UFP-, BC-, and $PM_{2.5}$- measurements and effect of dispersion conditions on concentration levels in a residential area affected by wood-smoke pollution from domestic heating during the winter months

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Abstract. The monitoring of ultrafine particle concentrations in ambient air is gaining relevance within the revision of the EU Ambient Air Quality Directive. A prominent source of ultrafine particles (UFP) are combustion processes (e.g. within the scope of wood-fired domestic heating) where the particle emission is typically led unfiltered into the environment contributing significantly to local air pollution. In this study, ultrafine particle concentrations were measured in a residential area affected by wood-smoke pollution during the winter months (Nov. 20, 2024 – Mar. 30, 2025) using a diffusion charge based UFP-monitor (AQ Guard Smart 2000 from Palas®). The measurements show a diurnal trend, where concentrations are significantly increased (e.g. > 10 000 cm^{-3}) above the background level (approx. 5 000 cm^{-3}) during the morning (approx. 08:00) and evening hours (approx. 19:00 – 22:00), whereby the source is wood-smoke from the surrounding neighbourhood. The dispersion conditions significantly affect the measured concentrations, as only in case of low (or zero) wind speeds, increased UFP concentrations are obtained demonstrating the relevance of local sources (wood-stove operation) on air quality. In the context of "good practice statements" offered by the World Health Organization's Air Quality guidelines, the maximum daily 1-hour mean concentration of 20 000 cm^{-3} is exceeded on approx. 33.6% of days during the measurement period. This significant peak exposure on smaller timescales requires monitoring on a high temporal resolution, as longer averaging periods (e.g. daily or annual mean concentrations) do not reflect temporal peak concentrations that can be especially dangerous for high-risk groups. There is no direct link between legally relevant particulate matter (e.g. $PM_{2.5}$) and ultrafine particle concentrations, as the size distribution of the wood-smoke emission is in the nanometer region and does not significantly contribute to mass-based particulate matter concentrations.

1 Introduction

While there has been significant progress to improve air quality and implement air quality monitoring across the globe, air pollution is still a major factor for health issues and premature deaths (WHO, 2021). Especially in developing countries, smog in cities and traffic hotspots is a regular occurrence significantly impacting the life of the corresponding population (Amin et al., 2024; Le Huong et al., 2024; Mohan et al., 2024; Moreno et al., 2025). When it comes to the European Union, measures to improve air quality have shown a positive effect over the last decades, however there is still room for improvement and recommendations regarding particulate matter concentrations proposed by the World Health Organization (WHO) in 2021 are not necessarily met universally across the European Union. Only recently, the Ambient Air Quality Directive has been revised in order to approach past recommendations set by the World Health Organization in 2005 (European Union, 2024; WHO, 2005). In the context of particulate pollutants, the limits for PM_{10} and $PM_{2.5}$ mean annual concentrations, as well as maximum mean daily concentrations and the number of exceedance days are lowered towards the year 2030 according to Table 1. Furthermore, a new focus is set on "pollutants of emerging concern", which are only rarely monitored by government official monitoring stations, such as ultrafine particles (UFP) and black carbon (BC). Ultrafine particles are suspected to be especially hazardous due to their ability to penetrate deep into the human body, yet the direct evidence of many studies remains inconclusive (Ohlwein et al., 2019). These pollutants (among others e.g. size distribution of UFP, oxidative potential, etc.) now have to be monitored by so called "supersites" to gather more data and better evaluate health effects. While monitoring of UFP and BC is becoming mandatory, there are no specified limits for these pollutants in the directive.

A universal limit for UFP would be difficult to implement, as there is no wide-spread measurement (yet) and the natural formation of UFP due to atmosphere chemistry can vary for different locations and result in different background levels and temporal behavior (e.g. particle growth; new particle formation) that would have to be considered in the context of quantitative UFP-limits [e.g. (Bianchi et al., 2016; Dunne et al., 2016; Marten et al., 2022; Pierce and Adams, 2007; Shrivastava et al., 2024). Nonetheless, the World Health Organization does offer some "good practice statements" when it comes to ultrafine particle concentrations (Table 1). It can be assumed, that the specified concentrations relate to hazardous substances (e.g. such as black-carbon) due to the possibility of non-hazardous high "background" concentrations due to the specified atmospheric processes.

Table 1 – Limits and recommendations for particulate pollutants by the WHO (2021) and the European Union (2024)

Pollutant	Type of Limit	Revised Ambient Air Quality Directive *Dec. 11, 2026* / Jan. 1, 2030	WHO Air Quality Guidelines (2021)
$PM_{2.5}$	Annual mean	*25 µg m^{-3}* 10 µg m^{-3}	5 µg m^{-3}
	Daily mean	*Not considered* 25 µg m^{-3} (18 exceedance days/year)	15 µg m^{-3} (approx. 3-4 exceedance days/year)
PM_{10}	Annual mean	*40 µg m^{-3}* 20 µg m^{-3}	15 µg m^{-3}
	Daily mean	*50 µg m^{-3} (35 exceedance days/year)* 45 µg m^{-3} (18 exceedance days/year)	45 µg m^{-3} (approx. 3-4 exceedance days/year)
UFP	Annual mean	No limit considered (Monitoring obligation)	Not considered
	Daily mean	No limit considered (Monitoring obligation)	Good practice statement: Distinction between high and low concentration low: C_n < 1000 cm^{-3} high: C_n > 10 000 cm^{-3}
	Hourly mean	No limit considered (Monitoring obligation)	Good practice statement: 20 000 cm^{-3}

