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BAERLIN2014 - The influence of land surface types on and the horizontal heterogeneity of air pollutant levels in Berlin

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Abstract. Urban air quality and human health are among the key aspects of future urban planning. In order to address pollutants such as ozone and particulate matter, efforts need to be made to quantify and reduce their concentrations. One important aspect in understanding urban air quality is the influence of urban vegetation which may act as both, emitter and sink for trace gases and aerosol particles. In this context, the "Berlin Air quality and Ecosystem Research: Local and long-range Impact of anthropogenic and Natural hydrocarbons 2014" (BAERLIN2014) campaign was conducted between the June 2nd and August 29th in the metropolitan area of Berlin-Brandenburg, Germany. The predominant goals of the campaign were (1) the characterization of urban gaseous and particulate pollution and its attribution to anthropogenic and natural sources in the region of interest, especially considering the connection between biogenic volatile organic compounds and particulates and ozone; (2) the quantification of the impact of urban vegetation on organic trace gas levels and the presence of oxidants such as ozone; and (3) to explain the local heterogeneity of pollutants by defining the distribution of sources and sinks relevant for the interpretation of model simulations. In order to do so, the campaign included stationary measurements at an urban background station and mobile observations carried out from bicycle, van and airborne platforms. This paper provides an overview of the mobile measurements (Mobile BAERLIN2014) and general conclusions drawn from the analysis. Bicycle measurements showed micro-scale variations of temperature and particulate matter, displaying a substantial reduction of temperature and particulates in the proximity of vegetated areas compared to typical urban residential area (background) measurements. Van measurements extended the area covered by bicycle observations and included continuous measurements of O_3, NO_x, CO, CO_2, and pointwise volatile organic compounds (VOCs) identification. The quantification displayed notable horizontal heterogeneity of the short lived gases and particle number concentrations. E.g. concentrations

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of the traffic related chemical species CO and NO varied by more than ±20 % and ±60 % on the scale of one hundred meters, respectively. Airborne observations revealed the dominant source of elevated urban particulate number and mass concentrations being local, i.e. not being caused by long range transport. Surface based observations related these two parameters predominantly to traffic sources. Vegetated areas lowered the pollutant concentrations substantially with ozone being reduced most by coniferous forests, which is most likely caused by their reactive biogenic VOC emissions. With respect to the overall potential to reduce air pollutant levels forests were found to result in the largest decrease, followed by parks and facilities for sports and leisure. Surface temperature was generally 0.6-2.1°C lower in vegetated regions, which in turn will have an impact on tropospheric chemical processes. Based on our findings effective future mitigation activities to provide a more sustainable and healthier urban environment would focus predominantly on reducing fossil-fuel emissions from traffic as well as on increasing vegetated areas.

1 Introduction

Today 54% of the Earth's population lives in urban areas (United Nations, 2015). This number is expected to increase beyond 60% within the next fifteen to twenty years. Due to the highly concentrated resource use, air pollution levels are closely related to population density, despite some success in reducing emissions (Lamsal et al., 2013). Numerous epidemiologic studies show that highly polluted conditions, such as experienced in many cities, are already causing major adverse health effects (e.g. Chen and Kann, 2008; Heinrich et al., 2013; WHO, 2013) expected to worsen with increasing urban areas. Therefore it is crucial to find means for improving air quality even under increased urbanization and traffic occurrence, which, however, requires a thorough understanding of sources and sinks of air pollutants.

Poor air quality has been documented in many metropolitan areas such as Bejing (Huang et al., 2015; Huo et al., 2015; Sua et al., 2015; Zhang et al., 2015), Los Angeles (Chen et al., 2013; Ensberg et al., 2014; McDonald et al., 2015), Paris (von der Weiden-Reinmüller et al., 2014) and for Europe in general (Henschel et al., 2015). Elevated levels of gaseous pollutants such as ozone (O_3), nitrogen oxides (NO_x = $NO+NO_2$), sulphur dioxide (SO_2), toxic agents such as aromatic hydrocarbons and of particulate matter (PM) have been attributed to anthropogenic emissions from urban sources, especially traffic and energy production (Downey et al., 2015; Hong et al., 2015; Huo et al., 2015; Padilla et al., 2014). Since atmospheric pollutants can affect the human respiratory system (e.g. oxygen capacity) and significantly reduce a person's working capacity and life expectancy (chronic obstructive pulmonary disease, acute lower respiratory illness, cerebrovascular disease, ischaemic heart disease and lung cancer) (Dockery et al., 1993; Peng et al., 2005; Pope et al., 2009, Lelieveld et al., 2015) with an intensity of effects depending on time scale, limits of daily and annual averages of pollutant concentrations have been proposed by national and international authorities (European Union, 2008; WHO, 2006).

In this context the European Union introduced legally binding limit values applying to all Member States in the Air Quality Framework Directive (Directive 2008/50/EC, European Union, 2008). If cities fail to meet these health related limit values, they are obliged to develop air quality programs capable of reducing the pollution concentration and the duration of elevated concentrations. As held by the European Court of Justice (ECJ), the

establishment of such air quality programs is a subjective right of any person directly concerned and can thus be claimed by citizens in court (*Janecek v. Bayern*, ECJ, 2008).

In Germany, the EU-limits for NO_2 and PM_{10} continue to be exceeded in many cities (including Berlin).As a result, in drawing up their air quality programs, the Federal Administrative Court ruled that authorities must implement all measures available to keep the time of exceedance as short as possible (Bundesverwaltungsgericht, 2012). Otherwise citizens and environmental associations can sue for an adjustment of the program, as has already happened in Darmstadt, Hamburg, Limburg, Mainz, Offenbach, Reutlingen and Wiesbaden.

In consequence Berlin, like every European city, has the legal obligation to provide air quality programs that are capable of substantially reducing nitrogen oxides and particulate matter. The Senate of Berlin adopted a respective program for 2011-2017 (Berlin Senate, 2013b). However, given that limit values continues to be exceeded, it is questionable whether the measures contained herein are sufficient to enable Berlin to comply with this obligation. An exceedance of these values is only permissible, when all necessary and appropriate measures at disposal are exhausted. So far Berlin has established an environment protection zone (German "Umweltzone", 2nd step, green level; Berlin Senate, 2011) in the city centre. This measure was set-up to lower traffic related emissions and the number of critical threshold exceedances according to EU law for NO_x and PM (see Table 1) in Berlin per year and resulted in an emission reduction by 20% for NO_x and 58% for soot by diesel engines (Berlin Senate, 2011). A substantial contribution to NO_x and particulate matter (PM) has been claimed to originate by long range transport from Polish industrialized areas (Kerschbaumer, 2007). Other PM sources can be attributed to nearby emission or gas-phase (secondary) PM production. As the city of Berlin is surrounded by and contains extensive forested regions, enclosed by three rivers (Havel, Spree and Dahme) and a couple of lakes (6% by area), the concentration of trace gases and particles will be influenced from both, i.e. local anthropogenic and biogenic (vegetation) sources (see e.g. Becker et al., 1999; Beekmann et al., 2007). Due to their provision of multiple ecosystem services, increasing green areas such as parks and forests are often considered as measures to counteract urban heat island effects (Fallmann et al., 2014; Grewe et al., 2013; Schubert and Grossman-Clake, 2013) and air pollution problems (Irga et al., 2015; Janhäll et al., 2015). Emission of biogenic BVOCs can affect chemical ozone production and destruction (Seinfeld and Pandis, 2006; Klemp, 2012) as well as secondary organic aerosol mass production (Hallquist et al., 2009) if higher terpenes are emitted. A high impact of reactive BVOCs on O_3 concentrations and vice versa has been observed during warm seasons in highly polluted temperate and semi-arid areas (Papiez, et al. 2009; Bourtsoukidis et al., 2012; Calfapietra et al., 2013; Situ, et al., 2013), while the influence in northern countries has been found generally smaller (Setälä et al., 2013, von Schneidemesser, et al. 2011). The reducing effect of vegetation on NO_x concentrations was described earlier by Velikova et al. (2005). The effects of vegetation and especially the emission of biogenic VOCs (BVOCs, Guenther et al., 1995; 2006; Ghirardo et al., 2015) have been neglected so far but are expected intensify in a warmer climate (e.g. Bonn, 2014; Churkina et al. 2015).

Given this background, the presented study tries to support city authorities by improving the knowledge about small-scale pollution sources and sinks with a focus on the role of vegetation, and thereby supporting authorities to meet target values and limits based on providing pertinent scientific information to support decision-making.

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2 Focus of the campaign and of this study

This study focusses on the Berlin-Brandenburg Metropolitan area (BBMA) with about four million inhabitants, and a hub for major transport routes through Europe. Both cities in this area, Berlin with approximately 3.3 million citizens and Potsdam, the capital of Brandenburg, with about 0.2 million inhabitants, are extraordinary among European metropolitan areas because of the large proportion of water and vegetated areas making up about 40% of the total land surface area in the cities (Berlin Senate, 2010; 2013b)(Table 2). Because of its large area vegetation is expected to have a notable impact on pollution levels (trace gas and aerosol particle concentrations), and thereby on pollution levels as it was found for other locations (Cowling and Furiness, 2004; Zaveri et al., 2012). Ambient air pollution levels generally meet the EU limit values with the exception of nitrogen oxides (NO_x = NO + NO_2) and of particulate matter (PM_{10} and $PM_{2.5}$). Based on previous studies in urban areas, and a limited number of studies in Berlin, the predominant sources of both pollutants are expected to be traffic, residential heating, industry and transport of primary and secondary particulate matter (Seinfeld and Pandis, 2006; Berlin Senate, 2013a; 2015). Earlier studies have indicated substantial deviations between observed and simulated NO_2 (mean: -20%) and PM values (mean: -10%) (see e.g. Tullius and Lutz, 2003), which both influence health (Fischer et al., 2015; Liu et al., 2016) and ozone production (Atkinson et al., 2004; Seinfeld and Pandis, 2006). *The deviations of PM are linked to secondary and semivolatile organic substances contributing to particulate mass. These contributions vary depending on ambient mixing ratios of VOC precursors as well as on temperature as the precursors' saturation vapour pressure and the total organic particle mass change, aspects, which are not or poorly represented in air quality models due to their complexity.*
Here we present the project "Berlin Air quality and Ecosytem Research: Local and long-range Impact of anthropogenic and Natural hydrocarbons 2014" (BAERLIN2014). Considering the context outlined in the paragraph above, it focused on the following questions:

(1) What is the spatial and temporal heterogeneity of pollutants in the BBMA area with a focus on Berlin and Potsdam?
(2) How do different vegetation types influence the levels of ozone, NO_x and VOCs in Berlin?
(3) What is the impact of different types of vegetated areas on urban environmental conditions i.e. temperature, humidity and particulate pollutants (number and mass)?
(4) And finally what is the contribution of anthropogenic and biogenic organic compounds to secondary organic aerosol and the total particulate mass in the Berlin and Potsdam area affecting health, both directly and indirectly through ozone production?

The present article provides an overview on the mobile measurements tackling points (1), (2) and (3) using observations in different environments, classifying the data by different vegetated and urban surface types, comparing to local observations (von Schneidemesser et al., in prep.) and their heterogeneity with respect to important pollution parameters (CO, NO_x, O_3 and particle number and mass). Especially aspect (4) is of interest for simulation studies when comparing model simulation results with measurements to draw conclusions about PM sources as well as on ozone sources and sinks. The aim of this study was to identify hotspots of pollution, the variability of basic air pollution trace gases, to quantify the impact of green areas and to exemplarily identify dominant VOC sources to support action plans such as made by the Berlin Senate (2013b).

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The mobile measurements described in this paper were conducted as part of the larger BAERLIN campaign, which included extensive stationary measurements at an air quality monitoring station in Berlin-Neukölln. The stationary measurements are described elsewhere (von Schneidemesser et al., in preparation). Both measurement types contribute to the identification of local sources and sinks as well as their effects on the urban background concentration of air pollutants. Further studies using atmospheric transport models are planned for assessing different mitigation options.

3 Methods

Mobile measurements were performed using different observation platforms, i.e. bicycles, a van and aircrafts (Table 3), with tracks throughout and around the BBMA area (Fig. 1). To allow for the comparison of different measurement types at different times of day and under different conditions a relative parameter method has been used, which is described in section 3.4. In order to characterize the spatial variation of parameters of interest a set of instruments and methods on different platforms were linked to form a complimentary set of observations. The different ranges and scales of observations were

1. Microscale (3.1 Bicycle measurements), ground-based, real-time and highly spatially-resolved observations: bicycle measurements covering a variety of routes during the three month period;
2. Mesoscale (3.2 Van measurements), ground-based, including source profiling (traffic and vegetation) and VOC source classification: van (Mercedes VITO) measurements (RC Jülich, Germany) for the first week in August; and
3. Mesoscale (3.3 Airborne measurements), airborne, in- and outflow of BBMA area: (1) ultralight aircraft (KIT, IMK-IFU, Garmisch-Partenkirchen, Germany) for outflow characteristics of BBMA including altitude information and (2) Diamond (DA42) twin-engine small airplane observations (TU Düsseldorf, Germany) circling around Berlin.

The parameters quantified are listed in Table 3 by measurement platform. All the instruments were calibrated a priori. Further details as to the timeframe of measurements, instrument information, and parameters measured can be found in Tables 3 and Table A1 in the Appendix). Finally the observations were classified according the predominant land use type (see section 3.5 Classification of observed data by land use types).

3.1 Bicycle measurements

Bicycles provide a level of flexibility and access to certain areas that cars cannot, in addition to their travel speed, which allows for well-resolved horizontal resolution of measurement points. Moreover this measurement type addresses best the conditions where humans are exposed to pollutants. Because of this, they were used as the basic mobile method for the majority of the time period (10th of June – 29th of August 2014). The instruments applied for quantifying meteorological and particulate values are listed with their characteristics in Table A1. In brief, a DiSCmini from Matter Aerosol (CH) was applied for detecting particle number concentrations using a charged equilibrium in the aerodynamic diameter size range of 10-500 nm. More technical information to the instrument can be found in Kaminski et al. (2013). The corresponding software supplied an algorithm estimating

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the lung deposited surface area (LDSA), a metric linked primarily to smaller particles and their size distribution providing a measure of potential health effects. Applied as well, was the optical particle counter GRIMM 1.108 (Airing, Germany) for detecting particles in the aerodynamic size range of 0.3–20 µm. The GRIMM 1.108 instrument measured accumulation and coarse mode aerosol particles with a time resolution of 6 s. It included an additional sensor for air temperature. Both instruments were transported in a backpack or pannier.

A detailed logbook was carried with the instruments and filled out by each cyclist. A Garmin Virb Elite HD action camera with GPS and WiFi mounted on the handlebar of the bicycle was used to record the exact time and location of the mobile measurement route and facilitate identification of sources. Please find more details on the measurements in Appendix A.

The measurement routes covered large parts from south west to the centre of the BBMA area with several repetitions of a number of the routes (see Fig. 1), such as between the IASS in Potsdam and Berlin-Charlottenburg. The majority of the routes followed commuter paths to and/or from the IASS. In total 80 routes, covering 1850 km were obtained during the three month campaign period. The mobile measurements are viewable online at http://baerlin.iass-potsdam.de.

It should be noted that the mobile measurements represent snapshots for a specific location at a certain point in time with substantial influence of local sources and sinks. In addition, scaling to daily and annual time periods is difficult due to the preferred measurement periods in the morning and afternoons, while the sampling frequency in Berlin-Neukölln was relatively high. Thus, in order to understand the daily pattern of the measured values and all the contributions in detail microscale simulations would be required. This is beyond the scope of the present study.

3.2 Mobile van measurements

Van measurements were carried out in a one week intensive period between the 31st of July and the 6th of August using the Research Centre of Jülich mobile laboratory MOBILAB. It consists of a Mercedes Vito van fitted with an isokinetic particle inlet and gas-phase inlets just above the van roof at ca. 2 m above ground level (Ehlers, 2013). The following quantities were measured: temperature, relative humidity, ozone, NO, NO_2, CO, CO_2, methane, total particle number concentration (2.5 nm - 3 µm), and size distribution of particles between 7 nm and 20 µm in diameter (ELPI). Location data was collected via GPS. A list of the instrumentation is provided in Tables 3 and A1 (Appendix).

In addition, “baseline” values were derived for CO as well as for the total number and mass of aerosol particles on the local scale measured in real-time. These “baseline” values were running mean values of the lowest 5% in a running time period of 180s for minimizing the effect of measurements affected directly by emissions for instance of cars right in front of the van (Ehlers, 2013).

Each day of the intensive period a specific track was carried out that lasted several hours. The measurement routes started at the IASS institute in Potsdam and followed cross-sections throughout Berlin and its surroundings (see Fig. 1 for more details). Some of the focus areas were industrial areas such as Siemensstadt and Rummelsburg, the Tiergarten tunnel (ca. 50,000 cars/day, Senate Berlin, 2011) and AVUS (ca. 50,000 cars/day at Grunewald and > 80,000 at Berlin West) for traffic emissions, and various urban green spaces,

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Grunewald (surrounding streets: <1,000 to 50,000 cars/day, 1 sample), Treptower Park (surrounding streets: 20,000 cars/day, 12 samples) and Pfaueninsel (>1,000 cars/day, 1 sample). In addition to the continuous measurements canister samples were carried out and analysed for volatile organic compounds (VOCs) by GC-MS right after return to Jülich (Ehlers, 2013). Further details of the set-up of the van and the analysis methods can be found elsewhere (Ehlers, 2013; Ehlers et al., 2014; 2015; Barker et al., 2006).

