributions of different black carbon sources in colder ($T < 5$ °C) and warmer periods ($T > 5$ °C) are presented on Figure 19 and summarized in Table 25. As expected, higher contributions to black carbon from biomass burning were observed in colder periods, which can be explained by the higher intensity of domestic heating. However, the total black carbon concentration in colder periods was lower than in warmer periods, since colder periods also include evening and night periods, when there are fewer black carbon emissions. This can be seen also from the arithmetic means for the two contributions: biomass burning concentration increases during the cold periods, while traffic decreases.

Table 25: Black carbon concentration (BC) (arithmetic mean – AM and standard deviation – SD), contribution of biomass burning (BC_{BB}) and contribution from traffic (BC_{TR}) for all measurement sites in the periods with air temperature lower and higher than 5 °C

	T	*BC* (ng m^{-3})		BC_{BB} (ng m^{-3})		BC_{TR} (ng m^{-3})	
		AM	SD	AM	SD	AM	SD
Vošnjakova (A)	>5 °C	6297	3272	830	693	5467	3124
	<5 °C	5851	2897	1038	508	4813	2735
Post Office (B)	>5 °C	5206	2545	1018	788	4188	2151
	<5 °C	4484	2191	1134	547	3350	1923
Barje (F1)	>5 °C	4840	2727	1099	919	3742	2168
	<5 °C	4441	2057	1106	516	3335	1833
Barje (F2)	>5 °C	3853	2548	1126	974	2727	1838
	<5 °C	3348	1617	1171	580	2177	1235
KIS (C)	>5 °C	3692	2277	834	649	2858	1864
	<5 °C	3368	1762	1061	527	2307	1397

Figure 19: Contribution of traffic and biomass burning to the average total black carbon concentration at all measurement sites in the periods with air temperature lower or higher than 5 °C



7.4.2 Temporal heterogeneity of black carbon sources

7.4.2.1 Diurnal profiles of black carbon in summer

Two background sites, KIS (C) and Brezovica (E) were included in the measurement campaign performed in summer 2014 with the aim of evaluating the difference in black carbon concentrations and temporal fluctuations between urban and suburban background location during the summer season. Measurements of particle concentration and size distribution in the size range below 1 µm were included in order to understand black carbon size distribution and its dependence on the type of the environment.

Atmospheric particles originate from different natural and anthropogenic sources. Concentration and size distribution of ambient aerosols are thus a result of the emission of primary particles from biomass burning or combustion of fossil fuels or natural processes, and, on the other hand, formation of secondary particles, which are formed by gas-to-particle conversion due to chemical and physical processes in the atmosphere. Aerosol size distribution changes with time as a consequence of physical and chemical processes in the atmosphere.

Aerosol emission sources' patterns differ during working days compared to their weekend pattern. Therefore mean diurnal number size distributions are presented separately for working days and weekends for suburban background (Brezovica - E, Figure 20) and urban background sites (KIS – C, Figure 21). Lower particle concentrations were observed at the suburban background site with peak particle concentration in the particle diameter range 40 – 110 nm in the morning rush hour (07:00 – 10:00) during the working days and in the late evening, which is consistent also with diurnal variation of black carbon concentration for working days at the Brezovica site (Figure 22). The same morning peak with high particle and black carbon concentration is even more significant at the KIS site, in the particle diameter range of 30 – 100 nm. Concentrations decrease during the day due to dilution in the planetary boundary layer until late afternoon (around 18:00) when aerosol concentration starts to increase again at both sites. At Brezovica site the highest particle concentrations are observed between 20:00 and 23:00, although the peak in black carbon concentration is shifted and reaches the highest values at around midnight. The evening peak is most probably the result of lower planetary boundary layer height and the emission of pollutants into a thinner residual layer and not a direct consequence of higher traffic emissions. Due to a different traffic regime, the morning peak is missing at both sites during the weekend, whereas the second evening peak is still present, which confirms the assumption of the mixing layer driven increase in aerosol concentration in the evening. At the same time, size distribution at KIS site during the evening peak changes from the highest particle concentration in the diameter range from 30 – 100 nm to the highest concentration of particles in the diameter range 100 – 110 nm, which indicates the absence of local sources of primary particles. An evident peak in the weekend morning at Brezovica site is caused by local sources of aerosols, most probably due to open fires (small scale agricultural burning, for example) in the neighborhood.

Figure 20: Averaged particle number size distribution for all working days (a) and weekend days (b) for Brezovica site (E - suburban background site) in August 2014

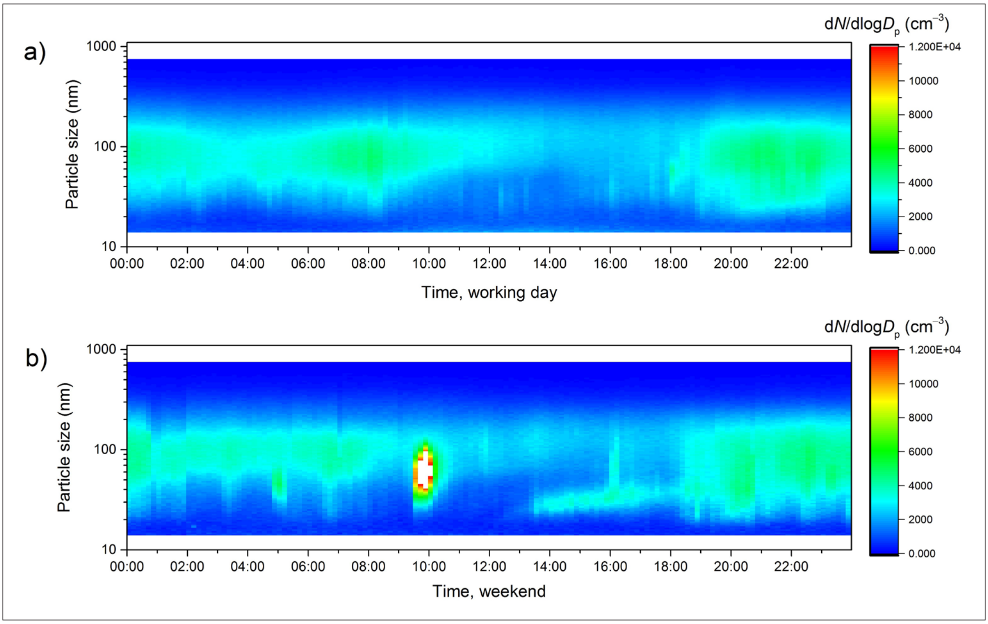


Figure 21: Averaged particle number size distribution of all working days (a) and all weekend days (b) for KIS site (C - urban background site) in August 2014

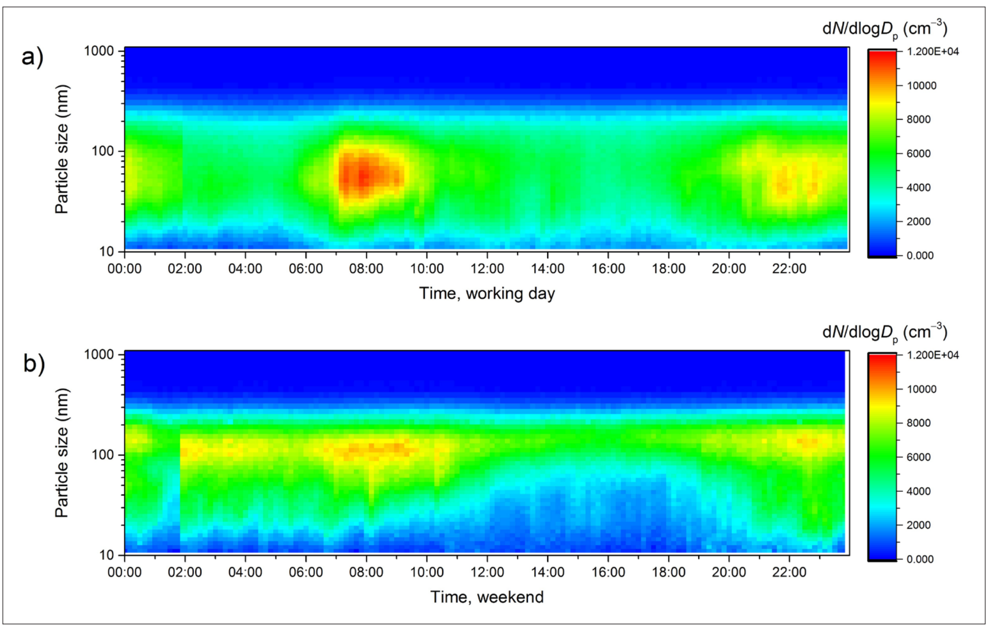


Figure 22: Diurnal variation of black carbon concentration at suburban background site (Brezovica – E) and at urban background site (KIS – C) for working days in summer 2014. Shaded area represents standard deviation