Two different 24-hour mean concentration levels are specified, whereby concentrations up to 1 000 cm^{-3} are considered "low" and concentration levels exceeding 10 000 cm^{-3} are considered "high" and should therefore be avoided to prevent long-term health effects. In addition to these daily means, a 1-hour maximum mean concentration of 20 000 cm^{-3} is specified in the good practice statements that reflects short-term exposure to UFP. This averaging period (1-hour) is rather unconventional for particulate pollutants where the shortest averaging period (PM_x fine-dust limit) is 24 hours. For short averaging periods concentration spikes that occur within limited timeframes are much more significant and require measurement technologies and data evaluation with sufficient temporal resolution (Thieringer et al., 2022). This is especially relevant due to the fluctuating nature of ultrafine particles, that are easily carried by wind and can occur due to secondary organic aerosol formation and coagulation.

In general (though unique regulation e.g. for small member states may apply), each member state has to provide 1 supersite at an urban / urban background location for each 1 000 000 inhabitants of the country and 1 supersite at a rural background location for each 100 000 km² area. The spatial resolution of these measurements is therefore limited and only several important sources of ultrafine particles and black carbon on ambient air quality (e.g. traffic, industry, etc.) may be covered by the supersites. A supersite should be located downwind the main wind direction of a relevant pollution source. There are many prominent anthropogenic sources for ultrafine particles that are considerably more harmful compared to the natural formation of UFP due to atmosphere chemistry. In literature, many studies focus on air pollution with UFPs in urban environments and traffic (e.g. Dall'Osto et al., 2013; Garcia-Marlès et al., 2024a; Garcia-Marlès et al., 2024b; Kumar et al., 2023; Samad et al., 2022; Trechera et al., 2023; Wang et al., 2011; Zhu et al., 2002).

One major source are combustion processes, where solid or liquid fuels can cause the release of large amounts of soot, ash and other toxic substances (e.g. secondary organic aerosols) into the atmosphere (Nyarku et al., 2021). Indoor sources linked to human activity are commonly studied in exposure assessments (Jeong et al., 2019; Turner et al., 2024). The penetration of particles from outdoor into indoor spaces can dictate the indoor background level and have a major impact on long-term exposure to pollutants (Matson, 2005). In many industrial sites (e.g. during metalworking processes) worker protection from UFP is an important aspect (Elihn et al., 2009; Brouwer et al., 2004). In the automotive and industrial sector, waste gas cleaning [e.g. (fabric) filters, electrostatic precipitators, diesel and gasoline particle filters] can be applied to significantly lower the particle emission of these processes so that they do not contribute to air pollution as significantly (Bächler et al., 2024b; Hammer et al., 2024). Due to the efficiency of waste-gas cleaning technologies and the introduction of EURO norms for vehicles, the impact of traffic-related exhaust emissions on ambient air quality has decreased (Garcia-Marlès et al., 2024b; Leopoldina, 2019). As a consequence, non-exhaust emissions like brake and tire wear are gaining relevance in the automotive sector (Beddows et al., 2023). Air traffic and airports are additional prominent sources / hotspots for ultrafine particles typically featured in literature, whereby the transport of the pollutants plays a major role (Chen et al., 2010; Dröge et al., 2024; Ridolfo et al., 2024; Stacey, 2019; Trebs et al., 2023; Tremper et al., 2022). The role of aerosol transport has also been demonstrated by Junkermann et al. (2022) during aerial measurements where plumes emitted from industrial firing plants at large heights were transported over long distances.

Areas that are comparably rarely featured in official measurements are residential areas in rural or suburban background locations (Dada et al., 2025). The role of wood-fired domestic heating on ambient air quality was shown in a past study for the heating period 2022 / 2023 in a German town (Bächler et al., 2024a). Bari et al. (2009) investigated the relevance of wood-smoke pollution for PM_{10} in a residential area and Thieringer et al. (2022) highlighted the relevance of short-term concentration peaks in the context of wood-smoke pollution from domestic heating. Especially during the evening hours, wood stoves are used for heating in individual homes and the resulting exhaust negatively impacts ambient air quality. The exposure relevance of residential areas is especially high, since high risk groups (e.g. children, elderly) are often staying in close proximity to their homes and wood-stove operation and the corresponding pollution falls into the evening hours where people are spending time at home. Furthermore, ultrafine particles / aerosols from domestic heating are suspected to have a higher toxicity compared to e.g. traffic sources (Utinger et al., 2025), though this of course depends on the exact origin of the particles (e.g. exhaust vs. non-exhaust emissions of cars). As an example, brake wear can cause the emission of and exposure to heavy metals (Neukirchen et al., 2025) that are very harmful to human health. In any case, the exposure to wood-smoke can show damaging health effects due to a large variety of potential gaseous and solid organic substances (Dilger et al., 2023).