3.3 Airborne measurements

Due to technical limitations and restrictions of flight permission over Berlin, air-borne measurements were carried out at the borders of the investigated region and used to characterize the in- and outflow of particles and trace gases. Two different platforms were applied, each during a separate period. Both measurement set-ups are based on long-term experience and included a number of measurements further described below.

The first set of observations was recorded by the KIT ultralight aircraft (Junkermann, 2005; Junkermann et al., 2011) on the 12th of June (11:53 am – 2:30 pm CEST) during the first days of the campaign. The flight originated in Schönhagen (EDAZ) south east of Potsdam and followed an eastbound trajectory to Eggersdorf (EDCE) near Fürstenwalde, from which it returned towards Schönhagen for a repetition of the track further to the south (see Figure 1). Due to the prevalent weather type on that particular day the outflow of Berlin was characterised. The aircraft was equipped with a set of instruments for aerosol number and size distributions, meteorological variables and trace gases (see Table A1; Junkermann, 2005; 2011). The aerosol size distribution instrumentation, consisted of a WRAS system, GRIMM (Ainring, Germany), measuring the ultrafine fraction with an Scanning Mobility Particle Spectrometer (SMPS + C, GRIMM, Model 5.403) in the size range from 4.5 to 350 nm and the fine fraction from 300 nm to 20 µm with an optical particle spectrometer (OPS, GRIMM, Model 1.108). The total number of ultrafine particles was measured with a separate fast (1 sec) condensation particle counter (GRIMM, CPC4).

The second flight took place on the 10th of October 2014 (9:30 – 10:45 am CEST) a month after mobile ground measurements had been finished. It was executed by the University of Applied Sciences in Düsseldorf in the context of a measurement campaign at Melpitz, close to Leipzig, organized by TROPOS (Leipzig, Germany). Particle size distributions, particle number concentrations, black carbon (BC), sulphur dioxide (SO_2) as well as temperature and relative humidity were measured from a Diamond (DA42) twin-engine small airplane. Air was sampled using an isokinetic inlet just below the pilots' right window. For details see Weber et al. (2012). Wind conditions on that particular day were as follows: ground level wind speed was 13 km/h from the south west and varied between 11 and 33 km/h on the flight level (see Figure S5.1 in supporting online information). The flight entered the Berlin area in the southeast and continued at the edge of the inner flight control zone making a clockwise circle around Berlin (see Fig. 1). Temperature and humidity data loggers (VOLTCRAFT, DL-121TH), unipolar charger and electrometer (GRIMM, NanoCheck 1320, ultrafine particle number concentration, 25 nm < D_p < 300 nm), optical particle counter (GRIMM, 1.109, accumulation and coarse mode particles, D_p > 0.25 µm), aethalometer (MAGEE, AE 33 Avio, BC), and an sulphur dioxide instrument (Horiba, APSA-370) measured continuously with a time resolution of 15 s (SO_2) or higher. The prevailing wind direction during the flight

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period was from southwest; both inflow and outflow were measured. A complete list of instruments and their time resolution can be found in Table A1.

3.4 Method of relative parameters

Over the course of the three month campaign, measurements were taken by different platforms, at different locations, under different meteorological conditions, and with different time resolution. To make all the data acquired comparable and to facilitate comparison independent of meteorological conditions such as daily maximum temperature, all mobile measurement values were related to the background value of the corresponding parameters at the reference site in Berlin-Neukölln (von Schneidemesser et al., in prep.) at the same time. Previous work on analysing mobile measurements (e.g. Van Poppel et al., 2013) has required an average background value (reference site). For comparison Van Poppel et al. (2013) subtracted this background value from the measured value (Van Poppel et al., 2013). The result is a direct marker of local changes with respect to the background site without any possibility for changes by time. Other approaches (e.g. Van den Bossche et al., 2015) subtract the current pollution level at the background site at identical time in addition to the method applied by Van Poppel et al. (2013). Except for temperature measurements, for which we applied the Van den Bossche et al. (2013) approach, we applied the "relative" approach for surface bound observations. The approach was as follows:

Calculation of the individual relative value by dividing the calibrated mobile measurement by the observation of the same parameter at the reference site at the corresponding time. For temperature (in degrees Celsius) this was done by subtraction instead of division as the difference is more representative than the ratio.

$$\Delta X_{rel} = X(\text{mobile})/X(\text{reference, MC042 or MW088}) \quad (1)$$

This method yields not the absolute difference, which varies for different meteorological conditions but the decreasing or increasing percentage compared to the background site (normalization).

The representative reference site was chosen as a permanent urban background measurement station (Shahraiyni et al., 2015a; 2015b) of the Berlin Senate, i.e. the aforementioned Nansenstraße monitoring network site in Berlin-Neukölln (MC042; Berlin Senate, 2015). The long-term measurements from this station (container MC042) provided reference data for O_3, CO, NO and NO_2. Additionally, further instruments for the observation of particle properties (mass, number and size) as well as for quantification of selected VOCs were placed in a measurement van (MW088, Berlin Senate) parked at a distance of about 5m next to the container MC042 in the street at the curb. In this way, a reference was provided against which the mobile measurements could be related to facilitate comparison over space and time. While the mobile measurements were taken on the order of seconds (see also Table A1) the reference site values were 30 min averages to reduce fluctuations and to minimize short term effects of the urban background.

The resulting dataset allowed for the assessment of the van and bicycle measurements at different times and locations to support the identification of different sources and the corresponding regions of impact. All data 'relativized' to the Nansenstraße urban background site in Berlin-Neukölln will be referred to as the 'relative values' of the urban background reference station.

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3.5 Classification of observed data by land use types

The mobile measured data were classified according to the CORINE land use map (Bossard et al., 2000; Waser and Schwarz, 2006; European Environment Agency, 2012). CORINE classifies several tenths of different categories of which 15 land use types representative for the area of interest were extracted and partially lumped. The categories relevant are listed in Table 4. The surface classification had a moderate resolution (100m x 100m) and referred to conditions in 2006 (European Environment Agency, 2012). A data point was associated with the predominant land use type for the grid in which it was located. There were three categories of forested areas (coniferous, deciduous and mixed forests), and two categories for urban residential areas (block arrangements (continuous buildings) and single houses (discontinuous buildings)) reflecting the effect of dilution and mixing of pollutants. Once mobile measurement values had been classified, the values were divided by values of identical parameters observed at the reference site in Neukölln at the same time. Results are displayed for classification types with sufficient data (>100 data points, Wilcoxon test) for analysis. Other classification types with partially sufficient data are displayed in shaded colours to indicate tendencies but were not used for detailed discussion.

4 Results and discussion

The measurement and analysis results and their discussion will be structured as follows: Trace gas measurements will be presented in Section 4.1, particle measurements in Section 4.2, and temperature measurements in Section 4.3. However there is a strong connection between these parameters, which will be taken into account for the discussion.

4.1 Trace gases: VOCs, CO, NOx, and ozone

4.1.1 Volatile organic compounds (VOCs)

Canister air samples were taken at different hotspots of traffic (anthropogenic) and vegetation (biogenic) dominated emission related sites in Berlin. A list of all the species quantified for six selected locations is provided in Table 5. These include two locations dominated by traffic emission (AVUS motorway and “Tiergarten tunnel”), three locations dominated by biogenic emissions (“Grunewald”, “Treptower Park” and “Pfaueninsel”) and one location for the representative urban background condition in Berlin-Neukölln with both, trees and minor amounts of traffic within the next 150m. A tentative sample was taken in the vicinity of a leaf blower being used, which is a common method for cleaning the pavements. This will be used for interpretation of observations made in residential areas, where a running leaf blower was turned on and may have affected the measurements. It is provided in the supporting online information document (Table S2.1). All compounds were considered to be representative for conditions at background level, where no direct emission sources were expected, e.g. toluene mixing ratios in vegetation dominated areas and isoprene and monoterpenes in traffic dominated areas. If the monitored concentrations exceeded the background level i.e. the level of vegetated areas

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unaffected by direct emissions of the corresponding compound (average of the two locations with the lowest mixing ratios + 2·standard deviation), they were marked in bold. Therefore, all compounds marked in bold colour represent substantial influence by anthropogenic emissions on the vegetation. The biogenic VOCs and oxidation products exceeding the average value plus two standard deviations in the traffic related areas are underlined, indicating substantial impact of BVOCs on the traffic dominated locations. In general, the mixing ratios of AVOCs observed at the AVUS (motorway in the western part of Berlin) were substantially higher than for all the other sites e.g. within the Tiergarten tunnel (city centre), Nansenstraße (reference site) or Grunewald. A compound concentration specific ratio of selected location/reference site larger than unity (= enhancement) was found between 2 and 27 for non-biogenic species, depending on the individual species. The sample results show substantially elevated (significance level of ±5%) levels of smaller alkanes, alkenes and alkynes such as ethane, butane, propene, ethyne and propyne (Table 5). As expected from previous studies (e.g. Caplain et al., 2006; Stojic et al., 2015, Valach et al., 2015), typical aromatic compounds like benzene, toluene, trimethylbenzenes (TMBs), ethylbenzene, and xylenes, as well as several alkanes and alkenes, methyl butene and ethanol were present in high quantities. Those compounds are related to fossil fuel consumption and are released either by incomplete combustion or by volatilisation from fuel tanks (Jedynska et al., 2015; Schmitz et al., 2000). Ethanol can be related to the increased usage of bioethanol in E10-fuel (10% of ethanol). The situation is similar within the Tiergarten tunnel, although the AVOCs were on average only 38±29% of the concentration levels at the AVUS. The ratio VOC(Tiergarten tunnel)/VOC(AVUS) is lowest for the most reactive species (alkenes such as butane and TMBs, 14-17%) and highest for general oxidation products of tropospheric chemistry (e.g. methanol 91%). Two exceptions were butanol and cyclopentane with +130%, indicating different sources or a different car fleet within the centre of Berlin controlled by the "Umweltzone", while independent investigations on vehicle identification numbers did not show a significant change in car types (Berlin Senate, 2011). Further information about the effect of the Berlin "Umweltzone" can be found elsewhere (Berlin Senate, 2011).

The "Grunewald" sample was typical for a forested area partially influenced by anthropogenic pollution, i.e. cross-cut by the motorway: Most VOC concentration levels stayed at quite low values. However, certain aromatic compounds like p-ethyl toluene, xylenes and ethyl benzene) displayed substantially enriched concentrations similar to octane. BVOCs displayed a mixture of coniferous and deciduous tree emissions with isoprene and monoterpenes and their corresponding primary oxidation products (methacrolein, methyl vinyl ketone and acetone). Different observations have been made for Treptower Park, with even elevated aromatic compounds levels, i.e. benzene with more than 200 ppt_v and toluene with 275 ppt_v. Values have been found significantly enhanced for smaller alkanes and alkenes including ethane, various derivatives of propane and general organic oxidations products. Ethyl toluene was significantly enhanced indicating a substantial influence of the nearby traffic on the vegetation of the park. Its primary biogenic emission was monoterpene with α-pinene highest among the vegetated sites. This location can be assessed as an exemplary case for vegetation impacted by anthropogenic emissions. The situation changed with respect to the Pfaueninsel location. Aromatic compound concentrations were fairly low and biogenic compounds such as isoprene and its oxidation products elevated. Methanol and acetone were highest among all the samples achieved. It is of interest however, that cyclopentane and 1-hexene displayed remarkably enriched levels as found in the Tiergarten tunnel samples pointing to present

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traffic sources potentially of smaller boats and the ferry close by. While benzene was low, toluene and dimethyl-pentane were highest for all the vegetated sites. TMBs and n-decane were enhanced too.

Different effects and impacts of anthropogenic and biogenic sources combined at the urban background site at Nansenstraße. While anthropogenic VOC concentrations at Nansenstrasse were found remarkably smaller than measured within the Tiergarten tunnel and at the AVUS their amounts were substantially larger than for the vegetated areas. At the same time BVOCS were elevated because of the nearby trees and plants, similar to Treptower Park with some exceptions. The BVOC composition changed somewhat because of a different vegetation composition and structure. α-pinene concentrations were smaller but isoprene and β-pinene concentrations were comparable to the conditions at Treptower Park. The Nansenstraße samples displayed higher levels of smaller alkanes and especially high levels of methanol and acetone, i.e. the highest sampled in this study.

For all the samples performed the individual contribution of isoprene and monoterpenes depend on the vegetation types, i.e. deciduous or coniferous, and the individual tree types close by (Guenther et al., 1995). While coniferous trees with elevated monoterpene emissions dominate in the Grunewald area, Treptower Park and the vegetation close to the Pfaueninsel consists primarily of deciduous trees, thus isoprene emitting ones (Berlin Senate, 2010; 2013b). The concentration difference reduces for the oxidation products such as methyl vinyl ketone and methacrolein, which have longer ambient lifetimes and are transported to a larger extent.

The high local levels of methanol and acetone found may be caused by different processes: Methanol is either of biogenic origin (McDonald and Fall, 1993; Folkers et al., 2008, Holst et al., 2009) or an oxidation product of a variety of organic compounds e.g. methane and toluene (Atkinson et al., 2006). Acetone is primarily a product of tropospheric oxidation chemistry of most organic species, including methane too (Atkinson et al., 2006). Direct emissions of methanol, acetone and acetaldehyde have been reported for forests elsewhere (Gordon et al., 2014, Rantala et al., 2015), which is expected to be growth related (Hüve et al., 2007). A potential further source are marshy type (Berlin Senate, 2010; 2013b) such as the flat water-soaked shoreline along the river Havel between the measurement sites and the Pfaueninsel yielding emissions from decaying organic matter (Warneke et al., 1999) and water based plant processes (Kreuzwieser et al., 2000). Notable amounts of acetaldehyde and acetone are expected to have formed by photochemical sources such as ethane and n-butane oxidation (Atkinson et al., 2006). In order to summarize, the canister samples provided snapshots of the change of the presence of VOCs with the urban area of Berlin. Depending on the distance of the closest anthropogenic or biogenic emission sources the corresponding VOCs were detected in significant amounts. Smaller alkanes and alkenes plus aromatic compounds were found as systematic markers for anthropogenic influence on the different types of vegetated urban areas, i.e. parks and forests. Biogenic VOCs were found in substantial concentrations in all of the locations and provided a significant contribution to urban background VOCs.

4.1.2 Carbon monoxide (CO)

The mobile observations displayed a similar pattern for all the traffic related gases (NO, NO_2, AVOCs and CO) and particulates. In addition to its major urban source from traffic (incomplete combustion of fossil fuels; Klemp et al., 2012) CO may originate to a smaller extent from photochemistry (Finlayson-Pitts and Pitts, 2000;

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Atkinson et al., 2006; 2006). Because of its longer atmospheric lifetime (1-4 months, Seinfeld and Pandis, 2006) compared to standard reactive gases such as ozone and NO_x emissions and atmospheric transport are the dominant processes influencing the spatial distribution of CO. The elevated CO mixing ratios due to high traffic intensity can be seen in the horizontal distribution of CO (all the measurements, CO all) and dampened in plots with the lowermost 5% of a running mean (180 s) (named 'CO baseline' in the following) (not shown). These running mean ("baseline") values excluded values affected by direct emissions from for instance nearby cars (Ehlers, 2013). The mobile measured values ranged between 100 ppb_v and 43.8 ppm_v for CO all and between 100 ppb_v and 3.8 ppm_v for CO baseline. The corresponding relative values of CO varied between 0.01 and about 230 times the value at the reference site in Neukölln. The spatial heterogeneity of the relative CO mixing ratio is displayed in Figure 2 on the top as general overview and at the bottom zoomed over a smaller area including the reference site in Berlin-Neukölln. Higher relative mixing ratios, likely owing to vehicle emissions in close proximity and/or substantial traffic emissions, are indicated by reddish colours and were found at hotspots at major traffic routes and crossings such as Zoological Garden, AVUS, Frankfurter Allee, Urbanstraße and Mehringdamm (Fig. 2). Unity identifies points with identical volume mixing ratios measured from the van and measured at the Neukölln station (BLUME station). For illustration purposes, the ratio of 1 (identity) ±10% is depicted in blue, smaller values are shown in yellow and higher ones in red.

4.1.3 Nitrogen oxides

The situation is similar for nitrogen oxides (NO_x). In the BBMA NO_x are emitted primarily from vehicles, specifically fossil fuel based internal combustion engines (Tullius and Lutz, 2003). Figure B1 of the appendix displays the mixing ratios of NO and NO_2 (top), as well as the relative values (bottom). Several locations had elevated mixing ratios and relative values: (i) the Tiergarten tunnel with accumulation of pollutants and substantial amounts of traffic, (ii) the "Straße des 17. Juni" across the Tiergarten and its continuation as "Unter den Linden" with a significant number of public transport and tourist busses and older vehicles, the major traffic routes such as (iii) "Frankfurter Allee" (East), (iv) "Mehringdamm" (South), (v) "Westkreuz" and (vi) AVUS (West) as well as (vii) around the Central station. The individual locations are indicated in Figure B1 as far as they are included in the plots.