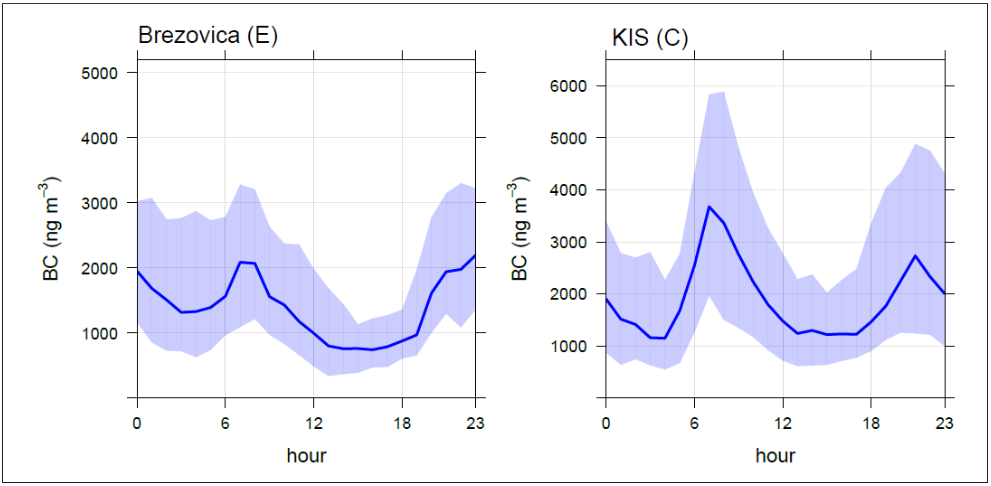
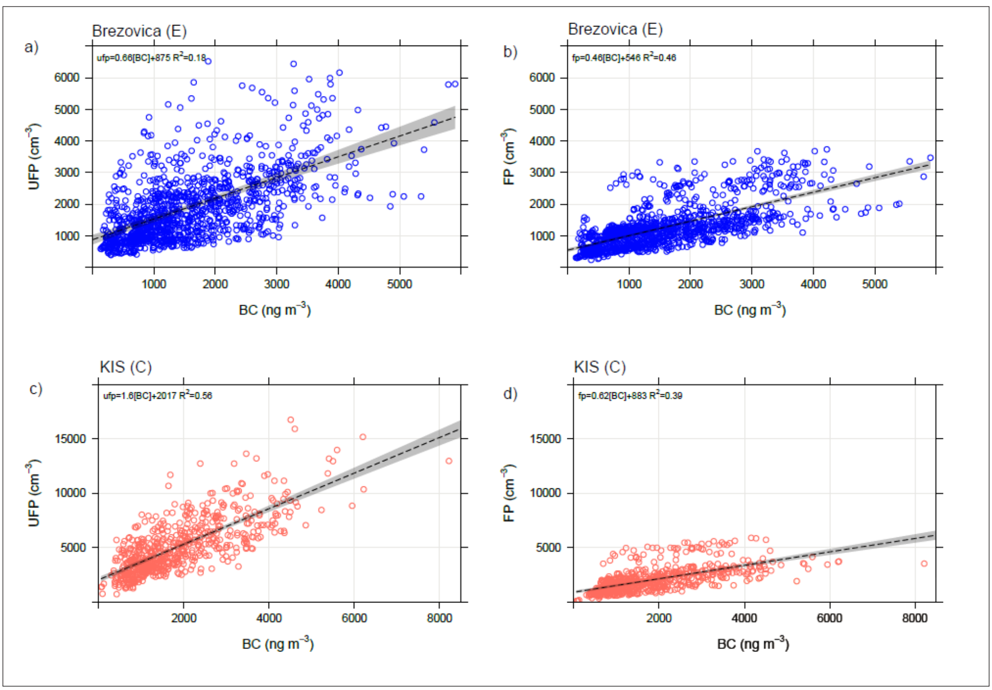


Figure 23: Correlation between black carbon concentration and number of ultrafine (UFP, < 100 nm in diameter) and fine particles (FP, 100 – 700 nm in diameter) for Brezovica suburban background site (a and b) and for KIS urban background site (c and d). Note the different scales.



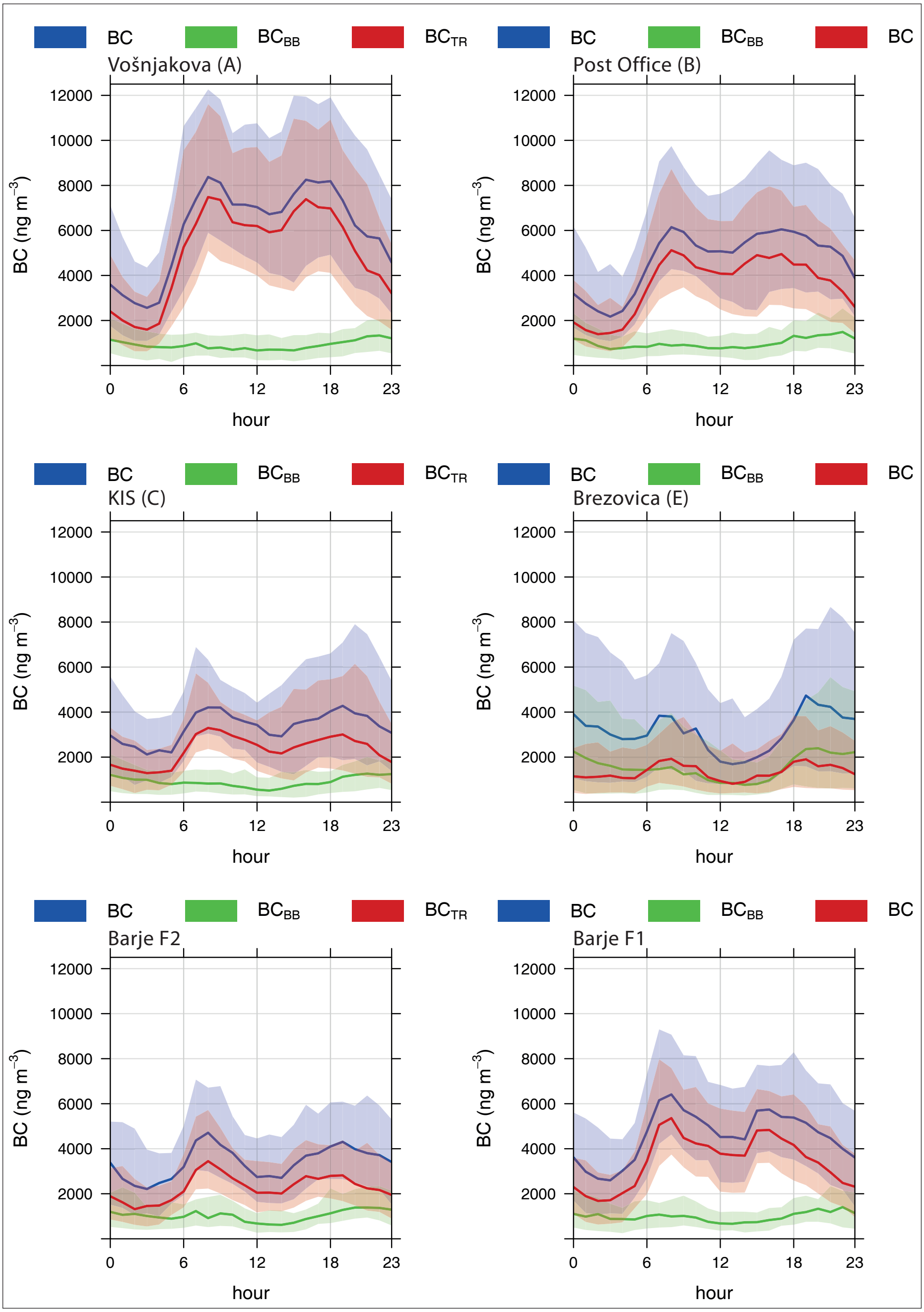
The total number concentration of particles smaller than 100 nm (ultrafine particles – UFP) and concentration of particles in the size range 100 – 700 nm (fine particles – FP) was calculated and compared with mass concentration of black carbon at 30-minute intervals at both background sites. A good correlation was observed between UFP and black carbon at the urban background site (Figure 23c), whereas the correlation of black carbon with FP was weaker (Figure 23d). Just the opposite is true for suburban background (Brezovica), where black carbon correlation with FP is better than correlation with UFP (Figure 23a and b). Since the main source of ultrafine particles are combustion sources, the level of agreement between black carbon and UFP reflects the distance from the emission sources (Zhang et al., 2004). Good correlation of black carbon and UFP at KIS site thus confirms the local contribution of traffic emissions within the city. So-called aging takes place soon after emission by the process of condensation of semi-volatile gases and coagulation with pre-existing particles (Fierce et al., 2015; Johnson et al., 2005), altering the size distribution and composition of aerosols, which is shown also in the better correlation of black carbon and FP at Brezovica site. UFP at Brezovica site are also probably influenced by biogenic sources and the presence of secondary particles, formed through photochemical reactions with precursor gases.

7.4.2.2 Diurnal profiles of black carbon in winter

Diurnal profiles represent average black carbon concentration for each hour of the day (Figure 24). Two peaks can be observed in the diurnal pattern of traffic contribution to black carbon; the first one caused by morning rush hour between 07:00 and 10:00 and the second one in the afternoon, which starts between 15:00 and 16:00 at the site close to the highway (F1) and at18:00 at urban traffic and background sites (A, B, C, F2). The strength of the peaks depends on the local terrain configuration of the site – for example, in the street canyon at the Post Office (site B), the peaks are less distinct than elsewhere. During the day, from 10:00 to 14:00, black carbon concentration decreases due to dilution in the increasing mixing height of the planetary boundary layer.

Analyses of diurnal variation of black carbon concentrations, contribution of traffic emissions (BC_{TR}) and biomass burning (BC_{BB}) (Figure 24) reveals significant differences between measurement sites. The highest impact of black carbon from traffic emissions was observed at roadside locations, at Vošnjakova (A) and near the highway (Barje – F1). These two sites are located very close to the source of emission, which means that much of the variability of total black carbon concentration is caused by the variability of sources, whereas meteorological influences are not so pronounced. Moreover, the diurnal variation pattern at Vošnjakova shows a typical street canyon pattern, with very weak dilution during the day, although this is not evident from the street configuration itself, with Tivoli Park close by and a smallish park located on the northern side of the road. The contribution of traffic to black carbon and its fluctuation decreases proportionally with increasing distance from road traffic. Thus, both urban background sites at KIS (C) and Barje (F2) are characterized by a very similar pattern of black carbon from traffic. Decreasing influence of traffic further from the source on the total black carbon concentration can be observed by comparing measurement sites at Barje (F1 and F2), where we see a substantial decrease of the two prominent traffic peaks in the morning and afternoon at site F2. There is a substantially lower contribution of black carbon

Figure 24: Diurnal variation of black carbon concentration (BC), contribution of biomass burning (BC_BB) and traffic (BC_{TR}) for working days at urban traffic (A, B, F1), urban background (C, F2) and suburban background (E) measurement sites in winter 2013/14 (A, B, C, F1, F2) and winter 2014/15 (E) . The shaded area represents standard deviation



from traffic in the low emission zone at Slovenska Street (B), although a morning peak due to numerous public buses is still evident. Black carbon concentrations from traffic are even lower at the suburban background site at Brezovica (Brezovica, E), with very weak morning and afternoon increases and stable standard deviation through the day. Besides fewer cars that drive close to the measurement site daily, the closest traffic emission source is a highway at a distance of approximately 600 m to the north and several km to the west (Figure 16). The influence of highway traffic seems to be negligible, since prevailing winds are in the easterly and westerly directions.