The significance of domestic heating on air quality is also addressed in the revision of the EU ambient air quality directive, as e.g. if certain fine-dust limits cannot be reached within the specified deadline by 2030 without replacing significant fractions of existing (wood-fired / fossil fuel related) domestic heating systems – it is possible to postpone the deadline until compliance with the new limits becomes mandatory. While this procedure is reasonable since the replacement of heating systems can be a large financial investment for individual people, the impact of domestic heating on air quality is still an important issue and

studies are not featured as visibly compared to more prominent pollution sources (e.g. traffic or air traffic). Gravimetrical fine-dust limits (compare Table 1) are known to not properly reflect air pollution with ultrafine particles which are predominantly emitted by wood fires and the corresponding wood-stoves (Trojanowski and Fthenakis, 2019; Wang et al., 2020). Thus, there is a dissonance of the particle emission (as well as particle emission limits for wood stoves that also relate to gravimetric concentrations) and particle size of the air pollutants. For smaller firing plants, e.g. for domestic heating, waste gas cleaning is not mandatory and the exhaust aerosol is let unfiltered into the environment, as the cost of gas-cleaning technologies (here: primarily electrostatic precipitators) and the lack of regulation is not promoting wide-spread application. The "Blauer Engel / blue angle – the german ecolabel" proclaims "clean" wood stoves and sets voluntary limits for mass (15 mg/m³) and number based (3 000 000 #/cm³) particle emissions (Blauer Engel, 2025). Within German regulation, such number based limits are not considered and only gravimetrical concentrations are relevant, whereby the concentrations are higher compared to the ecolabel [e.g. 40 mg/m³ for most types of wood stoves; 20 mg/m³ for pellet stoves with water compartments, 30 mg/m³ for pellet stoves without water compartments; values obtained from (Bundesministerium für Justiz und für Verbraucherschutz, 2010) for installations past the year 2014].

While the step towards number-based concentrations as limits for the emissions of combustion processes is addressing the dissonance between the emission limit and the actual emitted size distribution, the number concentration limit to be awarded the "Blauer Engel" is still high considering the mitigation potential that would be achievable with sophisticated waste-gas cleaning technology such as proper filtration systems (Mylläri et al., 2025; Bächler et al., 2024b; Schiller & Schmid, 2015; Matthes et al., 2016). Efficiencies of electrostatic precipitators are comparably low considering the high-particle number concentrations from the combustion process. Cornette et al., (2024) reported number based collection efficiencies of an electrostatic precipitator for wood-stoves of 83 – 92 %. Mukherjee et al., (2024) reported mass based removal efficiencies of approx. 70% that were linked to an increase in ultrafine particle emissions. Bürger and Riebel (2022) reported separation efficiencies of electrostatic precipitators in similar ranges for high temperature processes.

As such the effect on ambient air quality from wood-smoke emissions can be significant and is subject to many external factors such as the dispersion conditions (e.g. wind speed and direction) as well as the geometry of the surrounding buildings in the residential area (Blocken et al., 2011, Teutscher et al., 2025). The relevance of strong local sources on ambient air quality was demonstrated by Norra et al. (2023) during (indicative) air quality measurements using a bicycle in an urban environment that was heavily influenced by local sources outside the scope of official ambient air quality monitoring. A similar situation exists in residential areas, where many temporal local sources (in case of this study: wood-smoke) can contribute to air pollution.

This publication presents measurements of the concentration of ultrafine particles in a residential area for a large fraction of the heating period of the years 2024 / 2025, where wood-smoke from domestic heating significantly affects ambient air quality. A diffusion-charge based measurement device is used; this type of devices has shown great potential for indicative stationary and mobile measurements (Asbach et al., 2024). The data is evaluated with high temporal resolution and discussed in the context of the good practice statements offered by the World Health Organization. In addition to UFP concentration measurements, the effect of pollutant dispersion on the measured particle concentration is characterized.

2 Materials and Methods

2.1 Description of residential area and measurement setup

The measurements were performed in the rural German town "Stutensee" (approx. 25 000 inhabitants split among several districts; 45.68 km² area) close to the city of Karlsruhe. Figure 1 gives an overview of the residential area as well as the measurement setup, which was expanded (e.g. addition of BC and wind measurement) compared to a previous publication featuring exploratory measurements for the heating period of 2022 / 2023 (Bächler et al., 2024a). The measurement devices were installed on the 1st floor balcony on a garage of one of the buildings in a height of approx. 4 m. There was some obstruction (e.g. wall on the east side) that could influence the wind measurement to some degree, however no explicit wind-shielding was employed and there was no significant surrounding vegetation.

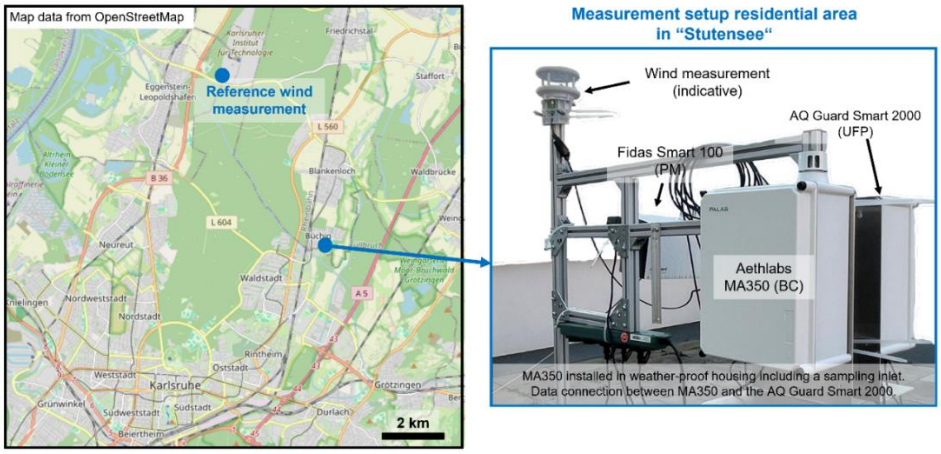


Figure 1: Measurement location in a residential area in "Stutensee" close to the German city of Karlsruhe, reference wind measurement at KIT Campus North and picture of the measurement setup including the aerosol measurement technology. © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