The observed median mixing ratios ranged between 5.6 ppb_v for NO and 0.7 ppb_v for NO_2 in more remote locations with little traffic, and 2.1 ppm_v NO and 2.9 ppm_v NO_2 in locations characterized by significant traffic, including in some cases traffic hubs at the intersection of major roads coinciding with bus terminals and other public transport infrastructure, e.g. "Hardenbergplatz" near "Zoologischer Garten". The relative values ranged from 0.5 to 4000 for NO and 0.2 to 500 for NO_2. The median relative values were 15.1 for NO and 1.3 for NO_2 for all measurements, whereas the median of the relative values for NO and NO_2 for areas classified as urban (continuous and discontinuous buildings) were 23.9 and 19.2, and 15.7 and 12.2 in commercial areas & transport, respectively (Figure 3). Therefore we can state that for most of the road related area analysed the mixing ratios were found to be higher than in Neukölln except the remote background sites such as forest or agricultural areas out of Berlin.

The emitted NO reacts with ambient ozone to be converted into NO_2. The NO_2 can subsequently be rapidly photolyzed back to NO and $O(^3P)$, which subsequently re-forms ozone, in the case of sufficiently strong solar

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radiation. Through these reactions, ozone is rapidly consumed by reaction with NO, if and only if NO is present in substantial amounts, and re-formed by the subsequent photolysis of NO_2. In a photostationary steady state (PSS), with no additional sources of NO_2, the relative mixing ratios of NO, NO_2, and ozone are determined by the photolysis rate of NO_2. NO measured on the road was often found to be approximately ≥15 times higher than the values recorded at the Neukölln urban background site and therefore converted to NO_2 by ozone if it was sufficiently available. However, the low ozone mixing ratios observed at the road sites, where high levels of both NO_x species were measured cannot be explained by the PSS chemistry alone, suggesting the presence of an additional source of NO_2. In this case the change in median NO_2 mixing ratio between urban residential areas with block buildings such as at the reference site at Nansenstraße is +39.6 ppb_v, while the decline in median ozone volume mixing ratio is only -7.2 ppb_v, i.e. an excess of 32.4 ppb_v with respect to NO_2 assuming a constant Ox value throughout the city (absence of substantial NO_x emissions). Thus, the expected NO_2 would be 23.9 ppb_v and the measured median one is 63.5 ppb_v. It is well known that substantial amounts of NO_2 are produced and released by oxidation catalytic converters of Diesel cars (Li et al., 2007). The car fleet of Berlin residents and companies consists of 29.9±3.5% diesel driven passenger cars and 93.1±0.7% of diesel consuming light-duty commercial vehicles (Berlin Senate, pers. comm.). Based on the study of Tullius and Lutz (2003) it is expected that this source type contributes significantly (33%) to the measured nitrogen oxides mixing ratios especially in urban areas with notable traffic and transport. Other sources like the energy industries, non-energy combustion, non-road transportation and industry provide the remaining 67% of NO_x production excluding ship emissions for which Tullius and Lutz (2003) did not have information. However a detailed calculation of the NO_x budget was out of the scope of this campaign.

4.1.4 Ozone (O_3) and Ox

The observed volume mixing ratios of ozone are a product of the different compounds discussed earlier on: VOCs (4.1.1), NO_x (4.1.3) and CO (4.1.2). Their photochemical reactions (Finlayson-Pitts and Pitts, 2000; Atkinson et al., 2004; 2006) depend on different intensities of local surface sources and sinks as well as on the transport of ozone and precursor species from other areas. As ozone is not directly emitted and forms exclusively in the gas-phase, it is secondary in nature. As described in Section 4.1.3, the urban ozone mixing ratio is closely related to the mixing ratios of NO and NO_2, as well as the photolysis rate of NO_2. When the PSS holds, the mixing ratios of ozone and NO_2 vary inversely with each other, with their sum being constant. This sum is referred to as "Ox", which is generally an invariant background quantity in the area of observation, as long as the PSS holds. Because of this ozone and Ox were expected to vary in space to a smaller amount than for instance CO and NO.

Mobile measured ozone mixing ratios were quantified between negligible values and 62 ppb_v (Fig. 4). Median values for urban residential areas were situated around 28 ppb_v for ozone and 52 ppb_v for Ox. The highest median ozone values were found in agricultural areas 46.5 ppb_v and the lowest in the vicinity of parks 17 ppb_v. Sport and leisure facilities displayed notably enhanced concentrations, while much lower concentrations were observed in forests (23-27 ppb_v) with the exact values depending on the forest tree type (Figure 5). Nevertheless notable variations of -70% to +30% of the mixing ratio of O_3 relative to the O_3 measured at the reference site in Neukölln (MC042) were identified within the surrounding 500 m (Fig. 5).

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4.1.5 Land use type effect on relative changes for gaseous pollutants

Trace gas mixing ratios displayed clear differences between different land use types. As frequency plots of measured gaseous mixing-ratios (not shown) provided evidence of non-normally distributed values, we provide median and 25th as well as 75th percentile values throughout this study. Figure 3 shows median values and interquartile ranges for CO, NO, and NO_2. Both, the measured values and the relative values are shown. As noted above, this relative approach allows for comparison of different conditions by reducing meteorological and large scale effects. In this context we assume meteorological conditions to be of minor relevance for the relative value approach used.

Several aspects are evident: Carbon monoxide and nitrogen oxides displayed quite similar land use type effects and therefore similar conclusions can be drawn. CO baseline and CO all mixing ratios (Fig. 3, top) were lowest in areas covered with vegetation, i.e. agricultural fields (-21% compared to urban values) and forests (-6% with respect to urban conditions), where emissions by traffic sources are expected to be smallest and dilution during the transport strongest. Baseline CO values were clearly elevated in industrial (+10%), commercial and transportation (+78%) affected areas. The effect on nitrogen oxides (Fig. B1, NO (middle) and NO_2 (bottom)) was even more pronounced and lower in areas covered with vegetation such as agricultural fields and forests (ca. -75%), and were highest in industrial (+86%) and commercial and transportation (+190%) affected areas. The relative NO_x values for residential urban areas were located between the higher values in the industrial, commercial and transportation affected areas and lower values in forests with increasing ventilation reducing the NO_x concentrations notably. Nearby parks nitrogen oxides were found at elevated levels (+100%) likely owing to nearby traffic sources and accumulation (less ventilation, reduced photolysis rates near the surface). Finally, median NO_x levels in- and outside of Berlin were investigated to indicate the predominant local source: Total NO_x in urban residential areas and the measured roadside NO_x showed increases of 293 % and 906 % relative to forested areas depending on the type and the route, respectively. This presents evidence that dominant summertime NO_x sources in Berlin are local and these are likely to originate primarily from traffic.

Measurements of Ox (sum of NO_2 and O_3) were constant, i.e. within the range of the notches, over most surface types, at about 51 ppb_v (Fig. 5). Exceptions to this were forests, where median Ox varied between 42 (deciduous and coniferous) and 52 ppb_v (mixed), and areas classified as “commercial and transport”, where median values reached about 84 ppb_v. Within and near forests, observed ozone mixing ratios declined along with Ox mixing ratios, consistent with a sink of ozone due to reaction with biogenic VOCs (see below). Over “commercial and transport” areas, observed ozone mixing ratios increased together with Ox mixing ratios (median increase by about 40 ppb_v, see section 4.1.3 for details), which together with elevated levels of NO_x, is consistent with a local primary source of NO_2 due to diesel vehicles resulting in a 40 ppb_v higher NO_2 value than expected from the PSS.

Ozone mixing ratios over land surface types other than forests and “commercial and transport”, were quite different from each other, despite having similar levels of Ox. Ozone substantially increased (+30%) in agricultural areas and decreased in industrial (-27%) areas, while NO_2 decreased (-28%) in agricultural areas and increased by +100% in industrial areas. Agricultural areas are predominantly located in the outskirts of the city,

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and are characterised by low mixing ratios of NO_x. Industrial areas are generally closer to the centre, and display higher NO_x mixing ratios (Fig. 3). For a certain group of surface usage types (urban residential areas, industry, airport and parks) the Ox value stayed constant within 5% confidence interval based on-road measurements, for which an inverse relationship between the mixing ratio of NO_x and the mixing ratio of ozone was found. This is consistent with the assumption of NO_x-saturated chemistry over an urban area, in which increased emissions of NO lead to "titration" of ozone. A different situation was found for sport and leisure facilities such as Tempelhof Air Field and Olympic area in Ruhleben, where Ox was significantly smaller (relative Ox = 0.88, i.e. -12%) with NO_2 reduction by 5.1% and ozone reduction by 36.9%. Either the situation is non-NO_x-saturated or the PSS was not achieved.

Ozone mixing ratios and nitrogen dioxide in forests are lower than those in the urban background (exception mixed forests), while the relative Ox change (-24.6%) that is smaller than the reduction in NO_2 (-26.7%) and in O_3 (-31.4%) (Figs. 3 and 5). The van based observations indicate a NO_x-limited ozone production scheme, which is associated with notable emissions of terpene and of isoprene. This may be caused by the vegetation stress response to ozone pollution (Bonn, 2014) with an enhanced release of VOCs (Guenther et al., 1995) reacting with ozone and thus acting as a local sink for ozone, and thus Ox. According to Bourtsoukidis et al. (2012) coniferous spruces start emitting notably more amounts of terpene species above 35 ppb_v of ozone, with the emission controlled more and more by ozone the higher the stressor gets. Subsequent to emission, those particularly high reactive terpenoid species destroy ozone (Atkinson et al., 2006) and their oxidation products form new aerosol particles in number and secondary organic aerosol mass (Bonn and Moortgat, 2003; Griffin et al., 1999; Sakulyanontvittaya et al., 2008). Total NO_x is also lower in forests (Fig. 3), likely due to lower emissions from vehicles. Combined with the sink of Ox, this leads to lower mixing ratios of NO_2 in forests. A similar reduction in Ox over 'parks' such as the 'Tiergarten' area is not seen in the BAERLIN results (Fig. 5). Generally, ozone concentrations in parks were found to be significantly smaller (-36%) than in Neukölln, while NO and NO_2 were enhanced by +98 and +86%. Parks seem to represent a mixture of urban residential areas and the nearby traffic sources, with the corresponding median Ox value is within the ±5% range of 'background' Ox values.

Our results indicate that the main impact of vegetated areas on gaseous processes and concentrations in Berlin may be the chemical deposition effect that is particularly high over monoterpene emitting coniferous forests within the urban area. The relatively small ozone reduction found in the vicinity of isoprene emitting deciduous trees may indicate that ozone formation partly compensates ozone deposition at these sites.

4.2 Particulate pollution

Aerosol particles were potentially among the most challenging aspects of this campaign, as they can originate from long-range transport and local primary particle sources or gaseous precursors, depending on individual sources and are influenced by the presence of clouds and precipitation and their loss depend on size and hygroscopicity too. They may possess an atmospheric lifetime of up to ten days and secondary (semi-volatile gaseous) constituents adjust their phase distribution according to temperature and their vapour pressure related gaseous mixing ratios. Thus, for a detailed analysis of interactions between secondary organic particular mass and ozone for example a box model approach is required to track the related semi-volatile compounds in both

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phases. This box model analysis is beyond the scope of this article, which will serve as characterising the conditions for a follow up publication (Bonn et al., in prep.). The different mobile approaches were implemented to look at small scale variation across the city and so to help distinguish local traffic from large scale sources. The airborne measurements were used for identifying the transport of pollutants and precursors into the entire area and to gain insight into the dominant sources at elevated levels.

4.2.1 Airborne measurements: City sources vs. transported particulate pollution

Upper boundary layer values of total particle number concentrations (PNC) above 4.5 nm in diameter (D_p) in an altitude of about 300 to 500 m above ground were about 2,500 particles cm^{-3} ($PNC_{4.5}$ displayed as UFP, Fig. 6) at the edges of the city of Berlin and increased to 9,000 – 12,000 cm^{-3} when passing through the Berlin city plume. The city plume values were in agreement with the ones found at urban background conditions in Neukölln (PNC_{10}, 8,800±5,000 cm^{-3}, D_p > 10 nm), indicating a very similar atmospheric composition and a minor contribution of particles between 4 and 10 nm in aerodynamic particle diameter. The mixed layer height on the 12th of June (ultralight aircraft flight) was about 1,500 m a.g.l. (derived from HYSPLIT (Draxler and Rolph, 2013) and observed cloud base temperature). Additionally on top of this city plume two well defined plumes were observed on both flight sections W→ E (ca. 12:45-13:00) and returning E→W (ca. 13:15-13:30) with a $PNC^{4.5}$ of 35,00-55,000 cm^{-3} and a PNC_{10} of 35,000 cm^{-3} with a geometric mean diameter (GMD) of 12 nm and 45,000 cm^{-3} at a GMD of 15 nm. These two plumes were nearly exactly downwind of the two coal fired power stations located inside the city limits, Reutter West (600 MW), North of the Olympic Stadium in Berlin-Charlottenburg (West, N 52° 32' 6.25" E 13° 14' 30.59"), and Klingenberg (680 MW), in Berlin-Rummelsburg (East, 52° 29′ 24″ N, 13° 29′ 42″ O). This was concluded from back trajectory analysis (HYSPLIT; Draxler and Rolph, 2013) obtained for different positions of the flight. The observed small geometric mean particle diameters clearly indicate recent particle number formation events, which are likely to have occurred either within the exhaust chimney or within the plume of the individual power plant. The same applied for the airplane measurements in October. When crossing the corresponding areal sector of a power plant with south westerly winds (Fig. S1), number and mass concentration increased significantly with the sulphur dioxide (SO_2) concentration displaying small jumps as the ultrafine particle number concentration (UFP, 25nm < D_p < 300 nm) increased (Fig. 7). However, SO_2 was higher at smaller UFP and so this was apparently not the limiting quantity for nucleation. At the times of highest UFP the smallest concentration of BC was found on that particular flight, indicating smallest total particulate mass burden and coagulation sink potentially allowing the newly formed particles to survive longer and to grow before being captured by pre-existing larger particles. Up to 4000 ultrafine particles cm^{-3} were detected at around 1,500 m altitude, i.e. around the uppermost mixing layer height or slightly above. The flight around Berlin on the 10th of October 2014 (see Figs. 2 and S1) displayed a strong gradient throughout the BBMA area (Figs. 7 and B1), from rather clean conditions around 1,000 cm^{-3} downwind of BBMA to 4,000 cm^{-3} in UFP upwind of BBMA, i.e. behaving the opposite to major PM sources. These sources would enhance the condensation sink, i.e. reduce the lifetime, of condensable species and a new particle formation would occur either in a much smaller intensity or would be prevented (Kulmala et al., 2001; Lehntinen et al., 2003). This clearly indicates that the majority of sources have to be found within the city boundaries at

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both times of measurements (Figs. 6, 7 and B1). This is confirmed and even highlighted by the ultralight aircraft flight on the 12th of June at a lower altitude, with total $PNC_{4.5}$ reaching up to 45,000 cm^{-3}, a value that is similar to urban concentrations above a particle diameter of 10 nm within continuous traffic situations.

In contrast to $PNC_{4.5}$, PM_{10} and $PM_{2.5}$ flight level mass concentrations were substantially lower (PM_{10}: ca. 8 $\mu g/m^3$, $PM_{2.5}$: ca. 6 $\mu g/m^3$) compared to the value detected at the surface at urban BLUME monitoring sites in the city centre (PM_{10}: 20-25 $\mu g/m^3$). Particle mass concentrations were similar to concentrations observed at the city border on the flight day at measurement stations in Grunewald (west) and in Friedrichshagen (southeast) with PM_{10} values between 9 and 10 $\mu g/m^3$ (BLUME, von Stülpnagel et al., 2015). Only in the Northeast of Berlin (downwind of the city), close to Buch and Bernau, were moderately elevated mean concentrations of 16 $\mu g/m^3$ observed at the surface measurement stations (BLUME, von Stülpnagel et al., 2015) and at flight level (15 $\mu g/m^3$, this study). As a conclusion of this part, it can be stated clearly that there was a moderate background concentration of particle number and particular mass, which increased substantially inside the Berlin area because of city based emissions.