The contribution of biomass burning at all sites within the city is around 1 μg m^{-3} and has a very low diurnal variation. A slight increase is observed in the morning and evening hours, which is evident especially at the background sites not located centrally in the city (measurement sites at Barje, F1 and F2) and a strong increase in the evening at Brezovica (E) due to the vicinity of the local domestic heating sources. The highest concentration of wood smoke of 1.8 ± 1.8 μg m^{-3} was measured at the suburban background site (E), where during the night, contribution of biomass burning even exceeds black carbon concentrations from traffic. Proximity of local sources of wood smoke causes increased concentration of black carbon apportioned to biomass burning from 18:00 to 06:00, due to domestic heating.

Diurnal variation of black carbon is thus governed mainly by increased emissions either from traffic (urban sites) or from biomass burning (suburban site), and additionally influenced by the daily evolution of the planetary boundary layer and its stability, which will be described in more detail later on.

7.5 The influence of wind on black carbon concentrations

Concentrations of black carbon in the atmosphere and thus air quality are additionally influenced by wind direction, controlling the transport of aerosols. Bivariate polar plots of concentration (Figure 25 and Figure 26) represent the potential location of source contribution from traffic and biomass burning, depending on wind speed and wind direction (Carslaw and Beevers, 2013; Carslaw et al., 2006; Henry et al., 2009).

Contribution from traffic to black carbon concentrations at the traffic site close to the highway (Barje – F1) clearly show speed-direction dependence, with higher black carbon concentrations associated with potential location of source in the direction of the highway (Figure 25). The site Barje (F2) is similar to the nearby site F1, but the dependence is much weaker due to the increased distance from the source, consistent with our previous observation that the site F2 is a background site. No significant pattern can be extracted for the Post Office site, since wind speed dependence of concentrations in a street canyon can be very complex with locally specific and turbulent wind fields. Similarly, a locally turbulent wind field can also mask speed-direction dependence of traffic related black carbon concentrations at Vošnjakova Street, although higher concentrations can be related to weak western winds. The background location KIS (C) is not directly influenced by local traffic emissions and thus more or less shows homogeneous decreasing of black carbon (BC_{TR}) with wind speed.

Figure 25: Dependence of black carbon concentration apportioned to traffic (BC_{TR}, ng m^{-3}, color scale) on the wind speed (ws, m s^{-1}) and direction for all measurement sites

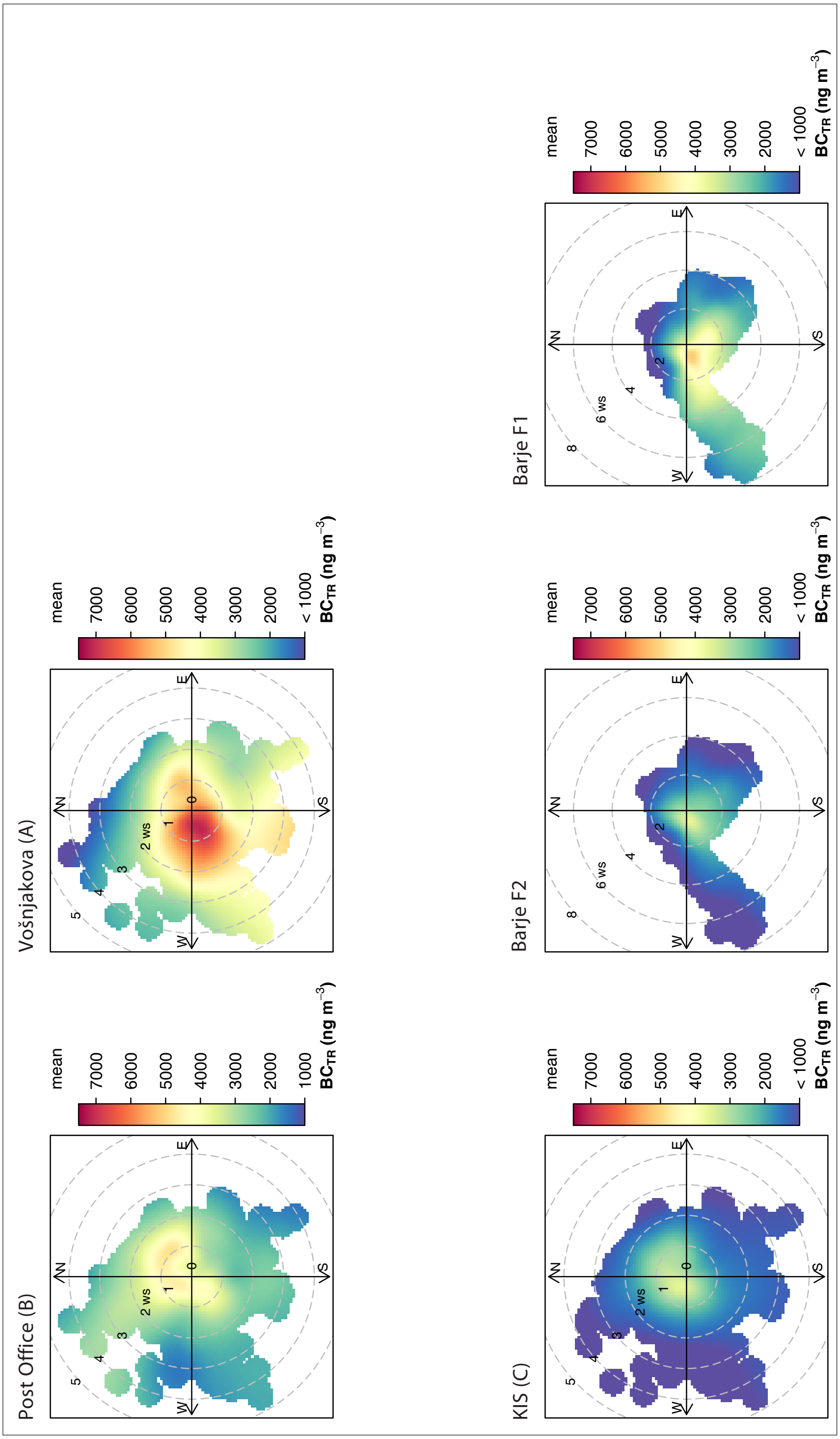
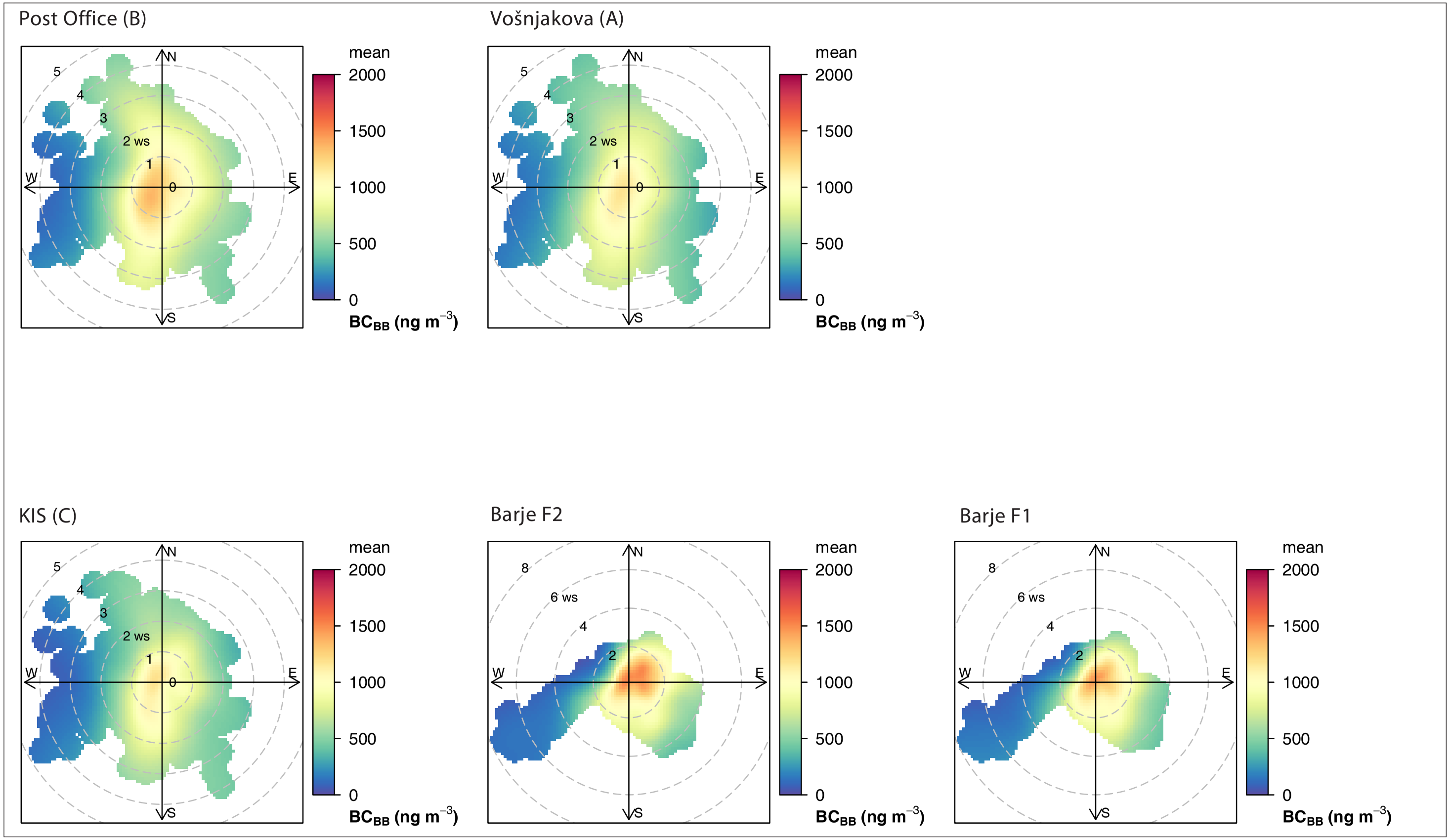


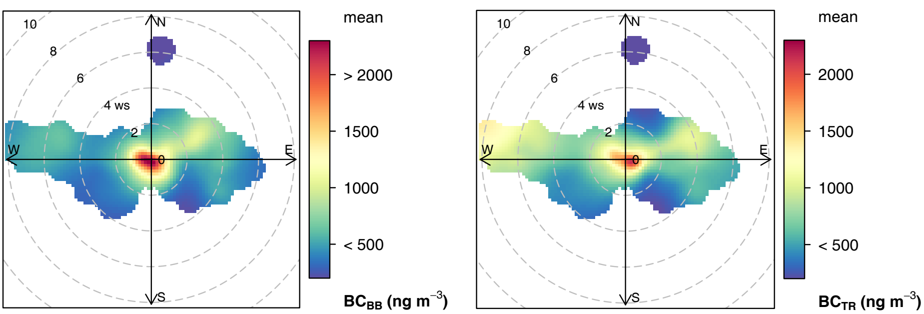
Figure 26: Dependence of black carbon concentration apportioned to biomass burning (BC_{BB}, ng m^{-3}, color scale) on the wind speed (ws, m s^{-1}) and direction for all measurement sites



Contribution of biomass burning, on the other hand, shows similar speed-direction dependence at all measurement sites (Figure 26), indicating homogenous distribution of wood smoke within the Ljubljana city limits, which is observed also in the diurnal variation of black carbon concentration apportioned to biomass burning (Figure 20). Western winds tend to reduce black carbon from biomass burning (BC_{BB}) in Ljubljana, whereas only a slight decrease is caused by southern and northern winds.