The measurement devices shown in Figure 1 are the AQ Guard Smart 2000 (diffusion charge based UFP monitor; manufacturer: Palas® – compare subsection 2.2), a Fidas Smart 100 (aerosol spectrometer; manufacturer: Palas®) and an MA350 (BC measurement; manufacturer: Aethlabs). The wind measurement serves only as an indication on the local wind speed and wind direction and is not necessarily representative of the meteorological wind situation for the entire area. In the map in Figure 1, the position of KITmast, a 200 m high tower for accurate meteorological wind measurements is shown that serves as a reference to the locally measured wind speed and direction (compare chapter 2.3). This publication focuses on UFP measurements in the context of pollutant dispersion during the majority of the heating season of 2024 / 2025 (data from Nov. 20, 2024 up to Mar. 30, 2025). Explorative Black carbon measurements (MA350) will be presented in sect. 3.1 to offer further context regarding source apportionment. A follow-up publication for further analysis of the temporal behavior and the correlation between UFP, PM_x and BC will analyze the MA350 data in detail. Further data on relative humidity, ambient temperature and pressure from the Fidas Smart 100 can be found in the supplementary information.

2.2 Description of diffusion-charge based UFP-monitor

The UFP particle number concentration was measured using an AQ Guard Smart 2000 from the manufacturer Palas®. The specifications of the measurement device are summarized in Table 2.

Table 2 – Specifications of AQ Guard Smart 2000 according to the manufacturer (Palas, 2025)

Measurement principle	Diffusion charging
Measurements	Particle number concentration, Median particle diameter, Lung deposited surface area, pressure, temperature, relative humidity
Particle number concentration range	1 000 – 10^8 cm^{-3}
Lower particle size detection limit	10 nm
Temperature range	-20°C - +40 °C
Dimensions	530 mm · 270 mm · 208 mm
Weight	Approx. 6 kg
Miscellaneous information	Heated inlet, cloud data storage on "MyAtmosphere" platform

The working principle is based on unipolar diffusion charging of the sample aerosol. At the inlet the sample aerosol is heated to avoid any humidity or condensation effects. Ionized sheath air (filtered by HEPA and activated carbon filters) is generated through unipolar corona discharge. The ambient aerosol is mixed with the ionized sheath air in an ejector / dilutor system at a fixed ratio. Thus, the aerosol is charged by coagulation and excess ions are removed in an ion trap before the charged aerosol (known charge distribution) passes a faraday cup electrometer and the generated current is measured. A mobility analyzer with varying voltage serves as a classifier and generates information on particle size.

The data is collected on the cloud database "MyAtmosphere" (my-atmosphere.net) provided by the manufacturer and can be accessed in varying temporal resolutions (1-minute; 15-minute; 1-hour; 24-hours). The wind measurement was linked to the cloud as well enabling a direct allocation of UFP concentration, wind speed and wind direction with high temporal resolution. The data was post-processed regarding incorrect concentration measurements (e.g. unplausibly high or negative concentration readings). This affected only a negligible fraction of the data. The (raw-)dataset is freely available and published under an open-access license according to data availability statement at the end of the article (Bächler et al., 2025).

2.3 Characterization of the dispersion conditions

Since the wind measurement was located together with the aerosol measurement devices on the 1st floor balcony of a garage of one of the buildings in the residential area, the corresponding wind data is influenced by the building geometry of the surrounding neighborhood, as e.g. the flow of wind may be obstructed by the buildings. Nonetheless, the measurement serves as an indicator for pollutant dispersion, where high wind speeds reflect a high degree of pollutant dispersion / dilution and low (or non-measurable) wind speeds are an indication for a low degree of pollutant dispersion.

In addition to this local wind measurement, data from a meteorological measurement station (compare Figure 1) was provided (Kohler et al., 2018). Figure 2 shows a wind-rose comparing the local wind speed and direction at the measurement setup in "Stutensee" with the meteorological reference measurement (compare figure 1) from KITmast (40 m height) as well as the average diurnal wind behavior that was calculated for the entire measurement period. Here, in case of the reference measurement from KITmast, data from 40 m height and 2 m height is evaluated, whereby wind direction is only measured at 40 m height. The measurement at 40 m height is unobstructed by the vegetation zone of the nearby forest and offers representative data "close" to the ground, while the 2 m measurement is located on a clearing where vegetation has a comparably low impact but still influences the corresponding measurements. Both datasets are presented to offer a holistic comparison to the wind measurement in the residential area. For the data obtained at the residential area, only wind direction data with wind speeds > 0 km/h are evaluated, as the device reports 0° wind direction for wind speeds of zero. The wind rose shows the probability / fraction of the dataset of different wind speeds (above zero) coming from a corresponding wind direction in %.