4.2.2 Van measurements: The regional and local situation

Next we focus on surface bound measurements on the regional and local scale. As the elevated particulate number and mass concentrations tend to originate locally, the van measurement facility of RC Jülich quantified particulate number and mass concentrations for cross-sections of the BBMA area. Simultaneous gas-phase detection supported the attribution of sources and sinks. An overview of median particle number and mass (PM_{10}) concentrations and their variations is given in Tables 6 and 7. Again the parameters displayed a non-normal distributed frequency plot. Details for further parameters such as PM1 can be obtained from the supporting online information. The local sources and the heterogeneity of particle concentrations in the city become obvious in Figs. 8, C2 and C3. As done for the standard gases measured, all measurements have also been divided ("normalized") by the measurements at the reference site at the same time for comparison. Relative particle number concentration ratios (relPNC ($2.5\ nm < D_p < 7\ \mu m$ (NanoCPC) vs. $4\ nm < D_p < 3\ \mu m$ (GRIMM5.416)) were gained from different instruments with different cut off sizes. However with respect to particle number concentration, particles above a diameter of several hundred nm have been found negligible for most conditions when compared to particle numbers at smaller sizes (Seinfeld and Pandis, 2006; Friedlander, 2000). Due to intense emissions in the urban area and the subsequent coagulation of smaller partially unstable particles the detection of sizes between 2.5 and 4 nm in particle diameter is usually scarce and the vast majority of particle number is located between 50 and 100 nm. Comparisons of both types at the reference site displayed no significant difference between both observations used for comparison, i.e. the NanoCPC by RC Jülich and the GRIMM 5.416 by UBA.

The focus is set on the baseline concentrations (lowest 5% in a moving 180s time interval) as for CO, as particle number concentrations e.g. directly behind an emitting passenger car provide short term peaks that last for seconds only and which are hard to compare with measurements on the flight level (always off from the emitter, thus baseline) or at the urban reference site. Nevertheless, ranges for peak values will be noted as available. RelPNC values found for the van measurements ranged from about 30% of the urban reference value outside of

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the area of Berlin, to the 85fold in areas with substantial traffic density and in street canyons with less ventilation. Peak values exceeded the 200fold concentration of the reference site. Highest values appeared at motorways and the primary entering routes into Berlin, i.e. Hohenzollerndamm, Hasenheide, Karl-Marx-Straße and the neighbouring streets in Kreuzberg and major crossings such as the Hardenbergplatz (Zoologischer Garten).

Similar patterns but much more moderate increases have been seen for particulate masses. This can be explained as follows: As remarkable fractions of particle mass are of secondary organic origin (mass closure at reference site in Berlin-Neukölln: 38.2±9.4%; Kofahl et al., 2012; von Schneidemesser et al., in prep.), new particle formation and particle mass production require different process times and sink strengths. The formation process of particles is rapid and occurs in seconds to minutes depending on the precursor concentration and is suppressed by high coagulation sink values i.e. substantial particulate matter already present. Mass production requires gaseous and multiphase oxidation with a timescale of minutes to days and present particular mass to condense on (inorganic species) or partition to (organic compounds). Consequently, depending on source strength the observed relationship between source and PM may result in a smeared picture in the vicinity (tens of metres) of sources, with greater enhancement for particle numbers.

4.2.3 Bicycle measurements: Quantifying the microscale on different timescales

As different areas have been probed by the van measurements two aspects could not be addressed: (i) Pollution levels in different distances to major sources such as cars, (i.e. roads, cycling paths, bus stops, walking path and parks) and (ii) the temporal variation at a particular site of interest. The bicycle measurements were able to contribute to answering those points. For comparison with van measurements, two routes were done with both platforms, i.e. bicycle and van, of which the 4th of August is shown in Fig. 9. As the bicycle measurements focussed primarily on particle classification, two graphs are shown, the left one for total particle number concentration (bicycle: DISCmini (10nm < D_p < 500nm) + GRIMM 1.108 (500nm < D_p < 20µm), van: (a) nanoCPC (2.5nm < D_p < 3µm) and (b) ELPI (30nm < D_p < 10µm), see Tab. 3) and the right one for particulate mass below 10 µm in diameter (GRIMM1.108 (D_p > 270 nm) vs. ELPI, Tab. 3). The van measurements of particulate mass were considered twice, i.e. all the measurements and the lowest 5% (bg = baseline) in a moving 3 min period to exclude peak values. In this case the PM_{10} comparison is displayed.

Please take into account that the measurements were conducted with the van following the cyclist at street level in order to exclude the vans exhaust. The different heights of the inlets for van around 2 m a.g.l. (Ehlers, 2013) and cyclist measurements at about 1m a.g.l. had impact on results very close to the sources. While the baseline values i.e. NanoCPC and DISCmini for number concentrations and GRIMM1.108 and ELPI for total particulate matter measured by the different platforms agreed well, peak values showed only a moderate agreement. As noted above the causes for these differences were most likely small and short term pollution drops, i.e. strong horizontal and vertical changes, as measurements were performed next to the location of particle number formation with rapid particle dynamics and growth processes associated with. Moreover both platforms were not always able to drive right next to each other because of traffic density and changing lanes. As can be seen in Fig. 9 on the left the comparison of both total number measurements of the van i.e. NanoCPC and ELPI disagreed in

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magnitude because of the different cut-off limits of both instruments. While the upper limit was less critical for total number concentration, the major effect was caused by the difference in lower detection limit with 3nm for NanoCPC, 10 nm for the DiSCmini and 30 nm for the ELPI with respect to the lowest particle diameter detectable. As freshly formed new particles from traffic are expected to appear at sizes below 30 to 40 nm in diameter the notable gap between DiSCmini and ELPI instruments became important (Fig. 9, left plot). With respect to total aerosol mass, displayed here as PM10, the van results (ELPI) are slightly higher than the bicycle observations (GRIMM 1.108). Baseline values were enriched by 16.4±0.1% and all values measured by 58.1±0.2%. This can be traced back to the different detection range of both instruments with the ELPI including particle masses between 0.03 and 0.3 µm and excluding the size range between 10 and 20 µm, and the different time resolution, $\Delta t(ELPI) = 1s$ and $\Delta t(GRIMM1.108) = 6s$. Because of this, smaller disturbances and emissions of passing vehicles caused a larger variation in van (ELPI) data than for the bicycle data (GRIMM 1.108) and the latter agreed better with the baseline ELPI values as stated above.

Two benefits of combining bicycle and van measurements were as follows: (1) the different speed at usual conditions and thus an improved horizontal resolution and higher local variation of data with respect to particle number concentration of bicycle measurements at identical time resolution and potential parallel observations at identical time at different distance to the particle source; (2) the impact of the particles lifetime on the agreement of number (relevant for smaller sizes) and mass (relevant for larger sizes) concentrations observed by the two platforms. With respect to (1) the exhaust of for instance a car gathering speed and therefore contributing to new particle formation was found to enhance the $PNC_{2.5}$ of the van in a more intense way than for PNC_{10} for bicycles, while hardly any change between both platforms was seen with respect to the mass (2).

While in general the complete area was of interest, several routes were frequently sampled by bicycle: (1) Potsdam – IASS to Berlin-Charlottenburg (26 times), (2) a central round track in Berlin including Schöneberg, Kreuzberg, Neukölln and Wilmersdorf (8 times) as well as (3) a cross-section of Berlin from Berlin-Charlottenburg via Tiergarten to Friedrichshain (11 times). In the following we concentrated on those tracks with the entire datasets (i.e. GPS and particle properties) with no gap in between were obtained and track (1) especially for demonstration purposes (Fig. 10).

During route (1) the focus was set on the differences between residential and forested areas as well as motorways (next to), while during track (2) the surrounding of the measurement site in Neukölln and the multitude of parks were of particular interest. Route (3) was an exemplary study of changing the full range of conditions from the west to the east driving along the major roads such as “Straße des 17. Juni” and “Unter den Linden”. It started at “Heerstraße” - one of the most frequented roads-, continued through the Tiergarten area with urban green space and terminated east of the touristic hotspots of Brandenburg Gate and Alexanderplatz.

As an exemplary track route (1) is shown (Fig. 10) and discussed. Forested and vegetated areas evidently displayed reduced pollution levels because of reduced sources and enlarged sinks. Relating distances to locations, the first maximum was seen (upper plot) close to Berlin-Charlottenburg at its western edge, crossing major transport ways of railway and cars (motorway AVUS). Subsequently, the cyclist rode across the Grunewald – a forest of substantial size (see above) – that is crossed by the motorway to Potsdam in its south eastern part. The cycling track was always west of the motorway inside the forest. During the transfer from forest paths to streets influenced by notable traffic (30,000-40,000 cars/day) near Wannsee, pollution levels

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increased remarkably with intermittent peaks due to passing busses and cars until reaching the Glienicker Bridge when entering Potsdam. Once wind was opposite to the predominant direction from the North West (300°, Fig. 10 lower graph) the pollution was transported from the nearby motorway to the bicycle track through the Grunewald forest more efficiently (south easterly winds, 140°). At one of two times with exceptionally high particle numbers in Grunewald (morning of the 14th of August, track 61 at Tempelhof) no wind direction was available from the record by the German Weather Service. However, before the gap starting at 4 am, i.e. four hours before the measurements the wind direction was around 160-180° (south easterly), agreeing with the other case of increase PNC_{10}.

4.2.4 Aerosol particle pollution characteristics and effect of land surface types

The aerosol particle burden quantified matched fairly well with pollution levels measured in a range of Central European cities (e.g. project UFIREG; UFIREG 2014). Our measurements provide evidence that both mobile measurement types can be combined for characterizing different land use types and for checking the reliability of the results from each method.

As done in the case of the gaseous parameters the observations were classified by the land use type based on the CORINE land cover (number: Fig. B2, mass: Fig. 11). Several aspects are particularly obvious: The urban areas with block buildings (continuous buildings) show a slightly enhanced particle level compared to areas with single houses (discontinuous buildings). Particle number concentration also tends to increase with decreasing street canyon width. This is apparent in the city centre comparing different street positions with a changing width, e.g. starting at Fehrbelliner Platz (widest) along the Hohenzollerndamm via Lietzenburger Straße (+26% in PNC compared to Fehrbelliner Platz) until Urania (denser, +96% in PNC compared to Fehrbelliner Platz). This indicates that ventilation effects do play an important role and thus need to be considered for urban planning. Second, changes in particle concentrations were largest for particle number concentrations. They were found to be highest in industrial and commercial areas with notable transport and production of goods (e.g. Kurfürstendamm, Kantstraße, Greifswalder Straße and Frankfurter Allee): +47±11% for baseline concentrations and +63±10% for all the observations (van). Observations in sport and leisure facilities did not display significant changes, but the ones in parks resulted in a different outcome for bicycle based measurements (-15±7%) and for van based measurements (baseline: no significant change, all: +55±28%), which evidently feeds back to the coarse surface classification of CORINE (Bossard et al., 2000) with 100m x 100m. While the van was unable to enter the parks and measured at the edges on the road, the cyclist passed through. In this case the bicycle seems the more appropriate platform, while for industrial areas and transport the van was optimum. For forests the particle number effect was identical within the confidence limit (bicycle: 0.67±0.04, van(baseline): 0.72±0.04; van(all): 0.66±0.10). It can be concluded that in vegetated areas PNC declined substantially except for sport and leisure facilities and that PNC was enhanced substantially in industrial, commercial and transport affected parts of the city.

The situation was less clear for particulate masses as e.g. PM10. While no significant change was observed for van(all) values between any of the types, van(all) was significantly smaller in parks (0.91±0.02) but not in forests (1.02±0.09) or sport and leisure facilities (1.01±0.01). Only the bicycle measurements displayed some expected changes: PM10 increased in industrial, commercial and transport affected areas by 44±9% and

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decreased for parks by 18±8% and for forests by 35±8%. A tendency but no significance for decrease was found in sport and leisure facilities (-17±14%). Thus we can conclude that vegetation affected surface areas reduced substantially the burden of particulate mass and particle number displayed best by bicycle measurements. Differences between the bicycle and van platform data likely stem from the circumstance that different tracks had to be used and the coarse CORINE classification treating sometimes even major roads next to a park as park surface.

This was for example the case for "forests". Rather large motorways crossings exist in some forests such as the Grunewald, and the van was either passing the forest on the western edge at the river Havel or on the motorway in the centre, while the cyclists always rode through the forest on a bicycle only route. At a moderate resolution (100m x 100m) this difference is not visible on the surface map used for classification (CORINE). For this reason, we consider the particle measurement values for forests to those obtained by the cyclists as a better proxy. Those are in line with what would be expected for a low-pollution land use type with concentrations between 55% and maximum 70% of the values found in Berlin-Neukölln.

Initial analyses of individual bicycle videos have indicated primarily traffic related sources for occurrences of high concentrations of particles, such as old double decker busses, mopeds and single ships when crossing bridges. Detailed results from this investigation will be published elsewhere.

4.3 Temperature

Bicycle and van measurements were combined to investigate the presence of the urban heat island effect (Collier, 2006; Seinfeld and Pandis, 2006). For most of the land use type classifications the differences between the van and bicycle measurements agree within the associated uncertainty. While the urban heat island effect was present, it was not as pronounced as in other metropolitan areas such as Paris or London (Dousset et al., 2011; Jones and Lister, 2009) with about +4 °C (Paris) and +2 °C (London, Jones et al., 2009) and ca. +1.3 °C in Berlin (von Stülpnagel, 2015), possibly attributable to the excellent ventilation and substantial green areas in BBMA. The change in temperature classified by surface types can be seen in Fig. C1. Please note that the observations have been made at daytime, which resulted in larger temperature differences between different surface usage types than for the average day within the Berlin metropolitan area (Fenner et al., 2015). A map (not shown) with the differences of measured temperature by mobile platforms and in Neukölln displayed only moderate changes as wind tends to equilibrate and changes were limited to tenths of degrees C on the local scale. However, certain land use types and wind circulation conditions enhanced cooling and mixing of air in the case of forests, larger park areas and areas with nearby water bodies. For instance forests are found to be cooler by ca. 2 °C while commercial and transport affected areas are found to be warmest (+0.3 °C). This is in agreement with the study of Dousset et al. (2011) stating that an increase of vegetation by 1% would result in a cooling effect of 0.2 °C in Paris. For some land use types such as for parks and commercial areas the results of both measurement platforms deviate substantially from each other. This is likely caused by a) the different time scale of measurements and time of day, as well as b) partially by using different pathways, e.g. by proceeding faster on the bicycle route, while the van is stuck in dense traffic, with the asphalt street heating up more in the sunlight. There is a difference in the surface temperature measured in urban areas with continuous buildings measured by the mobile devices and the reference station of -0.3 to -0.4 °C, i.e. the reference site displays warmer

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temperatures. This is caused by the shielding container set-up with only gently air movement present due to the surrounding vegetation, while at the street level in the shadow the surface may cool down easier, as the same temperature difference was observed between the temperature observed on top of the permanently parked van of Berlin Senate and on top of the container at Neukölln.

5 Conclusions

The mobile measurements with bicycle, van and air plane/glider as part of the BAERLIN2014 measurement campaign has demonstrated the ability of integrated measurement platforms to characterise air quality on multiple scales. Van-based measurements were used to cover a large geographical area in and around the city of Berlin, while bicycles, covered a range of main streets, but also penetrated to areas inaccessible for cars (pedestrian areas, parks and forested areas). Bicycles were found to be a cheap, flexible and reliable platform for characterising the spatiotemporal variations in pollutant concentrations and meteorological conditions over the three month campaign period. Comparison of van and bicycle measurements (particulate properties and temperature only) agreed within the uncertainty level when measured under identical conditions. The "relative value" approach used for individual parameters to compare different measurements of trace gases and aerosol particle by different platforms in different conditions was found to be very applicable to our observations.

During the period of investigation the elevated air pollutant concentrations found in Berlin were most likely produced in the vicinity of the observation and originated from local pollutant sources. Air plane measurements displayed additional substantially elevated particle number concentrations in air masses from both coal-fired power plants and within the flight corridor of Tegel airport. Van and bicycle based measurements observed elevated particle number and particulate mass concentrations as well as NO, NO_2, CO and VOC mixing ratios in traffic affected areas. As a consequence, emissions within the urban area of Berlin were responsible for the elevated particle levels between June and August 2014. Canister samples displayed the presence of remarkably elevated AVOCs between 19 times and 50 times higher values than the corresponding values at the urban background site. These observations are in good agreement with other studies (e.g. von der Weiden-Reinmüller et al., 2014).

During the campaign period, a significant influence of vegetation on pollutant concentrations was observed too with quite substantial amounts of isoprene and terpenes. Differences in effects were noted between three broadly different types of vegetation: agricultural areas, urban parks and urban forests. While agricultural areas showed similar particle number and mass concentrations relative to the urban background, significantly reduced particle concentrations (number and mass) were observed in both forests (-33%) and parks (-15%) indicating a reduced production of and/or a substantial sink for particles.

This vegetation effect however was dependent on vegetation dimensions. Urban parks with a much smaller extension than urban forested areas were shown to not have significantly lower but rather elevated NO or NO_2 concentrations than the urban background station in Neukölln (NO: >+45% and NO_2: >100%). This is in contrast with both agricultural areas and urban forests, which both showed significantly lower mixing ratios of NO_2 compared with the urban background. Ox was substantially reduced in forests (-17.9±7.7%) compared to urban

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residential areas (reference site) with a VOC sink strength only about 50% of the corresponding air at the urban residential area in Neukölln (see sections 4.1.1 and 4.1.4). Ozone mixing ratios were significantly reduced in forests, and higher in agricultural areas. Similar effects on ozone and NO_2 were not observed in urban park areas, perhaps due to the smaller park size and since the measurements conducted on the street near-by. Bicycle based measurements would be needed for an improved classification.