Wind speed-direction dependence of black carbon concentrations at Brezovica (Figure 27) shows a very local but symmetric dependence of biomass burning contribution to black carbon on the wind field. The decrease of black carbon (BC_{BB}) concentration with increasing wind speed is clearly observed, which indicates strong local biomass burning sources. This is in agreement with the location of the sampling site in a residential area with single-family houses heated by biomass. The only direction in which wind carries slightly higher concentrations of wood smoke is the NE direction, transporting air masses from the denser residential part of Brezovica. A heterogeneous wind speed-direction dependence of black carbon from traffic can be noticed from the polar plot. The concentration generally decreases with wind speed, but clearly indicates a potential source to the west, which is the direction of the highway, located at a distance of several km to the west. The second potential source of traffic-related black carbon is from the east-northeast, from the location of the train station. This contribution might be related to the introduction of diesel locomotives after the ice storm in January 2014, which caused major damage to the railway system and its electrical infrastructure, preventing the use of electrical locomotives.

Figure 27: Dependence of black carbon from biomass burning (BC_{BB}) and from traffic (BC_{TR}) (ng m^{-3}, color scale) on the wind speed (ws, m s^{-1}) and direction for Brezovica site in winter 2015



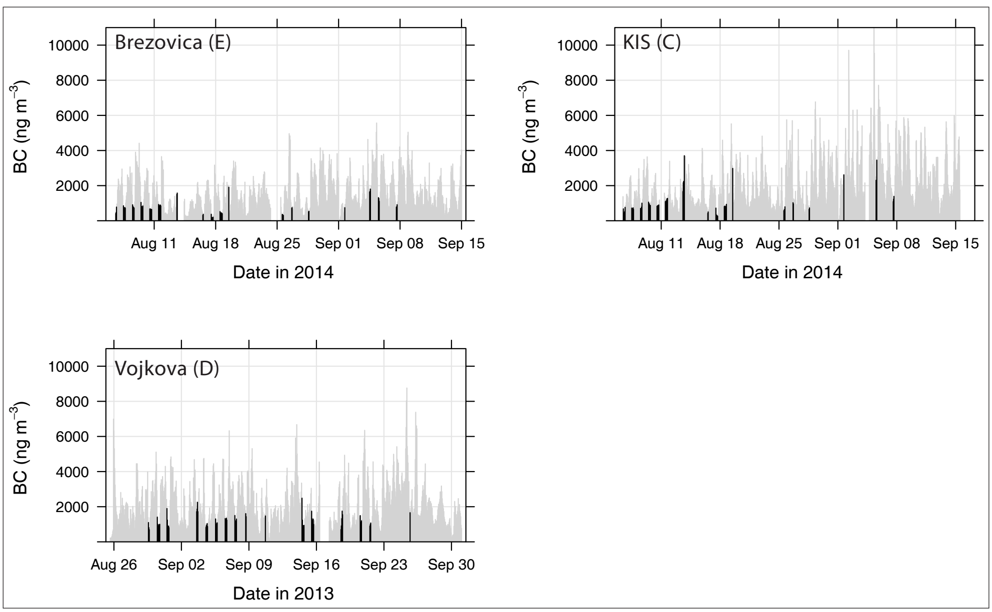
7.6 Regional background contribution

Dynamics and daily evolution of the planetary boundary layer control the uplift of aerosols through vertical mixing and thus in periods of low atmospheric stability provide conditions in which aerosols from the ground sources can be uplifted and under favorable conditions also exported to the free troposphere, where their lifetime can be longer. This process also enables long-range transport and with that, transformation of local to regional air pollution (Donnell et al., 2001). Therefore, surface measurements of black carbon concentrations during the time of a fully mixed planetary boundary layer more or less reflect concentrations in the upper part of the planetary boundary layer as shown by Rosati et al. (2015).

Data from background sites in and around Ljubljana for three summer measurement campaigns were analyzed in order to assess regional black carbon concentrations. Black carbon concentrations in the periods when the planetary boundary layer depth z_i exceeded the height of 1000 m during the least stable atmospheric conditions (Pasquill stability class A or B) are marked with black color in the column plot for Brezovica and KIS measurement sites in summer 2014 and for Vojkova (D) measurement site in summer 2013 (Figure 28). Black carbon concentrations in the range from 0.5 – 2 μg m^{-3} were characteristic for periods of a fully mixed planetary boundary layer in 2014 and were comparable at both sites (KIS and Brezovica). A slightly increasing daily minimum black carbon concentration can be noticed during the first week of measurements in August 2014, when stable sunny weather with intense vertical mixing in the planetary boundary layer prevailed. This indicates low dispersion of aerosols within the planetary boundary layer in the week of stable meteorological conditions. Some of the higher values, exceeding 2 μg m^{-3} at KIS site could be assigned to the local contribution to measured black carbon.

Slightly higher regional black carbon concentrations in the range from 1 – 2 μg m^{-3} were observed in summer 2014 at Vojkova Street. A similar evolution of regional black carbon was noticed, showing day to day increase of minimum daily black carbon in

Figure 28: Black carbon concentrations during atmospheric conditions with intense vertical mixing in the planetary boundary layer (Pasquill stability class A or B and planetary boundary layer depth higher than 1000 m) for a) Brezovica b) KIS and c) Vojkova sites. Gray columns represent the whole time series; black columns show the periods of the least stable conditions in the planetary boundary layer.



the planetary boundary layer from September 4 – 9. These results show that during summer, regional transport represents a substantial source of pollution.

7.7 Influence of meteorology on local air quality

Local air quality is important for estimation of public exposure to particulate air pollution. It depends both on the pollution sources and dilution governed by local weather. Basic parameters describing the atmospheric mixing are wind speed and atmosphere stability.

7.7.1 Influence of wind speed on local air quality

Beside planetary boundary layer height, wind also has an important influence on black carbon concentration in the atmosphere, since it is responsible for transport and dispersion of black carbon, as well as other aerosols. Figure 29 represents the relationship between mean daily wind speed and mean daily black carbon concentration as measured during the winter campaign. The highest linear correlation was observed at the background measurement sites, KIS (C) and Barje F2, while the influence of wind speed diminishes while approaching the source of black carbon at traffic sites (Vošnjakova - A, Post Office - B). On average there is a 22-29% reduction of black carbon per 1 m/s of wind speed in Ljubljana.

7.7.2 Influence of atmosphere stability on local air quality

Structure of the planetary boundary layer depth evolves throughout the day due to the energy received by solar radiation. Generally the planetary boundary layer is more stable during the night and on cloudy days and less stable on clear sunny days due to vertical convective winds. Higher planetary boundary layer depth causes a decrease of aerosol concentrations due to dispersion (Quan et al., 2013), which can be observed in Figure 30, by comparing the temporal variation of minimum daily black carbon concentrations and planetary boundary layer depth (z_i). During the measurement period, black carbon concentrations were generally lower during days with larger planetary boundary layer depth than during days with smaller depth. A longer period of temperature inversion and stable atmospheric conditions that lasted from 27 January to 6 February 6 was characterized by increased black carbon concentrations at the beginning of this period, followed by decrease of black carbon due to the additional influence of wind and precipitation (February 2 – 4).

In particular, better mixing of the planetary boundary layer during sunny days, with the height of the planetary boundary layer being greater, is responsible for diluting black carbon concentration during the day. The same is also true for windy days. The influence of meteorological processes is weaker in the city center than in the background areas. Spatial homogeneity of the sources of biomass burning causes significantly lower fluctuation of black carbon from biomass burning than black carbon from traffic during the day.

Figure 29: Dependence of black carbon concentration on wind speed (daily average values). Linear regression is calculated after exclusion of days with precipitation (30 Jan – 4 Feb 2014); k represents the slope of the line of linear regression (reduction of black carbon per 1 m/s of wind speed).