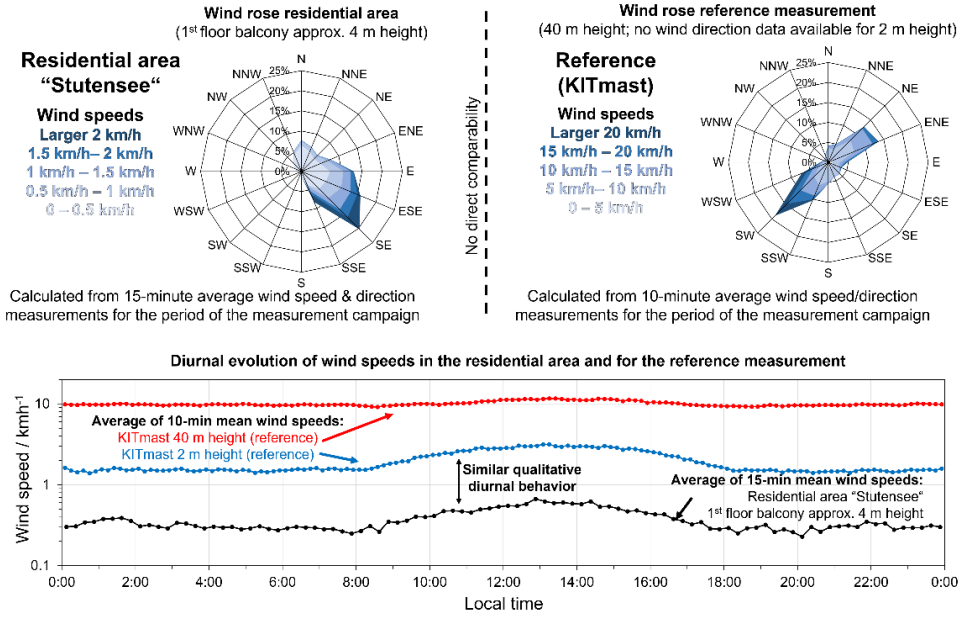


Figure 2: Wind rose and the average average daily behavior of the wind speed for the residential area and the reference measurement (KITmast) at 2 m and 40 m height (Kohler et al., 2018)

Main wind directions for the reference (NE, ENE and SW) are different from the residential area (SE). Note that the building geometry in the residential area can have a significant impact on the measured wind speed and direction. Thus, the absolute wind speeds obtained at the residential area and from the reference at 2 m height are differing significantly. At an increased height of 40 m where there is no impact of the vegetation zone, the measured wind speeds are significantly higher as is expected. Considering the qualitative behavior of the wind speed, all measurement positions show a similar trend, where average wind speeds are relatively stable ranging from 18:00 in the evening up to approx. 09:00 in the morning. In between 09:00 and 18:00 there is a temporal increase in wind speed (e.g. from 0.25 km/h up to 0.6 km/h for the residential area). This diurnal behavior has to be considered in the context of aerosol measurements. A similar profile was reported by Kuhlbusch et al. (2001) for another location in Germany. Due to the same trend between the reference and the wind measurement in the residential area, the locally obtained wind speeds are a valid indication for the corresponding pollutant dispersion conditions. Therefore, only the wind speeds at the measurement position in the residential area will be considered for further evaluation. A Heat Map showing 15-minute average wind speeds for the entire measurement period is provided in the supplementary information.

3 Results and Discussion

3.1 Temporal evolution of daily UFP concentration for the entire measurement period

Wood-stoves are commonly operated during the evening hours within the heating period, causing a characteristic diurnal pattern whereby increased concentrations above the background level are only detected during periods of source activity. Figure 3 shows a Heat-Map of 15-minute average UFP concentrations for the entire measurement period ranging from Nov. 20, 2024 up to Mar. 30, 2025, resulting in 131 days of complete measurement with 24 hour data availability. Concentrations below the background level of 5 000 cm^{-3} are in blue color. This threshold concentration corresponds to the common "natural" background level of the residential area – note however that the "low" concentration level according to the WHO good practice statement (Table 1) is lower by comparison and the color scale aims to highlight exceedances of the background concentration level. The color scale shifts towards yellow color that represents the "high" concentration level of 10 000 cm^{-3} according to the WHO good practice statements for exposure within a 24 hour mean concentration and to red color for values exceeding a concentration of 20 000 cm^{-3} which is classified as a daily maximum hourly mean UFP concentration according to the WHO good-practice statements.