These road based observations are consistent with a NO_x-saturated chemical regime throughout the majority of the urban campaign area. However, while the additional biogenic VOCs from forests acted as an additional sink for ozone, this did not compensate the strength of the AVOC sink within the areas affected by urban transport and within residential areas. As both NO_2 and Ox decreased substantially towards forests, a PSS cannot be assumed for the entire area of Berlin, rather only for residential areas, industrial, commercial and transport affected areas and parks. These results suggest that increased urban green spaces would be a viable method to reduce particulate pollution if substantial in dimension, however not necessarily for ozone or NO_2. Reduction of NO mixing ratios would require reduction in emissions from traffic, which would be expected to lead to an increase in the mixing ratio of ozone. The intensity of this increase would be dependent on the biogenic feedback processes involving the emission on BVOCs and the formation of secondary organic aerosol mass.

The new approach using bicycles in addition to van measurements for a detailed microscale investigation yielded important additional information for areas not accessible for road-based mobile platforms such as vans and for regions most relevant for pedestrians and cyclists. For instance particle number concentrations varied by orders of magnitude when shifting from the centre of the road to the walkway and when approaching bus stops or traffic lights from the pedestrian point of view. A further development of miniature observation instruments for other pollutants such as nitrogen oxides, CO and black carbon would be highly recommended to address not only the street centre but the area most relevant for the health of local citizens. The BAERLIN2014 campaign was conducted for summer time conditions (June to August 2014) in a selected region representing various environments present in of the whole overall area. Clearly planned annual observations of different urban conditions (in different environments) by a multitude of cheap bicycle observation methods, including making use of volunteers cyclists, would improve the basis for an observation based pollution map of the city. We underline the importance of a resolution improved and updated surface coverage map (compared to the current CORINE land cover) with more surface information such as vegetation type, street or buildings for any stratification approach based on surface-types too.

To explore the effects and sensitivities of different vegetated land cover types, we recommend investigating the data further with detailed atmosphere-biosphere-chemistry-transport models and box-model simulations, which can then be used to test mitigation scenarios.

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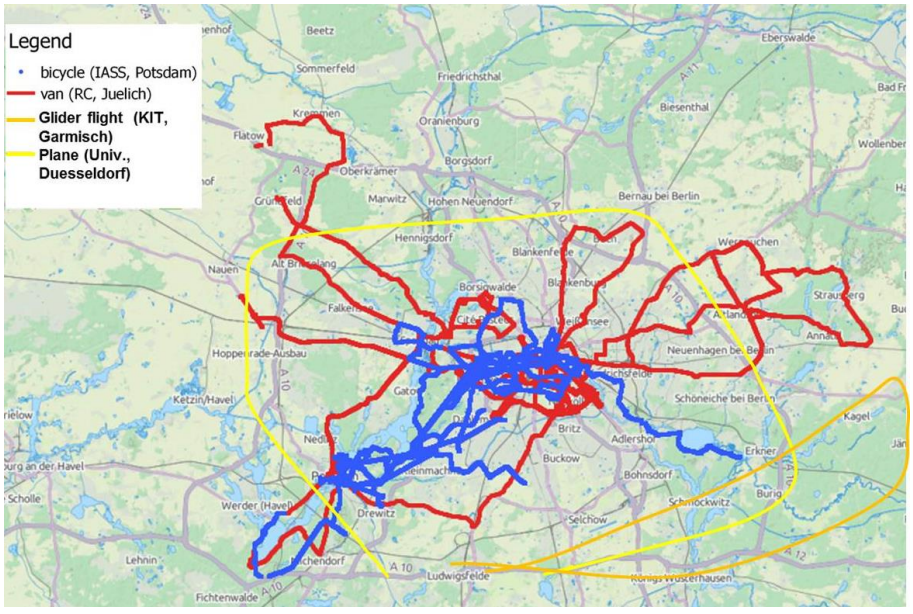

Figure 1. Mobile measurement routes in the BBMA area: bicycle routes in blue, van routes in red and airborne tracks in yellow (air plane) and orange (glider). Berlin is located in the centre and Potsdam at the south western concurrence of different bicycle and van tracks.

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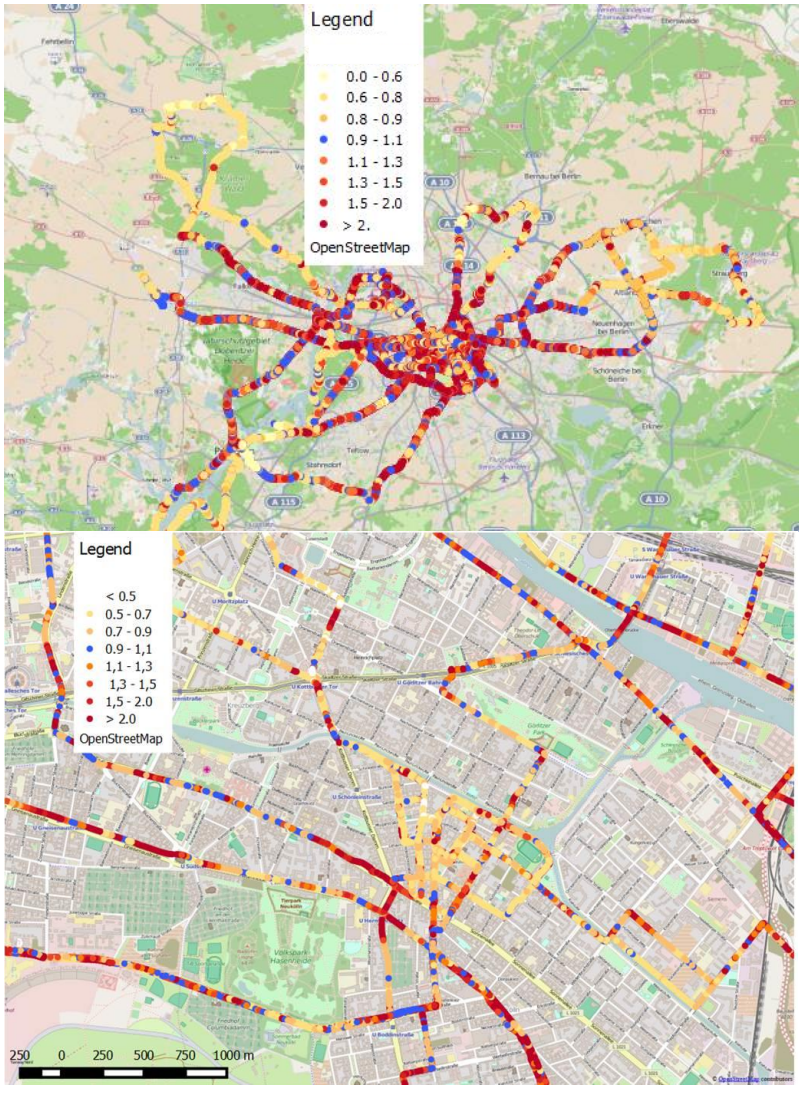

Figure 2. Relative values observed for carbon monoxide in the entire area of study (top) and for a zoom in Neukölln (bottom). Colours indicate the horizontal heterogeneity and the deviation to the reference in Neukölln. Blue indicates values ±10%.

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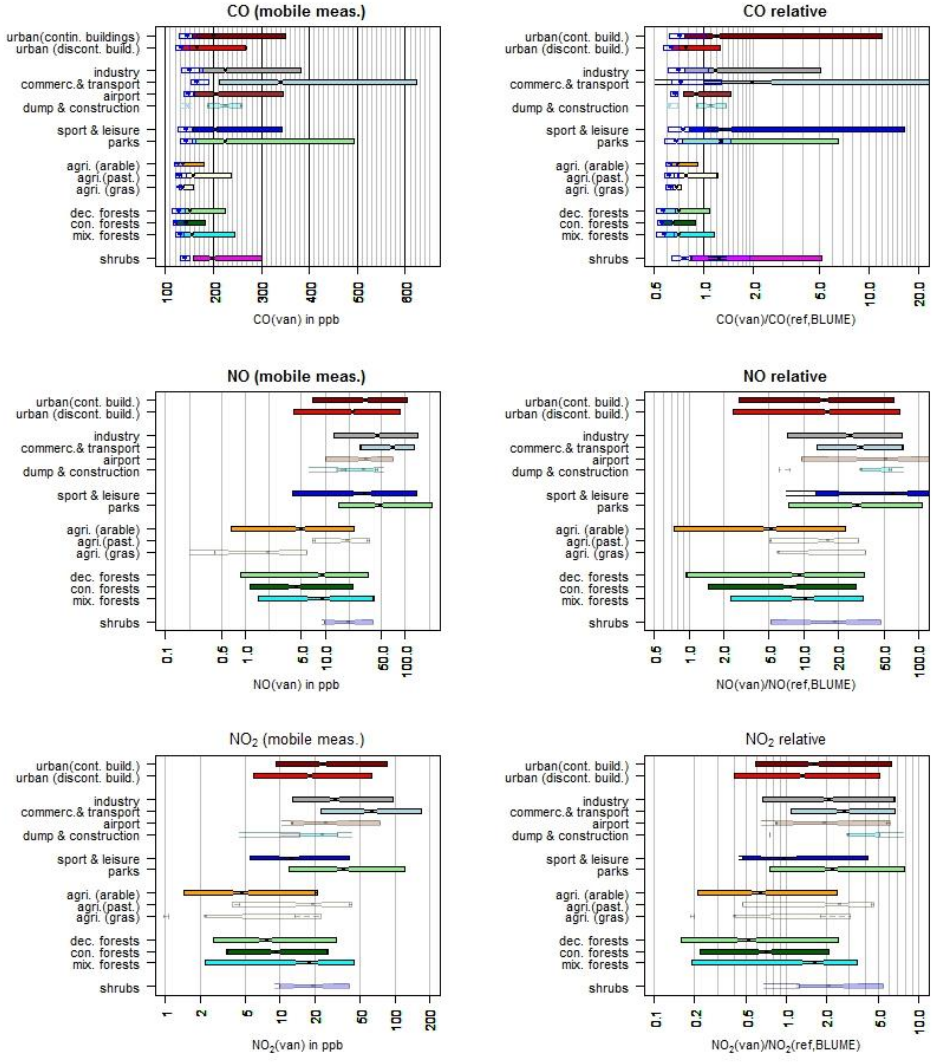

Figure 3. Boxplots of CO, NO and NO_2 mobile measurement values (upper graphs) and ratios of mobile measurements relative to Neukölln (lower graphs) in areas of different land use (CORINE). The boxplots start and end at the 25th and 75th percentile with a notch between the 45th and 55th percentiles. Blue surrounded transparent bars in the CO graphs refer to the so-called baseline values while the coloured bars represent all the observations. Shaded bars indicate an insufficient number of data points. Values and number of corresponding values are given in the supporting online information (SOI).

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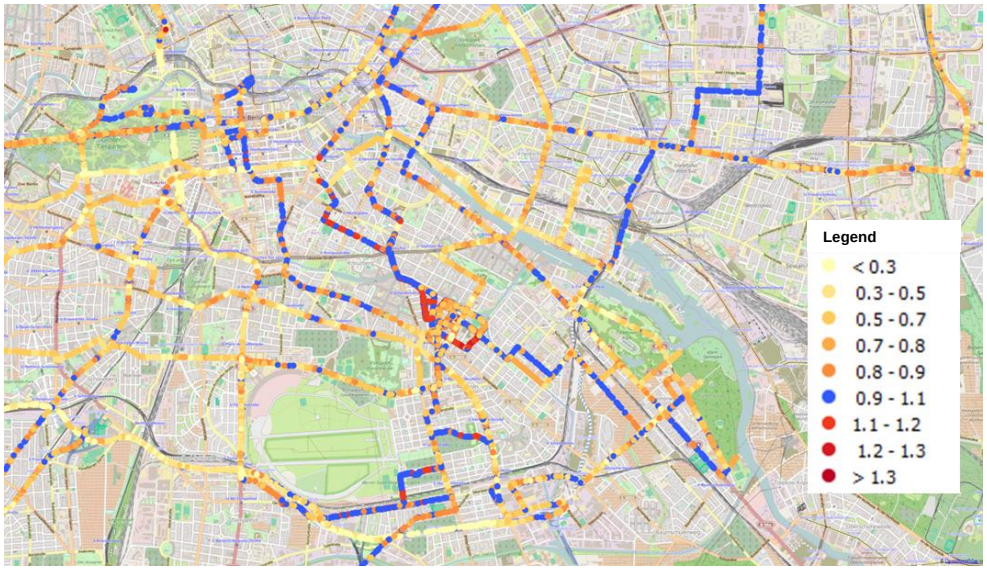

Figure 4. Horizontal variation of relative ozone mixing ratios, i.e. measured values relative to the ones at the same time in Berlin-Neukölln. As before, blue colour indicates a 10% difference to the reference site.

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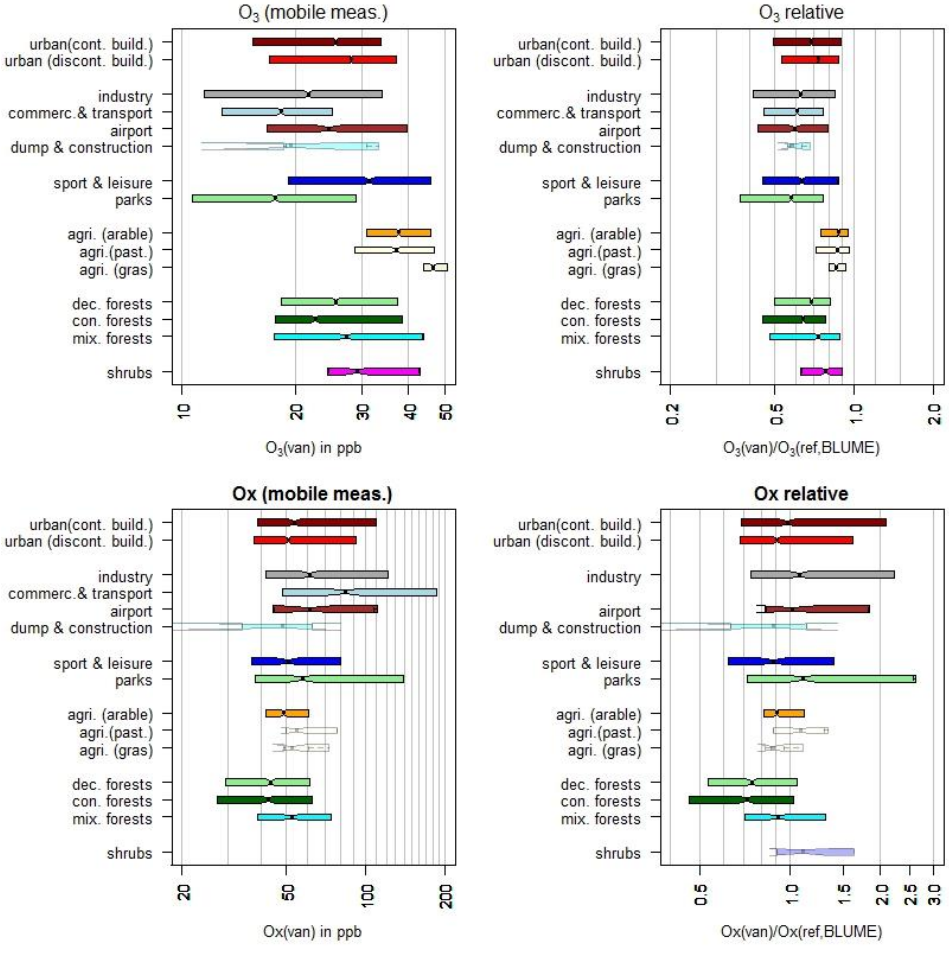

Figure 5. Boxplots of mobile measurements (left) and relative (right) values boxplots for ozone (top) and Ox (bottom) with respect to different surface type usage based on CORINE. Boxplots range from the 25th to the 75th percentile each with notches from the 45th to the 55th percentile centred round the median. Shaded bars indicate an insufficient number of data points. Values and the corresponding numbers of available data are provided in SOI.