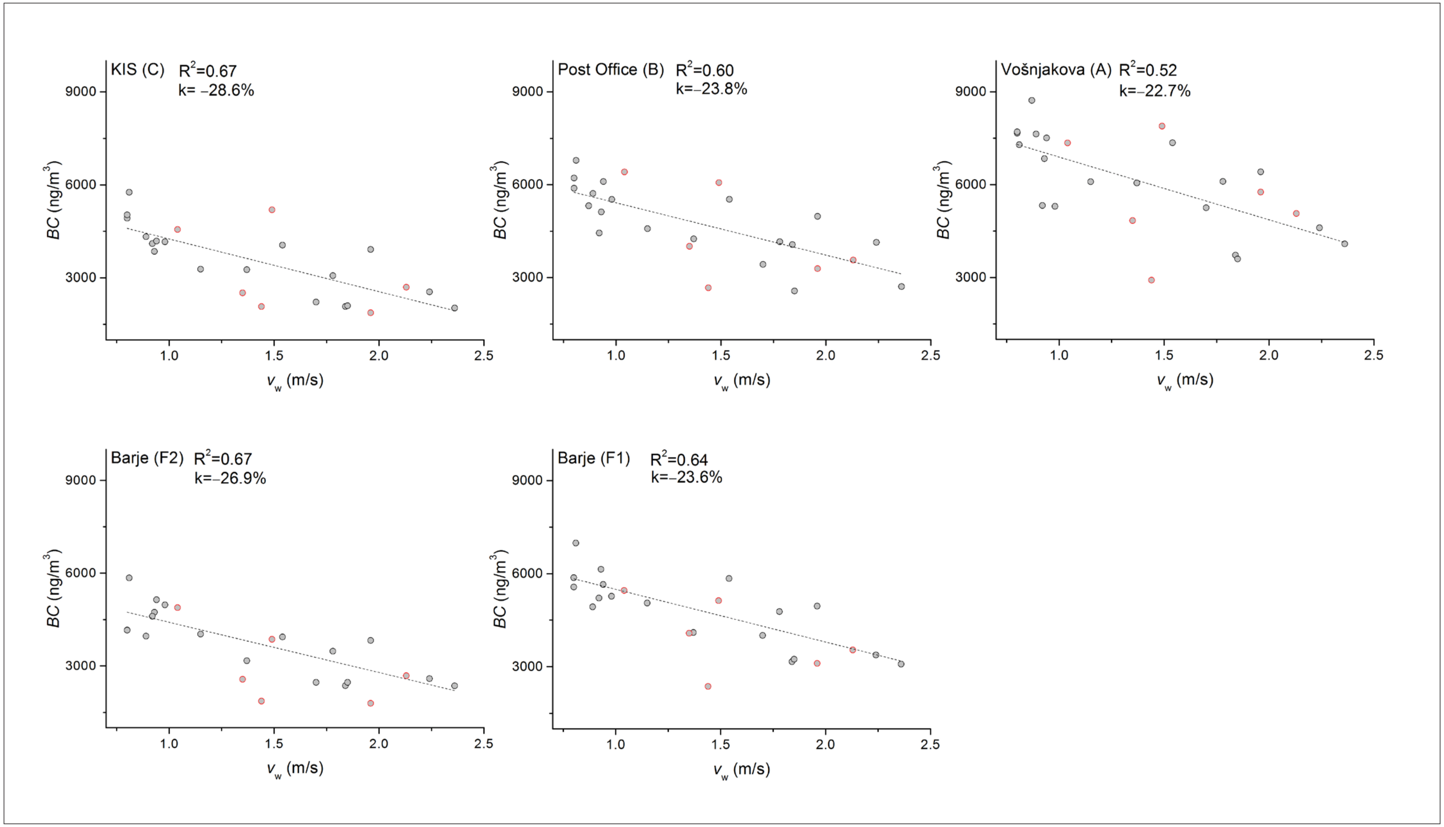
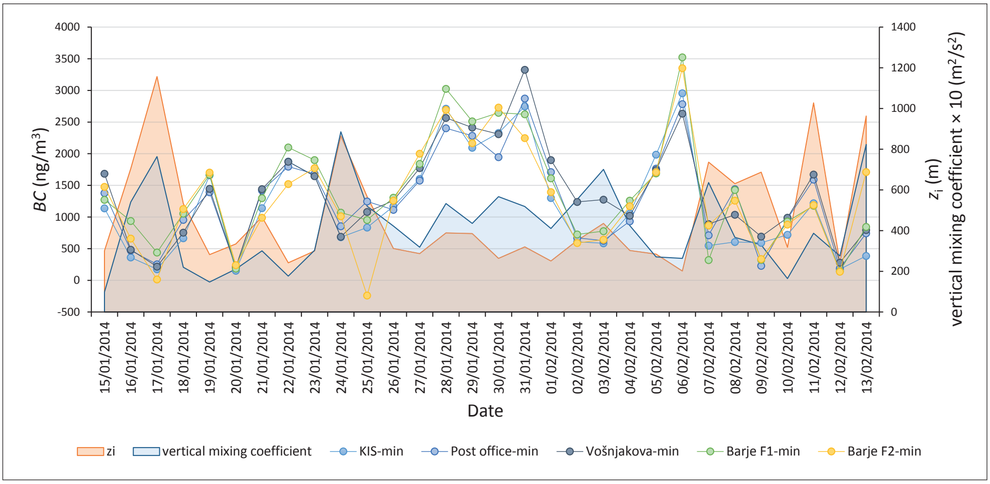


Figure 30: Temporal variation of minimum daily black carbon concentrations at all measurement sites, average planetary boundary layer depth (z_i) and vertical mixing coefficient

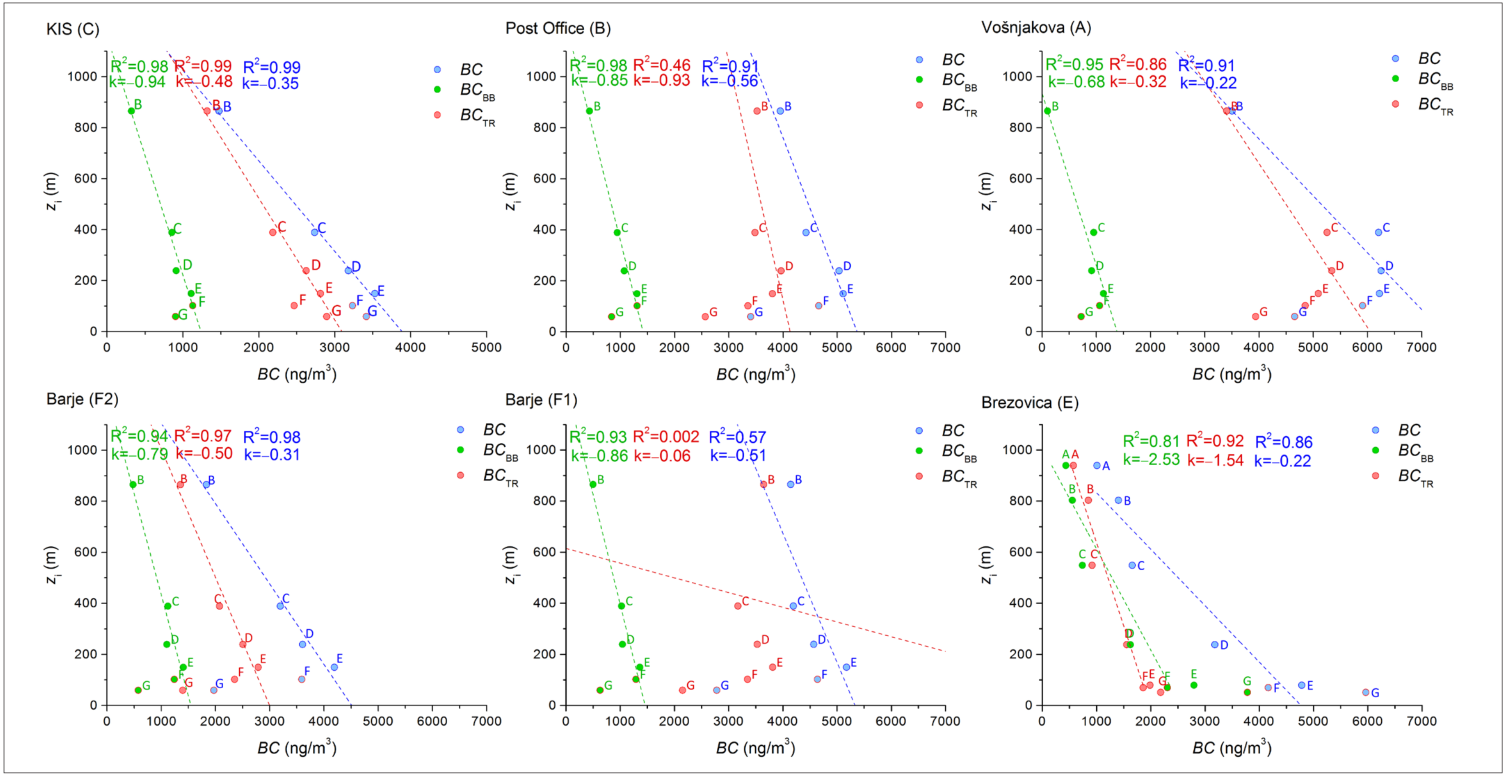


During the night the planetary boundary layer stabilizes and mixing of the boundary layer decreases. Contributions of traffic decrease, since the intensity of traffic decreases during the night. In contrast, sources of biomass burning emissions increase during late evening, with the effect emphasized by stable atmospheric conditions. This effect can be clearly observed at the background site Barje F2, where the biomass burning contribution can exceed 50% of the total black carbon concentration (Figure 24).

The mean height of the planetary boundary layer (z_i), mean black carbon concentration, as well as the contribution of traffic (BC_{TR}) and biomass burning (BC_{BB}) concentrations were calculated for each stability class PSQ in order to examine the influence of planetary boundary layer height and atmosphere mixing on black carbon from different sources (Figure 31). A falling linear relationship was observed between black carbon concentration and planetary boundary layer height. The highest agreement was observed at KIS measurement site - an urban background location that is not exposed directly to sources of black carbon. The weakest agreement is typical for measurement sites that are directly exposed to local sources of black carbon from traffic. Points representing mean black carbon concentrations in the F and G stability classes, which are used for night conditions (Table 21), do not follow the same pattern. Due to higher stability and lower planetary boundary layer height, higher black carbon values could be expected. However, this is not true, since the sources of black carbon are weaker during the night, in particular emissions from traffic, due to lower traffic density. Therefore, classes F and G were not considered in linear regression analyses.

The contribution of biomass burning (BC_{BB}) correlates very well with planetary boundary layer height at all measurement sites, suggesting a source of black carbon influenced by meteorological conditions at all sites. A similar slope of linear regression within the city of Ljubljana suggests a homogeneous spatial distribution

Figure 31: Correlation between average black carbon, biomass burning (BC_{BB}) and traffic (BC_{TR}) contributions within different stability classes PSQ (A, B, C, D, E, F, G) and average planetary boundary layer depth (z_i) for all measurement sites. Classes F and G were excluded from linear correlation



of black carbon from biomass burning and a homogeneous distribution of sources with equal mixing properties within the planetary boundary layer. In contrast, contribution of traffic (BC_{TR}) generally merely expresses weak correlation with the height of the planetary boundary layer, with the degree of correlation and slope of linear regression depending on the distance from the source. Higher slope indicates a more distant source of black carbon, with already diluted aerosol concentration. The weakest correlation was observed at measurement sites located adjacent to the road (Post Office, Vošnjakova, Barje F1), while the correlation increases with increasing distance from local traffic emissions (KIS, Barje F2).