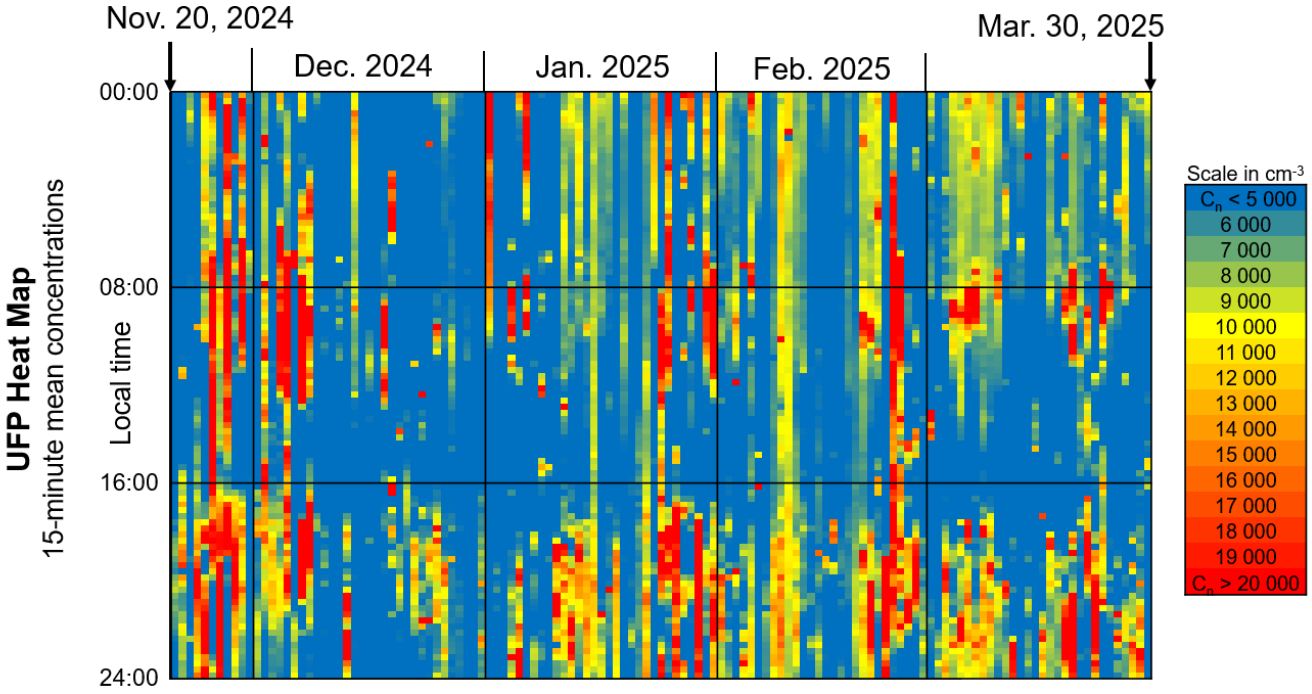


Figure 3 – Heat Map of 15-minute mean UFP-concentration for the entire duration of the measurements

The Heat Map illustrates, that a significant fraction of the measurement period is subject to air pollution in the morning and evening hours what is likely linked to human activity.

Further evaluating the data shown in the heatmap in Figure 3, an "average" diurnal particle concentration dynamic was calculated in Figure 4 and set into the context of the diurnal wind pattern (Figure 2). Here, the overall average 15-minute mean concentration in a fixed time interval e.g. from 09:00 to 09:15 is calculated for either the entire measurement period (left) or only the days where the 1-hour average concentration of 20,000 cm.3 was exceeded (right). E.g. for Fig. 4 left: the average concentration for an entire row of the Heat Map is calculated for each time interval to gain a "mean" diurnal pattern for the entire measurement period. The black curve represents the average 15-minute mean UFP-concentration for the entire measurement duration. Here, days with and without increased UFP concentrations during the evening hours are taken into account. Despite days with low concentrations impacting the calculated mean concentrations, the determined concentration profile shows a pronounced trend, where particle concentrations above the background level (reaching up to around 10 000 cm^{-3}) are measured during the morning hours (approx. 8:00 – 10:00) as well as the evening hours (approx. 18:00 – 22:00).

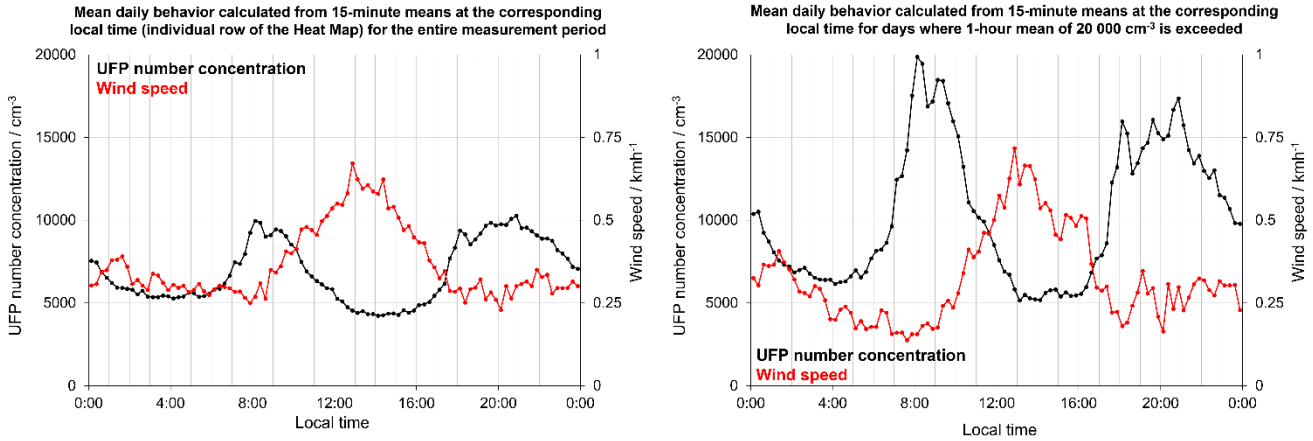


Figure 4 –Diurnal UFP and wind pattern calculated from 15- minute mean concentrations at the corresponding local time for the entire measurement period and measurement days where 1-hour mean concentration of 20 000 cm is exceeded (compare Figure 9)