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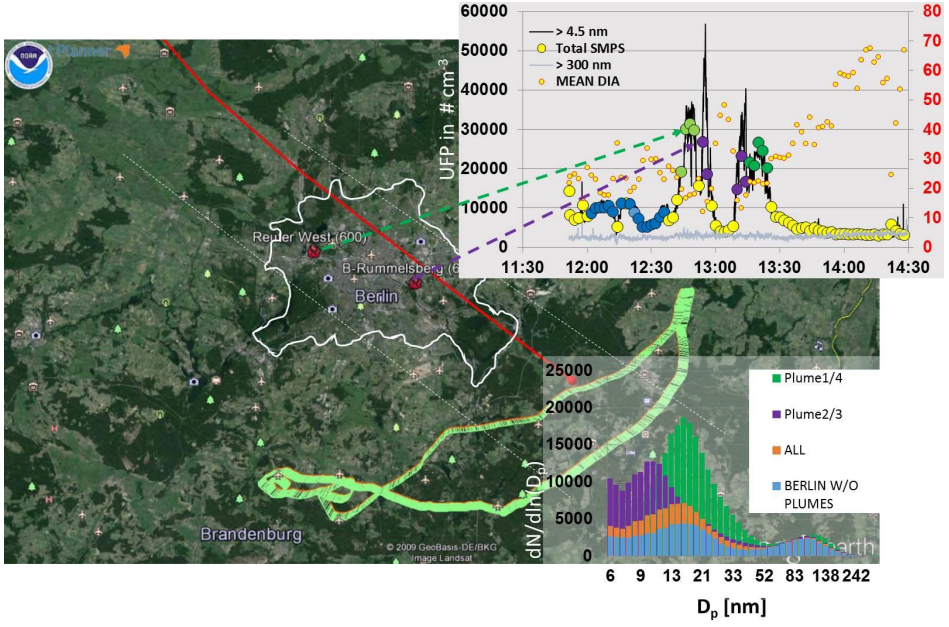

Figure 6. Particle number concentration (particle diameter D_p > 4.5nm) and mean particle diameters (right vertical axis in the upper right plot) on the 12th of June 2014 during the glider measurements (W. Junkermann, KIT, Garmisch-Partenkirchen). Maxima in UFP concentration and minima in mean particle diameter were found in the pollution plumes of the two power plants located in Rummelsburg and in Reutter-West (Plume 2/3, magenta size distribution).

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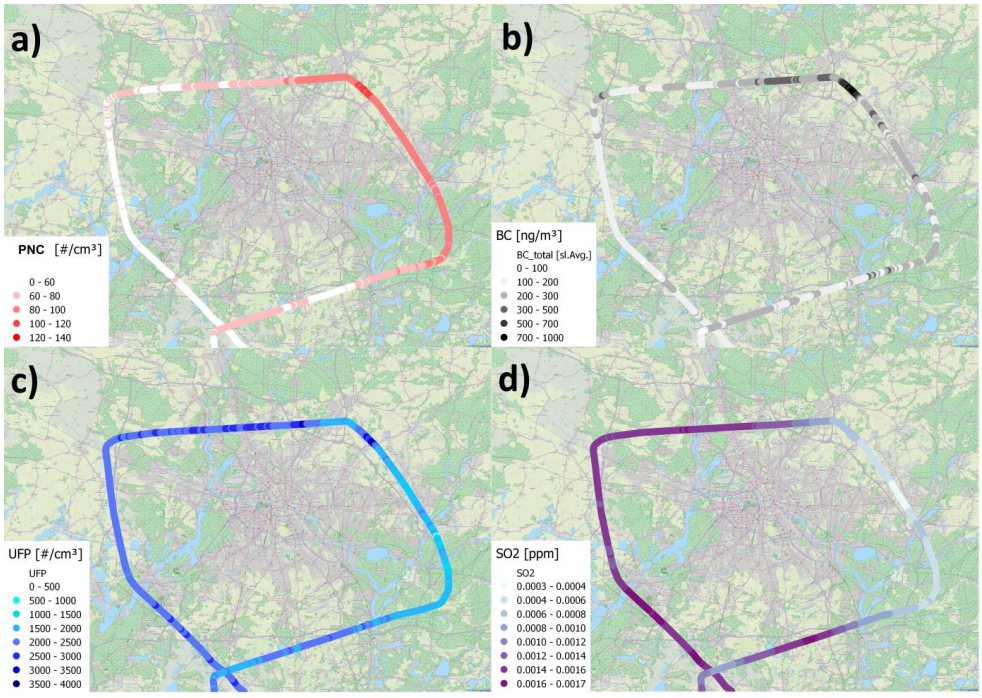

Figure 7. Spatial distribution of the air plane measurements on the 10th of October 2014: a) Coarse particle number concentration, b) BC, c) ultrafine particle number concentration, d) sulphur dioxide.

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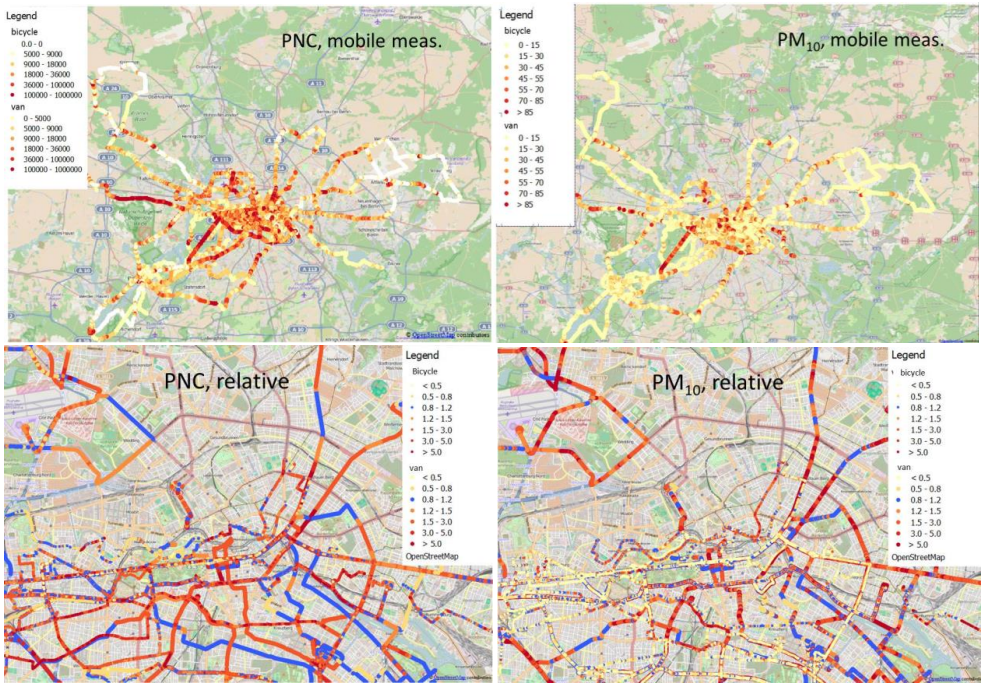

Figure 8. Heterogeneity of particle number (left) and mass (PM_{10}, right) concentrations in and around Berlin detected by bicycle and van sensors. The upper line displays the total area and the bottom line provides the relative values for number and PM_{10} concentrations.

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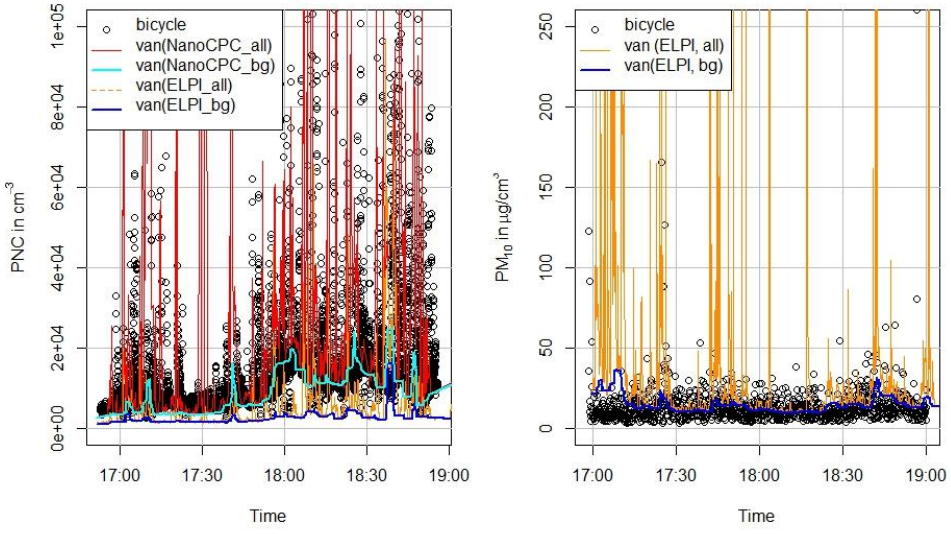

Figure 9. Comparison of bicycle and van based particle measurements: (left) total particle number concentration, (right) PM_{10} mass, on the 4th of August 2014. Van measurements are shown by the two colored lines, with the red line representing all measurements and the blue line the calculated background concentrations (10th percentile of 3 min running mean). The time is provided in CEST.

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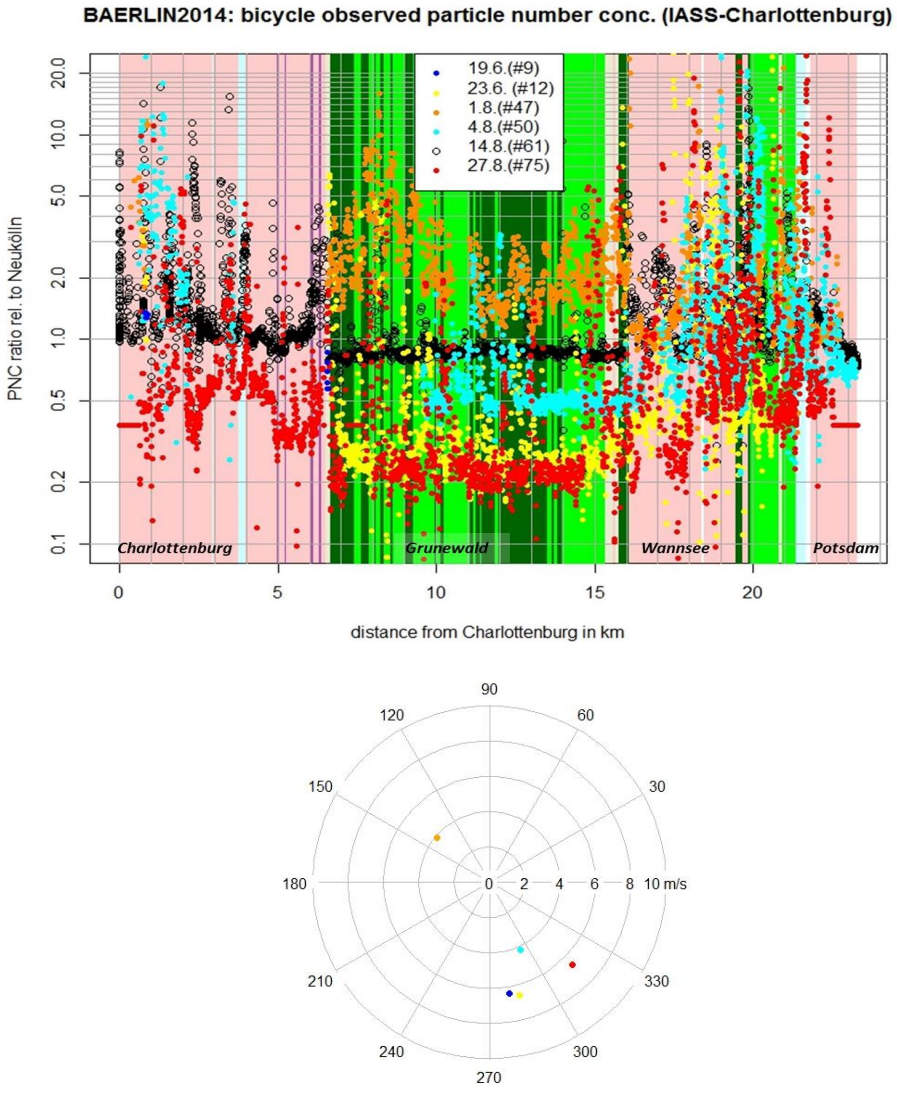

Figure 10. Top: Measurements by bicycle, following the same route, Berlin-Charlottenburg to Potsdam-IASS, on different days and during different times. The dots plotted are particle number concentration ratios relative to the stationary site in Neukölln with a time resolution of 10s. Green shaded areas are vegetated areas; pink shaded areas are anthropogenically dominated areas. Bottom: Wind rose and speed at Tempelhof (DWD) measured for the times of the individual tracks. The colour coding is identical with the one in the upper graph. Note, the corresponding wind data for track 61 is not available.

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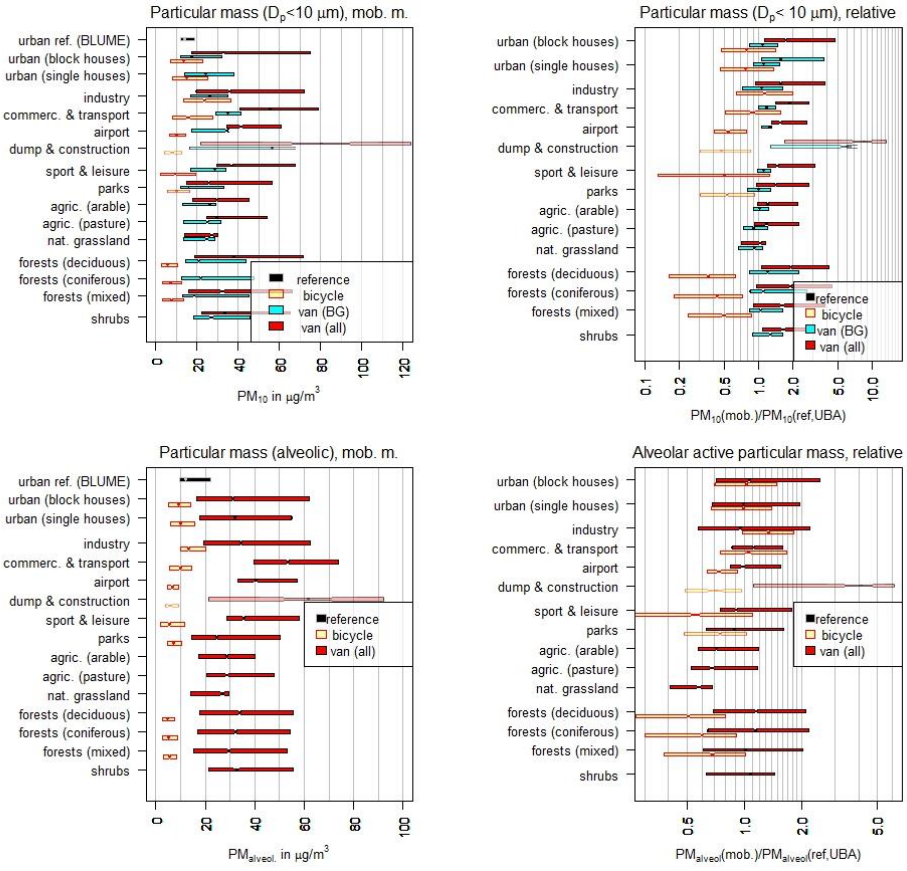

Figure 11. Particulate mass concentrations (left) and concentration ratios (right) for different land surface types and different observation platforms compared to the measurements in Berlin-Neukölln: top – PM_{10}, bottom – PM(alveolar).

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1 **Appendix**

2

3 **A1. Information on instrument and methods applied**

4 **Table A1.** List of applied instruments, time resolutions, uncertainties and detection limits/ranges, respectively.

Meas. platform (resp. inst.)	Parameter	Instrument	Time resolution	Uncertainty	Detection limit or range
Bicycle (IASS)	PNC, mod. mean size, LDSA	DiSCmini, Matter Aerosol (Wohlen, CH)	1 s	15% (500cm^{-3}), 30%, 15%	10^3-10^6 cm^{-3} µm^2/cm^3 (D_p: 10-500nm)
Bicycle (IASS)	PM_{10}, $PM_{2.5}$, PM_1, PM_{health}, PSD, MSD	Model 1.108, GRIMM (Ainring, D)	12 s	3% 3%	0.1-10^5µg/m^3 1-2x10^6 cm^{-3} (D_p: 0.3-20 µm)
Bicycle (IASS)	Temperature & RH	Model 1.154, GRIMM (Ainring, D)	12 s	±0.1°C/ 1% rH	0-80°C/ 10-95%
Van (RC Jülich)	particle number	ELPI, Dekati (Kangasala, FI)	1s	10%	0.1-10^7 cm^{-3} (f(size)) (D_p:0.007–10µm)
Van (RC Jülich)	particle number	NanoCPC 3788, TSI (Aachen, D)	1s	10%	0-4x10^5 cm^{-3} (D_p: 0.003-3µm)
Van (RC Jülich)	NO, NO_2, O_3	CLD 770, Chemiluminescence	5 s	5% (NO&NO_2) 10% (O_3)	40ppt(NO&O_3) 80 ppt (NO_2)
Van (RC Jülich)	CO	UV-Resonance-Fluorescence	1s	1.3 ppb_v	1 ppb_v
Van (RC Jülich)	CO_2, CH_4	Cavity-ringdown Spectrometer	0.1 s	≤ 200ppb_v (CO_2) ≤ 3 ppb_v (CH_4)	≈200ppb_v (CO_2) ≈ 3ppb_v (CH_4)
Van (RC Jülich)	temperature & RH	HMT 330, Vaisala (Helsinki, FI)	1 s	0.2°C 1% rH	-60 - +160°C 0-100%
Van (RC Jülich)	wind-direction & -speed	WMT 50 Vaisala (Helsinki, FI)	1 s	5%	0-60 m/s
Van (RC Jülich)	Position	WBT202, Wintec	1 s	±5 m	-

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		(Milpitas, USA)			
ultralight (KIT)	T, dew point	TP3-S, Meteolabor (Baiersdorf, D)	1 s	±0.25K ±0.25K	-30 - +50°C -80 - +60°C
ultralight (KIT)	N_{total} (D_p > 4.5 nm)	5.410 SKY OPC, GRIMM (Ainring, D)	1 s	10%	0.1-10^7 cm^{-3}
ultralight (KIT)	PSD: low. sizes, 4.5-350nm upp. sizes, 0.3-20µm, PM	SMPS 5.403, GRIMM (Ainring, D) OPC 1.108, GRIMM (Ainring, D)	2 min	3-15% (f(size)) 3%	0.1-10^7 cm^{-3} 0.1-10^5µg/m^3
ultralight (KIT)	Soot/BC	AE33 AVIO, AEROSOL d.o.o., (Ljubljana, SLO)	1 min	10%	0.03–100 µg/m^3 (1 min), 5 LPM.
DA42 (HSD)	T, rH	Voltcraft, DL-121 TH	2s	1°C, 3%rH	-40-(+70) °C
DA42 (HSD)	UF-N_{total} (D_p: 25-300 nm)	NanoCheck 1320, GRIMM (Ainring, D)	10 s	30%	5×10^2-5×10^5 cm^{-3}
DA42 (HSD)	PSD (0.25 – 32 µm), PM	1.109, Grimm (Ainring, D)	6 s	3%	1-10^6 cm^{-3}
DA42 (HSD)	Soot/BC	AE 33 Avio, Magee, Ljubliana, SLO	1 s	10%	0.03–100 µg/m^3 (1 min), 5 LPM.
DA42 (HSD)	SO_2	APSA-370, Horiba	15 s	1%	0-10pm

1

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A2. Additional information with respect to the bicycle measurements

As stated in section 3.1 of the study, both particle instruments, i.e. the GRIMM1.108 and the DiSCmini, were located in a backpack or a pannier which sampled ambient air by conductive inlet tubes. These inlet tubes (black silicone for the GRIMM, Tygon for DiSCmini, both ca. 50 cm in length) and the temperature sensor were fixed on the outside of backpack or pannier. Losses from inlets and tubing were accounted for with correction factors provided in Table A2.