At Brezovica site (E) the calculated linear regression was the highest for black carbon apportioned to traffic, which is in agreement with summer measurements, where the influence of local sources from traffic was found to be negligible. A very steep regression line also indicates a high degree of dilution due to a distant source of black carbon from traffic.

On the other hand, a potential weaker agreement between biomass burning contribution to black carbon and atmospheric stability indicates the proximity of local emissions. Local sources of biomass burning and their specific diurnal pattern are responsible for an exponential decrease of black carbon from biomass burning with increasing z_i. The highest mixing in the planetary boundary layer is typical for midday. At the same time, contribution of biomass burning in the middle of a day is lower not only due to dilution in the planetary boundary layer, but also due to decreased emissions during the day. Conversely, the high concentrations of aerosols within the thin nocturnal planetary boundary layer are additionally intensified by higher emissions due to domestic heating.

7.8 Black Carbon in Ljubljana

The highest black carbon concentrations were measured at the measurement sites located in the urban traffic zones at Vošnjakova (A) and near the highway at Barje F1 site. Urban background sites (KIS – C, Vojkova – D and Barje F2) are characterized by lower black carbon concentrations, whereas the lowest concentrations were measured at the suburban background site (E). Traffic emissions are responsible for higher black carbon concentrations and a higher fluctuation near busy roads.

A substantial decrease of black carbon concentration at Post Office measurement site in comparison to Vošnjakova site was observed after the implementation of a low emission zone in September 2013. Nevertheless, the impact of public bus transport at Slovenska Street on air quality in the city center is still evident.

Source apportionment of black carbon revealed different spatial and temporal heterogeneity of sources. Black carbon from traffic emissions prevails within the city, not only at traffic sites, but also at urban background sites. The contribution of traffic to black carbon concentrations diminishes very quickly the further away the measurement sites are from the road, and is reduced to the background level already at a distance of 150 m. On the other hand, homogeneous distribution of black carbon from biomass burning was observed within the whole city. Slightly higher contributions and greater dynamics of black carbon from biomass burning were observed only at Barje sites, indicating the local impact of biomass burning from domestic heating at the city outskirts and areas around Ljubljana.

The highest concentration of black carbon from biomass burning was measured at the suburban background site Brezovica (E), where during the night biomass burning contribution even exceeded black carbon concentration from traffic. Very weak morning and afternoon increase and stable variation (standard deviation) of traffic-related black carbon was observed through the day. It seems that biomass burning sources are homogeneously distributed and influenced by meteorological phenomena within the basin.

If we also consider dependence of black carbon concentration on wind speed and direction, it is possible to conclude that wood smoke is homogeneously dispersed in the Ljubljana basin in winter, with slightly higher fluctuation in the vicinity of local sources of domestic heating, as observed at the suburban background site (Brezovica). On the other hand, emissions from traffic reveal very local characteristics with a large deviation within the city, depending on the distance from the source.

Seasonal black carbon fluctuation, with higher winter and lower summer values, is governed partly by the seasonality of atmospheric stability, with planetary boundary layer height usually higher during the summer period, causing better dilution of aerosols emitted from the ground sources. Biomass burning in the heating season causes additional difference between summer and winter black carbon concentrations, whereas the contribution of traffic emissions does not have a seasonal pattern.

Mixing within the planetary boundary layer causes dilution of aerosols, which is more effective in less stable atmospheric conditions and when the source of emission is not too close to the measurement site. The falling linear relationship between black carbon concentration and planetary boundary layer height can be observed at all measurement sites. Significant correlation between black carbon concentrations and planetary boundary layer height is typical for measurement sites which are not directly influenced by black carbon sources (background sites).

Measurements of the particle size distribution at the urban and suburban background site during summer revealed different characteristics of both sites. Good correlation between ultrafine particles (< 100 nm) and black carbon concentration at the urban background site is consistent with the size range of freshly emitted soot particles, whereas better correlation with fine particles (100 – 700 nm) at the suburban background site confirms a more distant source of emissions with already aged and internally mixed aerosol. Analysis of black carbon during a fully mixed planetary boundary layer also shows that during summer, regional transport represents a substantial source of pollution measured at the background sites.

8. Conclusions

We have described the traffic-related air pollution in Ljubljana, as reflected in measurements of nitrogen dioxide and black carbon. This is without a doubt the most comprehensive work to date on this problem in and around Ljubljana. It turns out that air pollution is a dynamic process, influenced by atmospheric dynamics and reflecting the activities and habits of the society.

Based on the information in the previous chapters, we can identify four periods regarding pollution and air pollution in Ljubljana after the Second World War. The post-war decades up to and including the 1980s could be described as the period of fogginess. This time is characterized by massive pollution problems due to industry, household heating, and energy production, and to a lesser extent due to road transport. Dominating pollutants at this time consisted mainly of sulfur dioxide, soot, and coarser particles. This period is remembered for its long episodes of fog during the colder half of the year, lasting at times for up to several weeks, when Ljubljana was one of the foggiest cities in Europe, with more than 110 days of fog per year.

The period from the second half of the 1980s up to the end of the 20th century could be called the period of rapid cleanup of air pollution from industry and energy production. Ljubljana became less foggy and air quality improved; sulfur dioxide pollution in particular was noticeably reduced as energy sources were replaced. The transition to district heating also reduced emissions from household coal and biomass burning.

Traffic-related pollution increasingly appeared as a new threat to air quality in the beginning of the 21st century, due to the rapid growth of motorization. We can thus call the period from 2000 to roughly 2010 the period of pollution from road transport, characterized by, in addition to strong motorization and rapid growth of completed transportation work, the gradual introduction of cleaner technologies in vehicles, which to a certain extent mitigate the negative impacts of increasing traffic. Problems of air pollution are increasingly problems of traffic emissions, i.e. nitrogen oxides, volatile hydrocarbons, particulate matter, including black carbon, and ozone caused by emissions.

Due to large fluctuations and occasionally high prices of fossil fuels, the financial and economic crisis, and increasingly stronger promotion of renewable sources of energy, after 2010 the use of biomass as a fuel for household heating showed strong growth, and this caused the onset of a new period of air pollution. Thus in addition to traffic-related pollution, which has not significantly increased in recent years, and in certain cases has even fallen, pollution associated with biomass combustion has become increasingly important. Domestic heating with wood is not necessarily the primary method of heating, especially in cities, and is therefore underestimated in emission inventories while causing a large share of air pollution from particulate matter. We can refer to a new period, the period of biomass smoke. This is reflected in high concentrations of particulate matter and the portion of black carbon pollution contributed by biomass burning.

Regulatory limits are regularly exceeded in Ljubljana, but the number of exceedances is reducing slowly and at an uneven pace. Systematic efforts through technical and political measures have brought a noticeable improvement in air quality and the elimination of older problems, but changed conditions in Slovenia once again compel us to take measures to improve the situation. The impact of road traffic in Ljubljana can be seen not only in pollution of the air, but also in traffic congestion, noise pollution, traffic safety and pressure on those who use more environmentally friendly modes of transport. In recent years, the city of Ljubljana has done a great deal to mitigate and eliminate traffic problems, and been successful in these efforts. Parking is better regulated, and the volume of traffic in the city center is decreasing through the closing of the city center to motor vehicles, the introduction of one-way regimes on many streets, the reduction of parking areas and the introduction of fees for parking, which is most expensive in the city center. Public transport is becoming stronger through the introduction of new routes, priority (yellow) lanes on roadways, and construction of large car parks on city outskirts for the Park & Ride (P&R) system, and the network of cycle paths is being improved. But the path to a sustainable transportation arrangement for Ljubljana is still long and a few years of positive changes should not make us complacent. Measures at the level of the city urgently need to be coordinated with measures for the entire urban region around Ljubljana, which is a task for neighboring municipalities in cooperation with Ljubljana. The national government must also perform its share of the task, and so far it has done precious little in this regard. With regard to the traffic problems in Ljubljana, its urban vicinity, and in the country as a whole, the government continues to acknowledge the crucial challenges in increasing traffic flow on existing road infrastructure by adding new lanes (the Ljubljana ring, Dolenjska Street through Škofljica), by building completely new roads (the third development axis) or the construction of additional tunnels in places where they are not urgently needed for Slovenia (the A2 motorway, the Karavanke). Thus, there is still a prevailing mentality that all that is needed to solve traffic congestion is to build new road infrastructure. In modern and sustainably oriented societies this type of thinking was abandoned years ago. The traffic flow of roads should not be increased only by widening them with additional lanes or building new roads to relieve the load on existing ones, but by increasing the use of comfortable and convenient public transport, which is cheaper and in fact reduces unsustainable traffic demand. The role of the government and municipalities is to improve the supply of public transport options, both with respect to frequency of journeys as well as shortening the time it takes to travel somewhere. Excessive traffic must be addressed through sustainable transportation planning at the level of institutions, smaller regions or municipalities. The latter can also situate integrated transportation strategies, which treat sustainable mobility as the basis of transportation planning, in their development documents. The year 2015 represents a turning point for Slovenia in this area, since the country with the assistance of European funding for the first time provided financial support to municipalities in implementing integrated transportation strategies that will form the basis of the transportation development of municipalities in future. The introduction of new technologies into vehicles is equally important and can play an important role in reducing traffic-related pollution, but without a change in social and personal attitudes towards mobility, which must become one of the pillars of the transition to a sustainable society, the new technologies will merely alleviate growing environmental problems, they will not eliminate them.

The problem of particulate air pollution due to biomass combustion in Slovenian regions, especially during the colder half of the year, that we have been seeing in recent years is becoming ever greater. For densely settled areas, and not just in cities but also elsewhere, it would make sense to consider district heating. Everywhere where district heating systems are already in place, households should be required to be hooked up to them. The example of Velenje should serve as a model: because it gets a large share of district heating from the Šoštanj power plant it is the only town in the interior of Slovenia where the number of days with an exceeded daily limit concentration of particulate matter does not exceed the allowable number. In such areas, domestic heating using individual stoves (especially using systems that burn solid fuels) should be strongly regulated and treated as a payable luxury that would lessen the price advantage of wood. Elsewhere, where district heating systems are neither already established nor planned, heating systems should be adapted to local conditions connected with impact on air quality. The use of biomass is beneficial from the standpoint of reducing the use of fossil fuels, but this should not be allowed to happen at the expense of people's health and the quality of life locally and regionally – wood smoke is a regional pollutant. Much more should be invested in energy efficiency of households and quality heating systems that have a considerably lower use of energy and less harmful emissions.