During daytime, slightly increased wind speeds are measured (compare Figure 2) causing a larger degree of pollutant dispersion. So not only are the major sources likely not active during the lunch hours, pollutant dispersion has positive impacts on the particle concentration level. Identifying pollutant sources is not possible based on concentration data alone, however section 3.1 offers some insights regarding the corresponding source apportionment for the conclusions drawn from Fig. 3 and Fig. 4. Considering only measurement days with significant concentration spikes, where 1-hour mean concentrations of 20 000 cm^{-3} were exceeded (compare Figure 9 and sect. 3.4), the diurnal pattern is even more pronounced. The wind speed during these days with increased air pollution was in a similar region compared to the entire measurement period and also showed the typical diurnal pattern with no significant deviation regarding the higher wind speeds during the daytime. A similar diurnal pattern with corresponding concentration increases was reported by Dada et al., (2025) in rural Switzerland, where especially during winter and autumn increased concentrations were measured during morning (approx. 8 000 cm^{-3}) and evening hours (6 000 cm^{-3}) compared to the background level (4 000 cm^{-3}). The source was identified as domestic heating and aerosol transport

from rush-hours based on intercomparisons of various different measurements (e.g. SMPS, CPC, Catalytic Stripper, NAIS, Trace-gas analysis, Aethalometer, etc.). Another similar diurnal pattern for moderately traffic influenced urban and regional background sites regarding black carbon and aerosol particles in the range of 30 – 200 nm was reported by Sun et al. (2019) where peak concentrations occurred in the morning and evening hours that were allocated to traffic, cooking and heating. Kuhlbusch et al. (2001) also showed a similar diurnal pattern linked to traffic emissions in terms of PM-concentrations. Summarizing, daily UFP concentration evolution is strongly influenced by local sources (wood-stoves) and pollutant dispersion is a significant factor affecting the local concentration level and the measurements.

3.1 Source apportionment in the context of the dispersion conditions

Many different natural (e.g. atmosphere chemistry) and anthropogenic (e.g. wood-smoke, abrasion, etc.) sources can contribute to increased UFP concentrations. Previous investigations proposed wood-stoves as the main source for increased UFP concentration levels in this residential area. Of course elevated UFP concentrations alone are not sufficient to verify wood-smoke from domestic heating as the source – however there is sufficient evidence to unambiguously identify the wood-smoke pollution in the residential area:

- Smell and visual identification of plumes from chimneys of the surrounding neighborhood show the emission of wood-stove exhaust and are direct evidence, even though this is no quantifiable data.
- Additional black carbon measurements also show qualitatively similar concentration spikes in the evening so that the ultrafine particles likely contain soot from (incomplete) combustion. Unfortunately, the data availability for these measurements only covers several days of the measurement period. The focus of this article remains UFP-concentrations and the Black-Carbon data and the link between PM, UFP and BC on a temporal basis will be analyzed in detail in a follow-up publication. Figure 5 shows the Black-Carbon concentration obtained from the MA350 device for days with 24 hour data availability to serve as further indicative proof regarding the source of increased UFP and BC-concentration levels. Especially during the evening hours, Black-Carbon concentrations of approx. 5 µg m^{-3} are reached. For the inversion period including Feb. 8 and Feb. 9 (compare sect. 3.2.2.) concentrations up to 10 µg m^{-3} were measured regarding 15-minute average concentrations (potentially higher concentration spikes – maximum 15-minute average concentration of approx. 17 µg/m^3).

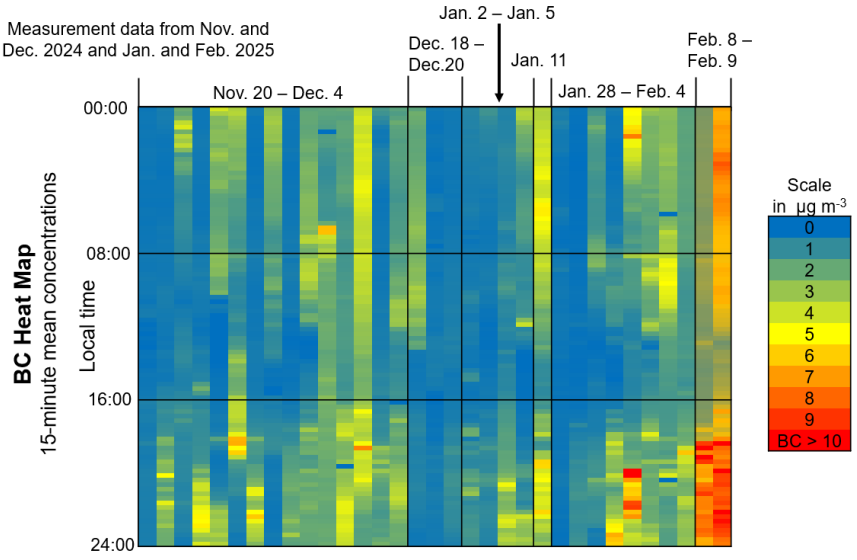


Figure 5 – Heat Map of 15-minute mean BC-concentration for several exemplary days (24-hour data availability) during the measurement period

- The increased concentrations in the evening are occurring outside typical rush hours and often reach their peak after 18:00. While there indeed is a highway (A5 in Figure 1) located in the main wind direction (according to the indicative wind measurement which may be influenced by building geometry) that could be a potential source of ultrafine particles from traffic – increased concentrations only occur for low wind speeds close to or below the detection limit of the wind measurement. As such, the transport of pollutants from the highway to the residential area can be ruled out or is at least unlikely to cause concentration spikes in that order of magnitude. As a consequence, increased concentrations in the residential area have to originate from local sources.
- New-particle formation events would have to coincide with other sources and do not occur in larger numbers. Such events should also be mostly independent of wind-speed. Song et al. (2024) did not report significant occurrence of new-particle formation events at another location at the outskirts of Karlsruhe within reasonable proximity to the measurement site. However these investigations were performed during the summer months and are not comparable.
- Other prominent UFP sources (e.g. air traffic) can be ruled out.