Based on the particle measurements of the GRIMM instrument its software calculated six particulate mass values corresponding to different size ranges and corresponding to potential health effects: PM_{10}, $PM_{2.5}$ and PM_1 as well as PM(inhalable), PM(thoracic) and PM(alveolar). The final three health-related quantities estimate the particle number concentration for those size fractions making it to the throat/upper respiratory system, lung, and blood system, respectively (EN 481; European Committee for Standardization, 1993).

All particle instruments except the instrument were calibrated a month prior to the campaign in a controlled comparison experiment at TROPOS in Leipzig. Both instruments used on the bicycle measurement platform - DiSCmini and GRIMM 1.108 – were repeatedly operated in parallel with the suite of calibrated particle instruments (GRIMM 1.108, 5.403 and 5.416, and a TSI NSAM provided by the Federal Environmental Agency, Berlin) set up at the reference site in Neukölln. This was used for both instruments to obtain the calibration factors including the inlet losses listed in Table A2.

Table A2. Correction factors and mean losses for different parameters of both bicycle instruments.

Instrument and parameter	Correction factor f	Mean loss
DiSCmini, tot. part. num. conc.	1.22±0.20	18.8±3.1%
DiSCmini, lung depos. surface area	1.15±0.13	13.0±9.0%
Grimm 1.108, PM10	1.24±0.46	19.3±7.1%
Grimm 1.108, PM2.5	1.24±0.29	19.6±4.5%
Grimm 1.108, PM1	1.29±0.12	22.6±2.1%
Grimm 1.108, PM(inhalable)	1.28±0.64	21.7±10.8%
Grimm 1.108, PM(thoracic)	1.25±0.47	19.7±7.5%
Grimm 1.108, PM(alveolic)	1.21±0.28	17.5±4.0%

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B. Additional gas-phase related results

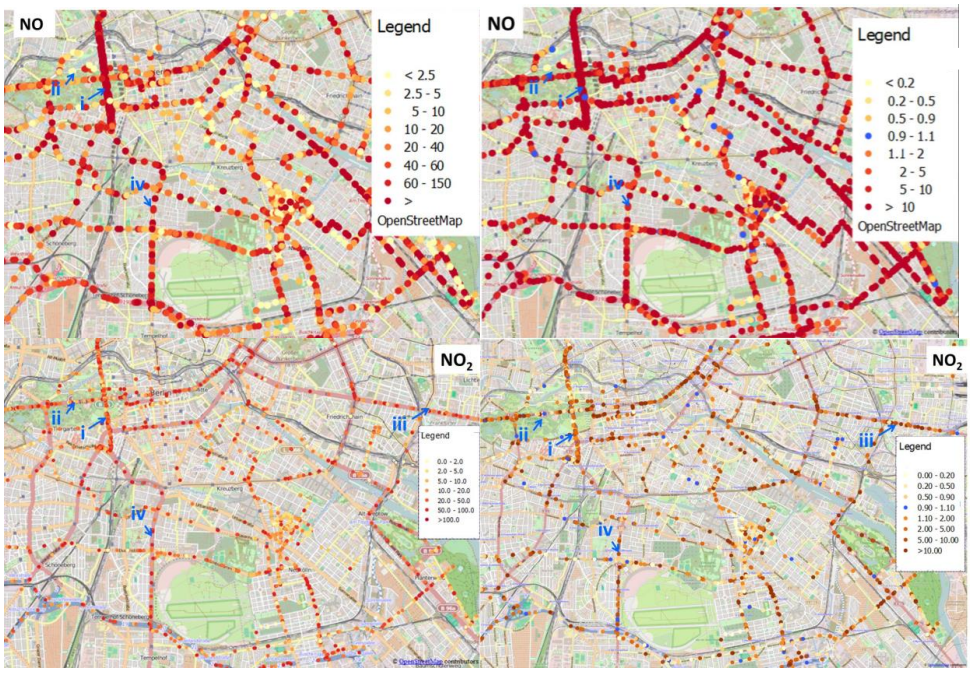

Figure B1. Mobile measurement data (left) and relative (right) graphs of nitrogen monoxide (NO, top) and dioxide (NO_2, bottom) observed by the measurement van. Mobile measured values are displayed in ppbv. Colours indicate the heterogeneity of the parameters, of the range (mobile measured values) and the variation with respect to reference value.

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C. Additional aerosol particle related results

Table C1. Particle mass (PM_{10}) burden characteristics (bicycle/van background (van all) meas.) at different land use types in µg/m^3. "-" indicates areas, which have not been tested by the method. This table provides the 25th, 50th and 75th percentiles as well as the mean and the number of available data points.

surface type	25th	median	75th	mean	no. of data
Urban - block build.	6.9/12.2(17.4)	13.6/17.2(32.8)	22.7/31.8(74.7)	24.3/25.7(75.6)	8260/21801
Urban -single build.	7.9/14.2(18.6)	15.0/24.3(34.3)	25.2/38.0(69.4)	29.0/28.7(67.9)	19143/82502
Industry	13.6/16.8(19.6)	23.9/26.1(35.9)	36.5/34.9(72.2)	30.7/28.2(73.9)	1464/14047
Com.+transp.	8.1/29.3(40.8)	15.9/34.8(55.5)	27.8/41.2(78.7)	23.2/35.8(77.2)	341/4875
Airport	6.6/17.5(34.4)	9.9/34.4(41.3)	14.7/35.2(60.8)	11.3/29.3(130.2)	137/738
Parks	5.5/11.9(14.8)	10.0/15.7(25.7)	16.3/31.8(56.6)	15.2/25.7(71.9)	2364/9598
Leisure area	2.3/17.1(29.5)	9.4/28.8(36.7)	19.5/33.8(67.7)	30.8/29.0(77.0)	623/3378
Arable land	-/13.0(18.1)	-/26.2(29.5)	-/29.0(45.3)	-/23.9(46.8)	-/9488
Pasture	-/13.3(24.7)	-/25.1(29.7)	-/31.5(53.9)	-/25.7(68.2)	-/938
Nat. grassl.	-/13.4(14.2)	-/24.7(27.4)	-/28.5(30.2)	-/21.1(27.0)	-/362
Dec. forest	2.8/14.4(19.1)	5.9/21.0(38.0)	10.4/43.7(71.4)	8.9/29.1(58.2)	2096/8874
Con. forest	3.2/12.4(17.8)	7.1/21.9(38.3)	12.6/47.7(70.9)	12.7/30.3(52.7)	4141/7078
mix. forest	3.4/13.1(15.8)	7.8/18.7(32.7)	13.5/45.0(65.9)	13.8/27.2(53.6)	694/1820

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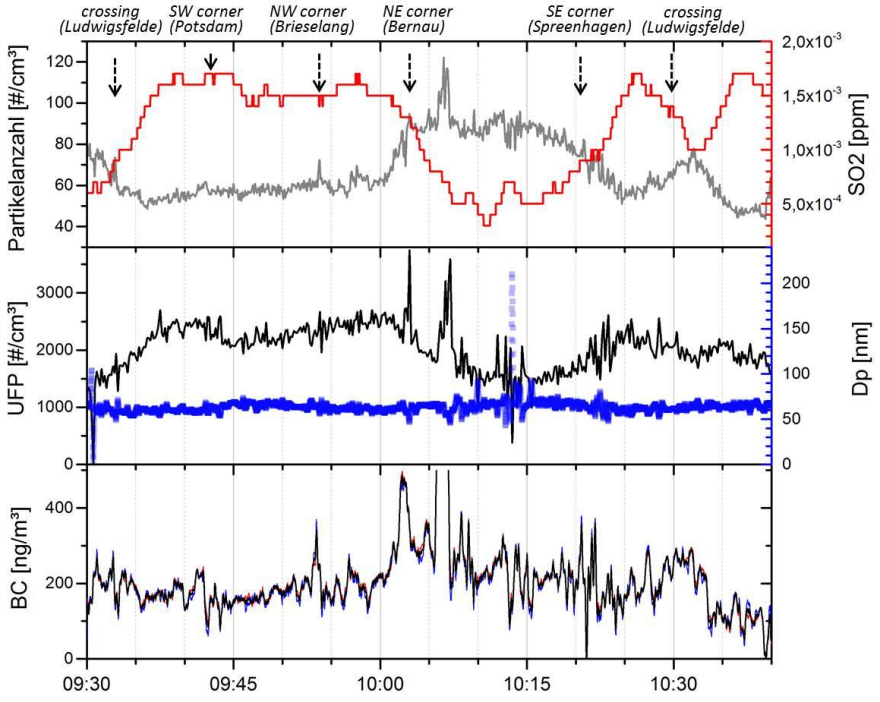

Figure C1. Particle parameters measured during the Oct. 10 flight around Berlin. Particle number concentration and sulphur dioxide (SO_2), UFP and UFP-diameter, Black Carbon (from top position towards bottom) as measured at a constant altitude of around 500 m (1700 ft).

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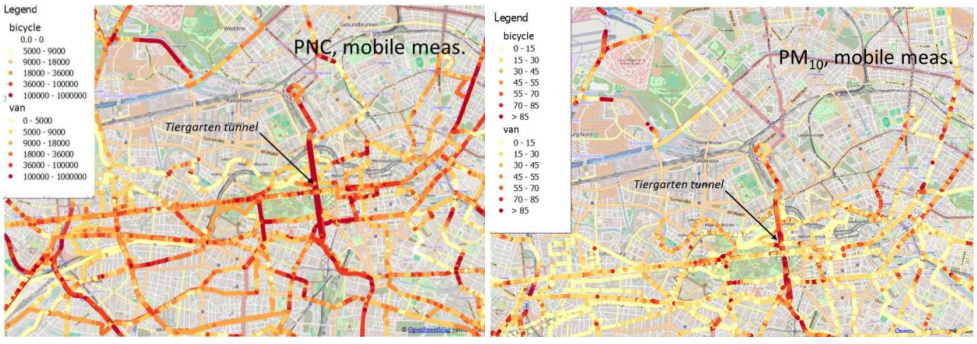

Figure C2. Zoomed heterogeneity of particle number (left) and mass (PM_{10}, right) concentrations in the center of Berlin displayed in absolute measured values. This figure is an extension of Fig. 8.

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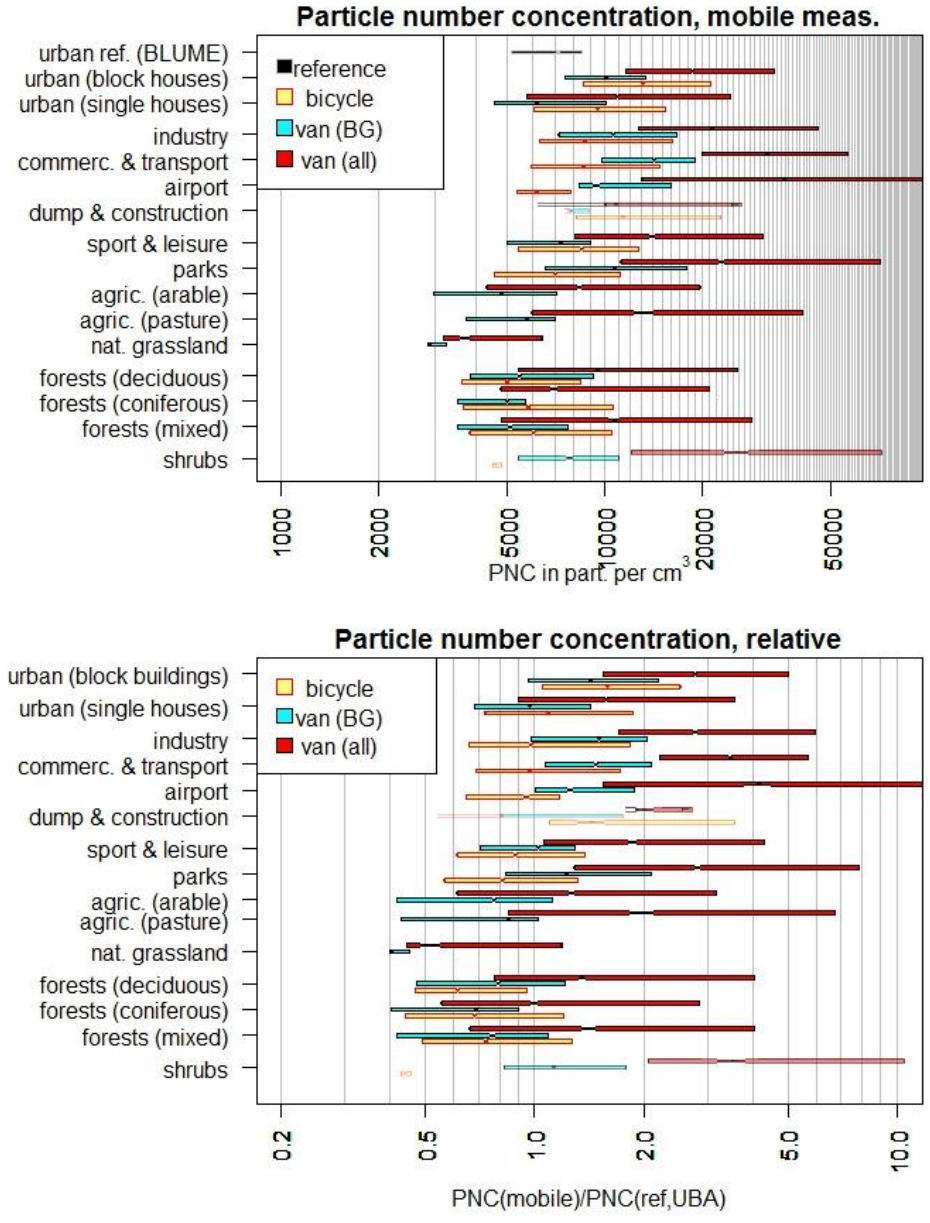

Figure C3. Boxplots of particle number concentration ratios for different land surface types (CORINE) and different observation platforms compared to the measurements in Berlin-Neukölln. The boxplots range from the 25th to the 75th percentile with notches from the 45th to the 55th percentile centered on the median.