Acknowledgements

Through the publication of this book in English we would like to present past efforts on behalf of air quality in Ljubljana and Slovenia and describe the current state of pollution from nitrogen dioxide and black carbon to a wider international audience, since we believe that this information is relevant and transcends national boundaries. None of this would have been possible were it not for the support of those listed below. The authors would like give our sincere thanks to them.

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Povzetek

Knjiga se posveča prometnemu onesnaževanju ozračja z dušikovim dioksidom in onesnaževanju s črnim ogljikom. V določeni meri vsebinsko nadgrajuje knjigi »Prometno onesnaževanje ozračja z dušikovim dioksidom v Ljubljani« iz leta 2008 in »Onesnaženost zraka v Ljubljani – Koncentracije dušikovih oksidov, ozona, benzena in črnega ogljika v letih 2013 in 2014« iz leta 2014. Knjiga zaključuje to trilogijo z vključevanjem primerjave rezultatov meritev v letih 2005/2006 in 2013/2014, vsebuje pa tudi rezultate poglobljene študije meritev črnega ogljika v Ljubljani in tako poleg prometnega, izpostavlja tudi onesnaževanje ozračja z zgorevanjem biomase, ki je v zadnjih letih ponovno vse bolj priljubljeno. Hkrati knjiga postavlja problematiko onesnaževanja ozračja v Ljubljani v širši kontekst varstva zraka po drugi svetovni vojni s kratkim zgodovinskim pregledom aktivnosti na področju varstva zraka in pregledom literature s tega področja.

Aktivnosti na področju kakovosti zraka so se v Sloveniji začele v šestdesetih letih prejšnjega stoletja. Po epizodah visokih koncentracij onesnaženja v Donori (Pensilvanija, ZDA) leta 1948 in Londonu leta 1952, ko so v dneh z zelo onesnaženim zrakom ugotovili močno povečano število smrti, so tudi pri nas začeli razmišljati o kakovosti zraka, ki so ga dihali v mestih. Prve meritve koncentracij žveplovega dioksida in dima so pokazale tako visoke koncentracije, da so najprej posumili v pravilnost rezultatov meritev. Ko so natančno preverili vse postopke, so spoznali, da je zrak v naših mestih med najbolj onesnaženimi na svetu, zato so se lotili raziskave vzrokov za takšno stanje. Pri tem je bilo treba začeti s sistematičnimi meritvami, raziskavami ter ukrepi.

Leta 1975 so meritve kakovosti zraka v Sloveniji prerasle v mrežo, ki je zajela večino večjih naselij. Za nekatera merilna mesta obstaja niz podatkov od leta 1968 do 2002, za druga pa krajši nizi, vendar je za najmanj 40 merilnih mest ta niz zagotovljen od leta 1975 do leta 2000. Vseh merilnih mest, tudi takih z le nekajmesečnimi meritvami, je bilo okoli 200.

Korak naprej pri meritvah je bil storjen leta 1983 z nakupom večjega števila samodejnih merilnikov onesnaženosti zraka Monitor Labs. Sistem so poimenovali Analitično Nadzorni Alarmni Sistem, krajše ANAS. Zamišljen je bil kot prenosni sistem desetih samodejnih postaj, a pokazalo se je, da samodejne meritve brez nadzora ne dajo dobrih rezultatov. Tako se je kazala potreba po stalnih postajah in izoblikovala se je mreža postaj v Ljubljani, Mariboru, Celju in v treh zasavskih mestih, kjer je bil zrak najbolj onesnažen. Večina postaj je imela merilnike žveplovega dioksida, na nekaterih postajah pa so postopoma dodali merilnike ozona, dušikovih oksidov, ogljikovega monoksida in delcev. Merilni sistem je bil nadgrajen leta 2001. Merilne postaje so bile modernizirane, dodani pa sta bili merilni mesti Nova Gorica in Murska Sobota z merilno postajo v Rakičanu.

Z vidika ugotavljanja prostorskih vzorcev onesnaženja se je že v predhodnih raziskavah (Ogrin, D., in sod., 2006; Ogrin, M., 2008) kot primerna metoda za ugotavljanje kakovosti zraka izkazala uporaba difuzivnih vzorčevalnikov, zato smo jo uporabili tudi v raziskavi 2013/2014 in s tem omogočili lažjo primerljivost rezultatov. Poleg ugotavljanja onesnaženosti z dušikovim dioksidom lahko s to metodo ugotavljamo tudi stopnjo onesnaženosti z ozonom, žveplovim dioksidom in benzenom. Metoda temelji na prenosu onesnaževala v vzorčevalniku s pomočjo molekularne difuzije. V omenjenih raziskavah smo uporabili Palmesove vzorčevalnike, ki se uporabljajo pogosto, odkar so bili leta 1976 prvič preizkušeni in opisani (Palmes in sod., 1976). Gre za 7,1 cm dolgo cevko z notranjim presekom 0,71 cm^2, ki ima na zaprtem koncu kovinsko mrežico, premazano z reagentom, ki deluje kot sorbent. Na enem koncu je cevka zaprta, na drugem pa v času meritev odprta. Skozi to odprtino v času vzorčenja vstopa zunanji zrak in s seboj prinaša tudi onesnaževala. Ko onesnaževalo v cevki doseže membrano in reagira z reagentom, se pretvori v novo snov, ki ostane na membrani. Tako je koncentracija onesnaževala, ki ga merimo, v neposredni bližini membrane vedno enaka nič, saj ga sorbent veže nase in spremeni. Zato se v cevki vedno, kadar je koncentracija merjenega onesnaževala vstopajočega zraka različna od nič, vzpostavi gradient koncentracije, ki zaradi molekularne difuzije povzroči tok molekul onesnaževala proti membrani z reagentom.

Pri ugotavljanju spreminjanja onesnaženosti zraka znotraj mesta je nujno postaviti gosto mrežo merilnih mest v različnih tipih mestnega prostora. V Ljubljani smo merilna mesta določili glede na tri predhodno opredeljene tipe mestnega prostora: urbano ozadje, odprt prostor ob cestah in cestni koridor. V knjigi smo za vsak tip mestnega prostora analizirali rezultate vseh opravljenih meritev za zimsko in poletno merilno obdobje merilnih sezon 2005/2006 in 2013/2014, vključno s primerjavo rezultatov med obema sezonama. Ker vsa izbrana merilna mesta v sezoni 2013/2014 niso sovpadala z vključenimi merilnimi mesti sezone 2005/2006, je primerjava omejena na manjše število skupnih merilnih mest. Kot sintezo meritev poletnega in zimskega merilnega obdobja v enem letu smo izračunali oceno letne onesnaženosti zraka z dušikovim dioksidom za vsa merilna mesta, kjer so potekale zimske in poletne meritve. Ocena temelji na izračunu koncentracij na podlagi letnih koncentracij izmerjenih s samodejno merilno napravo ARSO.

Primerjava ocene povprečne letne onesnaženosti z dušikovim dioksidom med sezonama 2005/2006 in 2013/2014 na istih merilnih mestih urbanega ozadja ne pokaže bistvene razlike. V sezoni 2005/2006 je povprečna letna koncentracija vseh merilnih mest znašala 29 $\mu g/m^3$, v sezoni 2013/2014 pa 30 $\mu g/m^3$. Na primeru skromnega števila istih merilnih mest, ki so bila vključena v obe obdobji in sezoni meritev, torej ne moremo sklepati o bistvenih razlikah v kakovosti zraka med tema dvema letoma na celoletni ravni. Primerjava koncentracij dušikovega dioksida v odprtem prostoru ob cestah v sezonah 2005/2006 in 2013/2014 je mogoča le na enem merilnem mestu. Gre za merilno mesto na Trgu Osvobodilne fronte ob glavni avtobusni postaji, kjer se kaže podobna stopnja onesnaženosti zraka v obeh poletjih in zimah, pri čemer je bila koncentracija dušikovega dioksida poleti 2013 (54 $\mu g/m^3$) malenkost nižja kot poleti 2005 (59 $\mu g/m^3$), pozimi 2014 (67 $\mu g/m^3$) pa malo višja kot pozimi 2006 (64 $\mu g/m^3$).

Ocena povprečne letne koncentracije dušikovega dioksida v cestnih koridorjih je pokazala, da so koncentracije tam povsod nad dopustno mejo, ki znaša 40 $\mu g/m^3$. V sezoni 2013/2014 je bila koncentracija nižja od tiste v sezoni 2005/2006 na Slovenski cesti pri Nami (74 µg/m^3 : 80 µg/m^3), Bavarskem dvoru (66 µg/m^3 : 72 µg/m^3) in A Banki (67 µg/m^3 : 77 µg/m^3). Po drugi strani pa ocena povprečne letne koncentracije na dveh merilnih mestih Slovenske ceste pri Figovcu (54 µg/m^3 : 53 µg/m^3) ter pri Kongresnem trgu (54 µg/m^3 : 51 µg/m^3) kaže na podobne oziroma celo nekoliko nižje koncentracije dušikovega dioksida v sezoni 2005/2006 kot v sezoni 2013/2014.

Sklenemo lahko, da na letni ravni povprečne ocenjene koncentracije dušikovega dioksida v sezoni 2013/2014 pri vseh tipih merilnih mest niso bile bistveno drugačne od tistih v sezoni 2005/2006. Koncentracije v merilnih obdobjih sezone 2013/2014 so bile sicer nižje, a k temu je veliko prispevalo vreme oziroma večja premešanost ozračja. To se pokaže pri preračunu na letno raven. Tudi delno zaprtje Slovenske ceste za osebni motorni promet, ki je bilo v zimskem merilnem obdobju 2014 že v veljavi, k izboljšanju stanja še ni bistveno prispevalo. Koncentracije dušikovega dioksida so tako marsikje v cestnih koridorjih še vedno previsoke, kar zahteva nadaljnje ukrepanje v smeri umirjanja prometa v mestnem središču, pomembno pa je tudi uvajanje čistejših tehnologij v javnem potniškem prometu kot tudi spodbujanje dnevnih migrantov po Ljubljani in v Ljubljano k čim večji uporabi javnega potniškega prometa ali (za notranje migracije) nemotoriziranih sredstev mobilnosti, kot sta kolo ali hoja.

V drugem delu knjige predstavljamo obširne rezultate meritev črnega ogljika (BC), ki je kot primarno onesnaževalo dober pokazatelj virov emisij. Meritve so potekale tekom zadnjih nekaj let (2012–2015) v Ljubljani in njeni bližnji okolici z namenom ugotavljanja onesnaženosti zraka v mestnem jedru, določanja virov ter prostorske in časovne spremenljivosti črnega ogljika tako v mestnem jedru kot tudi v širši Ljubljanski kotlini. S pomočjo večletnega spremljanja koncentracij črnega ogljika smo ocenili uspešnost ukrepov za zmanjševanje prometne obremenjenosti središča Ljubljane.

Skupno je bilo pri meritvah črnega ogljika v različnih obdobjih vključenih sedem merilnih mest, od tega sta dve merilni mesti predstavljali mestno prometno okolje (Vošnjakova cesta in Slovenska cesta pri pošti), dve mestno ozadje (Vojkova cesta in Hacquetova ulica pri Kmetijskem Institutu Slovenije – KIS), dve merilni mesti sta se nahajali ob južni obvoznici (Barje), eno merilno mesto pa se je nahajalo na primestnem ozadju na Brezovici. Raznolikost merilnih mest je omogočila študij prostorske in časovne heterogenosti koncentracij črnega ogljika in s tem ločevanje regionalnih in lokalnih virov emisij.

Meritve koncentracije aerosoliziranega črnega ogljika v zraku so potekale z Aethalometri (Magee Scientific / Aerosol d.o.o.). Aethalometer vzorči zrak s pretokom nekaj litrov na minuto skozi filtrski trak iz steklenih vlaken, na katerem se nabirajo aerosoli. Nad filtrom je vir svetlobe, pod njim pa so detektorji, ki merijo prepustnost traku za svetlobo. Koncentracijo črnega ogljika izračunamo iz sprememb atenuacije svetlobe z valovno dolžino 880 nm. Atenuacijo merimo relativno glede na vzporedno meritev optične prepustnosti referenčnega dela istega filtra, skozi katerega zrak ne teče. Atenuacija je definirana kot logaritem razmerja meritve intenzitete svetlobe pod referenčnim delom filtra in delom, na katerem se nabirajo aerosolizirani delci. Aethalometer AE33 omogoča meritve absorbcije svetlobe v širokem svetlobnem spektru (pri valovnih dolžinah 370 nm, 470 nm, 520 nm, 590 nm, 660 nm, 880 nm in 950 nm), kar omogoča karakterizacijo absorpcije aerosolov v področju od ultravijolične do infrardeče. Ångstromov eksponent opisuje, kako se absorpcijski koeficient aerosolov spreminja z valovno dolžino svetlobe in predstavlja parameter, na osnovi katerega je mogoče ločiti delež črnega ogljika, ki nastaja pri izgorevanju dizelskih goriv, in delež, ki nastaja pri izgorevanju lesa in biomase.

Najvišje koncentracije črnega ogljika smo izmerili na merilnih mestih na območjih obremenjenih s prometom (Vošnjakova: 6,8 ± 5,1 μg/m^3 v hladnem obdobju in Barje ob obvoznici: 4,6 ± 2,6 μg/m^3 v hladnem obdobju), medtem ko smo na mestnem ozadju izmerili nižje koncentracije črnega ogljika (KIS: 3,9 ± 3,5 μg/m^3 v hladnem obdobju, Vojkova: 2,0 ± 1,3 μg/m^3 v toplem obdobju in Barje – lokacija odmaknjena 150 m od obvoznice: 3,6 ± 2,1 μg/m^3 v hladnem obdobju), najnižje pa v primestnem okolju (Brezovica: 3,2 ± 2,5 μg/m^3 v hladnem obdobju). Izpusti iz prometa so odgovorni za višje koncentracije in večje nihanje koncentracij črnega ogljika v bližini prometnih cest.

Iz koncentracij črnega ogljika izmerjenih pred in po uvedbi ukrepov za zmanjšanje prometnih obremenitev v mestnem jedru septembra 2013, smo izmerili občutno znižanje prispevka lokalnih emisij BC za 72 % na merilnem mestu na Slovenski cesti. Kljub vsemu vpliv avtobusnega potniškega prometa na kakovost zraka v središču mesta ni zanemarljiv.

Z ločevanjem prispevkov prometa (BC_{TR}) in zgorevanja biomase (BC_{BB}) h koncentracijam črnega ogljika smo pokazali drugačno prostorsko in časovno porazdelitev črnega ogljika. V mestu predstavlja glavni prispevek h koncentracijam BC promet, ne le na prometnih območjih, ampak tudi na mestnem ozadju. Prispevek prometa h koncentracijam BC z oddaljevanjem od prometnih izpustov naglo pojema in lahko doseže nivo ozadja že na razdalji 150 m od vira emisij, kar so pokazale meritve ob ljubljanski južni obvoznici. Po drugi strani pa je v obdobju kurilne sezone črni ogljik, ki je posledica zgorevanja biomase, po mestu homogeno porazdeljen. Nekoliko višji prispevek lesnega dima in večje dnevno nihanje je opazno le na Barju ob južni obvoznici, kar kaže na lokalni vpliv kurjenja lesa za namen ogrevanja individualnih hiš na obrobju mesta in v okolici Ljubljane.

Največjo koncentracijo BC_{BB} smo izmerili na primestnem ozadju na merilnem mestu na Brezovici, kjer je lahko prispevek zgorevanja biomase ponoči celo višji od prispevka prometa. Glede na majhno dnevno spremenljivost, ki je omejena na jutranje in večerne ure, in primerljive vrednosti na vseh merilnih mestih, lahko zaključimo, da je lesni dim homogeno porazdeljen po Ljubljanski kotlini in odvisen od vremenskih vplivov. Temu ustreza tudi spremenljivost BC_{BB} z vetrom. Koncentracija BC_{BB} se z jakostjo vetra zaradi redčenja sicer manjša, vendar je skorajda neodvisna od smeri vetra. V nasprotju z lesnim dimom imajo emisije črnega ogljika iz prometa lokalni značaj, saj je porazdelitev BC_{TR} v mestu zelo heterogena in neposredno odvisna od oddaljenosti od prometnih virov.

Sezonsko nihanje koncentracij črnega ogljika, z visokimi koncentracijami v zimskem obdobju in nižjimi koncentracijami poleti, delno zavisi od stabilnosti ozračja, saj je poleti debelina prizemne mejne plasti (PBL) običajno večja, kar omogoča intenzivnejše vertikalno mešanje in s tem redčenje aerosolov v ozračju. Zgorevanje biomase v zimskem obdobju dodatno prispeva k večji razliki med poletnimi in zimskimi koncentracijami BC, medtem ko je vpliv prometa v obeh letnih časih enak. Mešanje znotraj PBL omogoča redčenje aerosolov, ki je intenzivnejše v manj stabilnem ozračju, v obdobjih stabilnejšega ozračja pa se aerosoli nabirajo znotraj PBL. Tako lahko na vseh merilnih mestih opazimo obratno sorazmerje med višino PBL in koncentracijo BC, pri čemer je odvisnost boljša na lokacijah, ki niso v neposredni bližini virov emisij.

Poleg meritev koncentracij črnega ogljika smo poleti 2014 opravili tudi meritve koncentracije in velikostne porazdelitve delcev manjših od 1 µm na mestnem (KIS) in primestnem ozadju (Brezovica). Med obema merilnima mestoma so se pokazale občutne razlike. Na mestnem ozadju opazimo večje ujemanje med koncentracijo BC in delci velikosti do 100 nm, kar se sklada z velikostjo delcev saj iz svežih emisij iz prometa. Na merilnem mestu na Brezovici se koncentracija BC bolje ujema z delci v velikostnem območju 100 nm do 1 µm, kar kaže na prisotnost staranih aerosolov iz nekoliko bolj oddaljenih izvorov.

Glede na opravljene meritve plinov in črnega ogljika v zadnjih letih lahko sklenemo, da stanje kakovosti zraka v Ljubljani ni kritično, a tudi ni rožnato. Dejstvo je, da je bilo v preteklih desetletjih marsikdaj precej slabše. Sistematična prizadevanja stroke in politike so prinesla opazno izboljšanje kakovosti zraka in odpravo starih grehov, nove razmere pa nas ponovno silijo k novim ukrepom izboljšanja stanja. V zadnjih letih je Ljubljana storila precej za blažitev in odpravo prometnih težav in bila na tem področju tudi uspešna. Ukrepe na mestni ravni pa je nujno povezati z ukrepi v celotni urbani regiji okoli Ljubljane, kar je naloga sosednjih občin v sodelovanju z Ljubljano.

Izkazalo se je, da je poleg prometnega onesnaževanja, ki v zadnjih letih bistveno več ne narašča, v določenih primerih pa celo upada, vse bolj pomembno onesnaževanje povezano z zgorevanjem biomase, ki je zlasti problematično na obrobju Ljubljane in tudi drugje po Sloveniji. Problem zadimljenosti slovenskih pokrajin zlasti v hladni polovici leta, ki smo mu priča v zadnjih letih, postaja vse večji. Za gosto naseljena območja, ne le v mestih, pač pa tudi drugje, je zato smiselno razmišljati o daljinskih sistemih ogrevanja.

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Authors

Dr. Luka Drinovec, Aerosol d. o. o., Kamniška 41, 1000 Ljubljana, e-mail: luka.drinovec@aerosol.si

Dr. Asta Gregorič, Centre for Atmospheric Research, University of Nova Gorica, Vipavska cesta 13, 5000 Nova Gorica, e-mail: asta.gregoric@ung.si

Dr. Griša Močnik, Aerosol d. o. o., Kamniška 41, 1000 Ljubljana, e-mail: grisa.mocnik@aerosol.si

Dr. Matej Ogrin, Department of Geography, Faculty of Arts, University of Ljubljana, Aškerčeva c. 2, 1000 Ljubljana, e-mail: matej.ogrin@ff.uni-lj.si

Dr. Katja Vintar Mally, Department of Geography, Faculty of Arts, University of Ljubljana, Aškerčeva c. 2, 1000 Ljubljana, e-mail: katja.vintar@ff.uni-lj.si

Anton Planinšek, retired at the end of 2014, before Slovenian Environment Agency (ARSO), Vojkova 1b, 1000 Ljubljana, e- mail: tone50.planinsek@gmail.com

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