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D. Information about further results – temperature

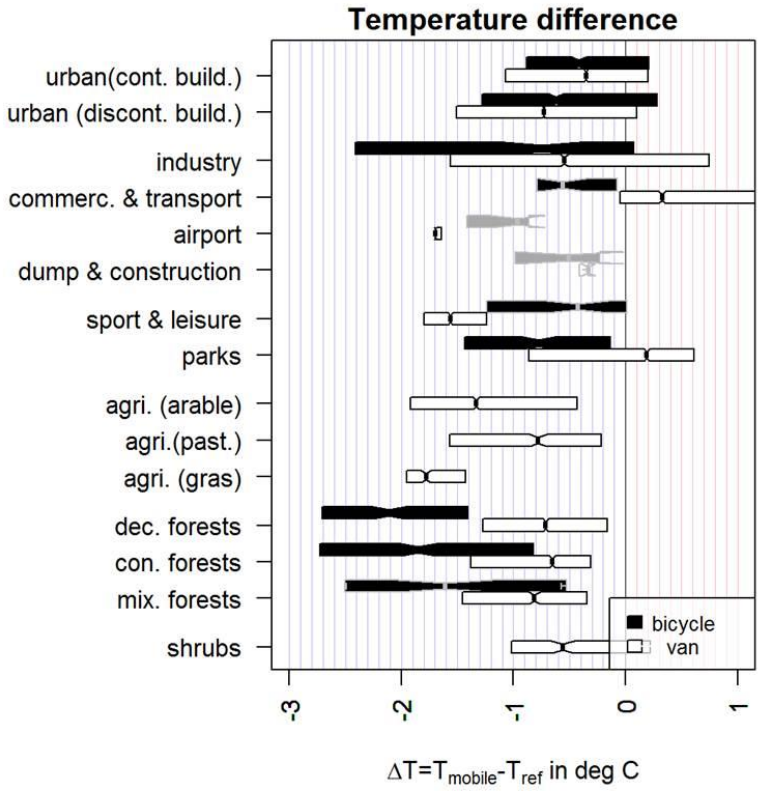

Figure D1. Boxplot of temperature differences for different land use types and different observation platforms compared to the measurements in Berlin-Neukölln. Displayed is the range between the 25th and the 75th percentile with a notch from 45th to 55th percentile. Grey borderlines of bars represent categories with insufficient data values, missing bars no data by the corresponding method.

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Supporting online information:

Further tables and graphs on frequency distributions of gases and particle properties are available in supporting online information.

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Table 1. European Union (EU) and U.S. (EPA) legislation on selected pollutant concentrations. *valid from 1st of January 2015 onward.

Pollutant	*EU*		*EPA*	
	daily	*annual*	*daily*	*annual*
Ozone (EU: target value EPA: limit value)	8h-mean: ≤ 120 µg/m^3 (≈60 ppb$_v$) not to be exceeded more than 18 times a year	-	8h-mean: 75 ppb$_v$	-
Nitrogen oxides (NO_2)	1h-mean: 200 µg/m^3 (≈100 ppb$_v$) not to be exceeded more than 18 times a year	Mean: 40 µg/m^3 (≈20 ppb$_v$)	1h-mean: 100 ppb$_v$	53 ppb$_v$
Benzene, toluene, xylenes (BTX) compounds	1h-mean: 5 µg/m^3 (≈1.9 ppb$_v$)	-	-	-
Particulate matter (PM)	24h-mean: PM_{10} ≤ 50 µg/m^3 not to be exceeded more than 35 times a year	Mean: PM_{10} ≤ 40 µg/m^3 $PM_{2.5}$ ≤ 25 µg/m^{3*}	24h-mean: PM_{100} ≤ 150 µg/m^3 $PM_{2.5}$ ≤ 35 µg/m^3	Mean of 3 years: $PM_{2.5,prim.}$ ≤ 12 µg/m^3 $PM_{2.5,sec.}$ ≤ 15 µg/m^3
Carbon monoxide (CO)	8h-mean: 10 mg/m^3 (≈10.3 ppm$_v$)	-	8h-mean: 9 ppm$_v$ 1h-mean: 35 ppm$_v$ both not to be exceeded more than once a year	-

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Table 2. Contribution of different surface types to the total surface area of Berlin.

Surface type	Area covered [ha]	Fraction of total [%]
Built-up areas, streets (19%)	49 975	56.1
Green areas:	29 275	32.8
Forests	*16 349*	*18.3*
Public green areas	*12 926*	*14.5*
Agricultural areas	3 953	4.4
Lakes, rivers	5 953	6.7
Total	*89 157*	*100*

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1 **Table 3.** List of applied mobile measurement platforms, parameters quantified and time scales.

Mobile meas. platform	Parameters measured	Time scale
bicycle	T, particle number concentration, PM_{10}, $PM_{2.5}$, PM_1, PM(health), LDSA	June, 10th – September, 5th
van	T, rH, O_3, NO, NO_2, CO, CO_2, CH_4, particle number conc., particle surface area, PM and canister samples (VOCs)	July, 31th – August, 6th
ultralight aircraft	T, dew point, O_3, particle number conc., particle size distribution	June, 12th
Air plane (DA 42)	T, dew point, SO_2, particle number, particle size distribution, soot	October, 10th

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Table 4. Land use types based on the CORINE classification. For number of measurement values (n) for each surface type for each instrument/parameter, see the SI.

No.	Surface type name	Surface character type
1	Urban (contin. build.)	Residential areas, block houses with several floors
2	Urban (discount. build.)	Residential areas, single houses, less dense setting
3	Industry	Industrial area
4	Commercial and transport	Commercial areas, streets, railways, motorway
5	Airport	Runways, airport related areas
6	Dump & construction	Dump and construction sites (2006)
7	Sport & leisure facilities	Vegetated areas linked with sporting facilities
8	Parks	Parks
9	Agriculture (arable land)	Arable land, used for food production
10	Agriculture (pasture)	Areas for livestock feeding
11	Agriculture (nat. grassland)	Areas with natural grassland
12	Forests (deciduous)	Deciduous forests
13	Forests (coniferous)	Coniferous forests
14	Forests (mixed)	Mixed forests
15	Shrubs	Areas with sparse smaller plants, bushes etc.

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Table 5. Canister samples analysed for VOC compositions. An ozone scrubber was applied in front of the inlet to prevent sampling losses and artefacts. All values are provided as mean volume mixing ratios in pptv. The different environments are grouped and the number of available samples is provided for each case. The third column represents urban background measurement conditions at Nansenstraße is considered (urban background standard). Elevated anthropogenic compounds with respect to vegetated background area concentration (>average+2STD of the two smaller mixing ratios of vegetated areas) are marked in bold. Underlined numbers mark biogenic compounds exceeding the average of the two smaller mixing ratios for anthropogenic dominated areas + 2 standard deviations. Marked numbers represent the compounds substantially affecting the area with no predominant emission of those. "b.d." abbreviates *below detection limit*.

Compound	***Locations dominated by engine related emissions***		***Urban background***	***Locations dominated by biogenic emissions***		
	Motorway, traffic jam	***Tiergarten tunnel***	***Nansen-straße***	***Pfauen-insel***	***Treptower Park***	***Grunewald***
	2 samples	***10 samples***	***14 samples***	***1 sample***	***11 samples***	***1 sample***
Ethene	**16973±1262**	**5113±1257**	**465±263**	197±39	247±96	**442±88**
Ethyne	**4981±627**	**2023±985**	286±239	103±21	236±**55**	331±66
Ethane	**3585±1018**	**1655±366**	**1686±1514**	866±173	**2978±1473**	771±154
Propene	**5119±758**	**1588±448**	251±64	187±37	228±55	256±51
Propane	**4723±3622**	**1533±779**	**825±613**	504±101	**1007±476**	257±51
Propyne	**681±38**	**351±182**	73±28	b.d.	66±19	b.d.
Acetaldehyde	**3067±2355**	**591±181**	**336±139**	91±18	**382±112**	b.d.
2-methylpropane	**2666±1878**	**660±542**	**504±441**	70±14	**255±134**	77±15
Methanol	**7275±4012**	**6631±2646**	**4996±3082**	**4192±838**	2608±612	2564±513
1-butene/ i-butene	**2482±304**	**740±297**	**300±412**	100±20	111±21	**156±31**
1,3-butadiene	**731±73**	**249±109**	43±11	b.d.	26±15	b.d.
n-butane	**6140±3760**	**1626±938**	b.d.	555±111	623±676	220±44
trans-2-butene	**814±314**	**123±30**	16±3	**61±12**	25±10	10±2
cis-2-butene	**784±301**	**130±39**	**74±38**	24±5	21±12	**81±16**
1,2-butadiene	**181±181**	b.d.	**33±7**	b.d.	b.d.	b.d.
Ethanol	**17622±8707**	**10462±7825**	333±189	229±46	312±93	113±23

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3-methyl-1-butene	**224±112**	**99±37**	52±6	b.d.	16±33	b.d.
2-methylbutane	**30906±10821**	**3913±1668**	465±178	b.d.	306±90	**656±131**
Acetone	**12328±7453**	**6827±5420**	**10721±24004**	**37040±7408**	3798±1856	2703±541
1-pentene	**605±220**	**86±39**	35±8	b.d.	29±16	26±5
2-propanol	**612±612**	**420±357**	44±14	b.d.	42±17	**81±16**
2-methyl-1-butene	**1014±173**	**71±108**	b.d.	b.d.	b.d.	b.d.
n-pentane	**7886±2785**	**1121±521**	242±106	57±11	165±52	241±48
Isoprene	b.d.	157±93	266±159	1414±283	1320±363	776±155
trans-2-pentene	**1421±173**	**214±91**	**28±13**	b.d.	b.d.	14±3
cis-2-pentene	**959±270**	**161±50**	22±9	15±3	b.d.	11±2
Propanal	**1251±1251**	**737±1120**	54±24	b.d.	58±79	76±15
2-methyl-2-butene	**40±40**	**36±66**	11±8	b.d.	b.d.	b.d.
Acetic acid methylic ester	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
1,3-pentadiene	b.d.	**47±117**	14±4	b.d.	b.d.	b.d.
Cyclopentadiene	b.d.	b.d.	35±14	b.d.	45±22	b.d.
2,2-dimethylbutane	**6385±1992**	**875±364**	117±111	67±13	112±110	**175±35**
2-butanol	b.d.	**3103±8097**	**117±156**	b.d.	59±23	102±20
1-propanol	**502±502**	**418±259**	**342±377**	94±19	b.d.	b.d.
Cyclopentene	**335±335**	**27±75**	**39±11**	b.d.	b.d.	b.d.
Methacrolein	b.d.	b.d.	80±37	287±57	147±49	200±40
Cyclopentane / 2,3-dimethylbutane	**2646±792**	**6075±15604**	**275±316**	**277±55**	88±27	139±28
2-methylpentane	**4772±2172**	**1274±500**	232±112	45±9	160±100	**291±58**
Methylvinylketone	b.d.	b.d.	102±	389±78	171±38	194±39
Butanal	**1319±877**	253±190	133±56	b.d.	126±99	b.d.
1-hexene	**47±47**	20±58	**113±68**	**129±26**	40±54	38±8
3-methylpentane	**2259±557**	**572±250**	**73±40**	42±8	54±19	**123±25**

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2-methyl-1-pentene	**243±85**	**54±55**	14±3	b.d.	b.d.	b.d.
n-hexane	**1848±516**	**484±204**	**127±99**	80±16	95±58	60±12
trans-2-hexene	**190±46**	**59±21**	**110±53**	15±3	**26±14**	11±2
cis-2-hexene	**111±38**	**65±41**	**107±21**	11±2	b.d.	b.d.
1,3-hexadiene (trans)	**85±85**	27±52	**53±10**	34±7	b.d.	b.d.
Methylcyclopentane	b.d.	**36±103**	**49±13**	22±4	b.d.	b.d.
2,4-dimethylpentane	**1490±410**	**361±180**	54±28	14±3	43±14	**111±22**
Methylcyclopentene	**333±79**	**54±98**	14±5	b.d.	b.d.	b.d.
Benzene	**2281±796**	**1383±349**	**303±238**	155±31	199±35	224±45
1-butanol	b.d.	**145±359**	28±14	b.d.	39±19	b.d.
Cyclohexane	**743±213**	**198±77**	39±23	18±4	33±14	**46±9**
2-methylhexane	**708±132**	**256±144**	36±14	23±5	34±24	35±7
2,3-dimethylpentane	**684±300**	**114±41**	23±14	**36±7**	17±16	18±4
3-methylhexane	**894±138**	**268±84**	82±34	54±11	109±33	110±22
Pentanal	**102±14**	12±22	11±2	b.d.	b.d.	b.d.
Cyclohexene	b.d.	b.d.	18±4	b.d.	b.d.	b.d.
1,3-dimethylcyclo-pentan (cis)	**287±2**	**74±40**	11±5	11±2	b.d.	19±4
1-heptene	**138±42**	25±31	17±10	b.d.	b.d.	13±3
2,2,4-trimethylpentane	**545±10**	**188±55**	28±15	b.d.	24±10	34±7
Heptane	**467±35**	**146±71**	32±11	18±4	29±9	37±7
2,3-dimethyl-2-pentene	b.d.	27±61	b.d.	b.d.	b.d.	b.d.
Octene	28±28	b.d.	b.d.	b.d.	b.d.	b.d.

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Methylcyclohexane	**146±78**	**122±46**	27±15	b.d.	18±15	14±3
2,3,4-trimethylpentane	**327±73**	**120±46**	20±14	24±5	19±5	10±2
Toluene	**8553±1675**	**2679±1012**	**407±237**	299±60	276±133	212±42
2-methylheptane	**253±110**	**114±63**	25±17	b.d.	17±12	10±2
4-methylheptane	**254±110**	**85±43**	14±9	b.d.	11±10	b.d.
3-methylheptane	**121+67**	**82±45**	17±13	68±14	b.d.	26±5
Hexanal	108±108	**52±86**	**72±46**	b.d.	**129±69**	12±2
Acetic acid butylic ester	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
n-octane	**208±45**	**107±93**	28±23	23±5	24±11	**34±7**
Dimethylcyclo-hexane isomer	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ethylbenzene	**1285±200**	**485±207**	76±40	21±4	55±31	**127±25**
m/p-xylene	**3301±568**	**1853±2411**	151±97	31±6	109±68	**263±53**
Heptanal	b,d.	b.d.	22±14	b.d.	93±62	b.d.
Styrene	**277±67**	**117±21**	57±40	b.d.	41±7	35±7
1-nonene	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
o-xylene	**1344±150**	**408±149**	64±38	13±3	49±28	**106±21**
n-nonane	**221±65**	**91±22**	21±4	12±2	20±6	19±4
i-propylbenzene	**92±36**	**50±15**	**30±70**	15±3	11±8	b.d.
α-pinene	b.d.	b.d.	31±26	30±6	176±370	81±16
n-propylbenzene	**271±48**	94±43	20±13	66±13	12±6	88±18
m-ethyltoluene	**832±136**	**214±131**	31±26	b.d.	25±15	**63±13**
p-ethyltoluene	**331±37**	**201±85**	24±14	b.d.	18±8	20±4
1,3,5-trimethylben-zene (1,3,5-TMB)	**278±77**	**210±122**	**46±55**	41±8	35±32	45±9
Sabinene	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
o-ethyltoluene	**336±45**	**159±64**	36±24	b.d.	**67±30**	30±6

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Octanal	b.d.	b.d.	13±5	b.d.	b.d.	b.d.
β-pinene	b.d.	b.d.	15±8	b.d.	18±10	36±7
1,2,4-trimethylbenzene/ t-butylbenzene	**1514+292**	**462±127**	**63±37**	**172±34**	43±19	45±9
n-decane	**305±159**	**92±49**	22±8	**101±20**	17±9	29±6
1,2,3-trimethyl-benzene (1,2,3-TMB)	**632±350**	**108±51**	**120±296**	**511±102**	27±20	49±10
limonene	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
eucalyptol	b.d.	b.d.	b.d.	57±11	b.d.	24±5
indane	71±71	b.d.	b.d.	49±10	b.d.	b.d.
1,3-diethylbenzene	**187±6**	**57±40**	13±11	b.d.	b.d.	17±3
1,4-diethylbenzene	**252±71**	**52±34**	**522±1380**	b.d.	b.d.	11±2
butylbenzene	**232±70**	**60±34**	b.d.l.	b.d.	b.d.	b.d.
n-undecane	**45±7**	16±6	10±13	b.d.	22±10	b.d.
n-dodecane	24±13	b.d.	26±24	b.d.	b.d.	b.d.
n-tridecane	b.d.	b.d.	b.d.	b.d.	b.d.	10±2

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Table 6. Particle number concentrations (bicycle/ van (background) measurements) for different land use types in particles per cm^3. "-" indicates areas, which have not been tested by the method. This table provides the 25^{th}, 50^{th} and 75^{th} percentiles as well as the mean and the number of available data points.

surface type	25th	median	75th	mean	no. of data
Urban - block build.	8589/7555	13050/10110	21160/32915	25860/13390	55132/21646
Urban -single build.	6021/4550	9490/6181	15400/10080	17040/8861	139597/81293
Industry	6269/7201	8624/10614	16220/16710	16990/14488	9966/13784
Com.+transp.	5918/9807	8553/14240	14810/19040	14390/16281	4367/4856
Airport	5364/8308	6146/9424	7855/15930	7214/21970	968/781
Parks	4561/6555	7053/10680	11160/17820	12770/16736	14493/10287
Arable land	-/2973	-/4817	-/7125	-/7388	-/9271
Pasture	-/3733	-/5733	-/7050	-/6343	-/934
Nat. grassl.	-/2878	-/2878	-/3233	-/3586	-/371
Dec. forest	3646/3846	5802/5467	10620/9169	12190/11865	28726/8806
Con. forest	3613/3501	4991/4993	8394/5658	8657/14630	38485/7020
mix. forest	3828/3501	6059/5093	10520/7685	11690/11865	7215/1810