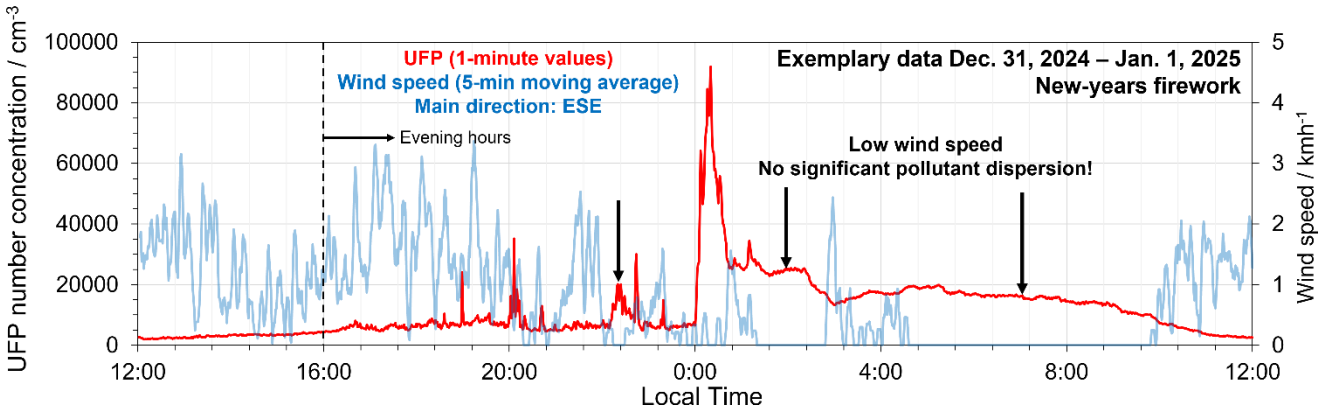
3.2 Effect of pollutant dispersion on short timeframes for several exemplary measurement periods

To further demonstrate the impact of pollutant dispersion on ultrafine particle concentrations, several exemplary days or periods are discussed in this section. Correlations for other ambient conditions such as temperature and pressure can be found in the supplementary information – though the impact of these parameters shows no distinctive trend compared to wind speed / pollutant dispersion.

3.2.1. New-years fireworks

A prominent example during the heating period where air pollution is prevalent is the New-Year's celebration, where fireworks are launched in large amounts at midnight (00:00). The explosion of fireworks contributes to air pollution and, while only being a temporal occurrence once a year, can demonstrate the dynamic behavior of UFP concentrations. Other authors also

310 featured the impact of firework celebrations on air pollution (Joshi et al., 2019). Figure 6 shows the UFP concentration in the
311 context of wind speed / dispersion conditions for the residential area featured in this publication for the year 2024/2025.



312

313 **Figure 6 – UFP number concentration and dispersion conditions during New-Year's fireworks.**

314 Over midday and up to the late afternoon at 4 PM, UFP concentrations were around a typical background level and the wind
315 speed was comparably high at the measurement position (compare Figure 2). In the evening hours from approx. 17:00 until
316 midnight, concentrations were fluctuating between 5 000 and (mostly) 10 000 cm^{-3}, whereby several short-term peaks reached
317 concentrations exceeding 20 000 cm^{-3}. This noise in the data is an indication for source activity, even though average
318 concentrations are not noticeably high. Reaching 00:00 and the start of the fireworks, concentrations quickly increase, where
319 a peak concentration of 90 000 cm^{-3} is reached at 00:30. The peak concentration disperses rather quickly until approx. 1:30
320 during a period, where elevated wind speeds were measured. Results from (Drewnick et al., 2006) showed larger peak
321 concentrations (up to 150 000 cm^{-3} – 5 minute average concentration) for a German city, however the measurement position
322 was situated close to the center of firework activity. Drutschke et al. (2011) also report higher peak concentration for firework
323 festivities up to 1 600 000 cm^{-3}. After the decay of the main concentration peak, the concentration level remains relatively
324 constant at approx. 21 000 cm^{-3}. From 2:30 up to approx. 5:00, concentrations fluctuate during a period of pollution dispersion.
325 Finally, from 5:00 up to the morning hours of 10:00, no wind speed is detected and the natural dispersion of the pollutants is
326 comparably slow so that concentrations decrease from 20 000 down to 10 000 cm^{-3} over a longer period of time before
327 increased wind speeds during lunch bring the UFP concentration to the background level.
328

3.2.2. Stationary temperature inversions / High-pressure-area

An example for a period of the measurement campaign, where the dispersion conditions for UFP and other air pollutants was significantly impaired was during the prevalence of the high-pressure-area “Elvira” in February 2025. The high-pressure-area / stationary temperature inversion prevented air exchange that led to the accumulation of air pollutants. This can have a significant impact on air quality, especially for cities located in basins with unfavourable dispersion conditions (Zhang et al., 2024). This effect on air pollution can also be observed on a temporally resolved basis in the residential area regarding UFP concentrations (Figure 7) and was prominently featured across different news platforms in Germany. It is also clearly visible within the $PM_{2.5}$ Heat Map shown in the supplementary information.

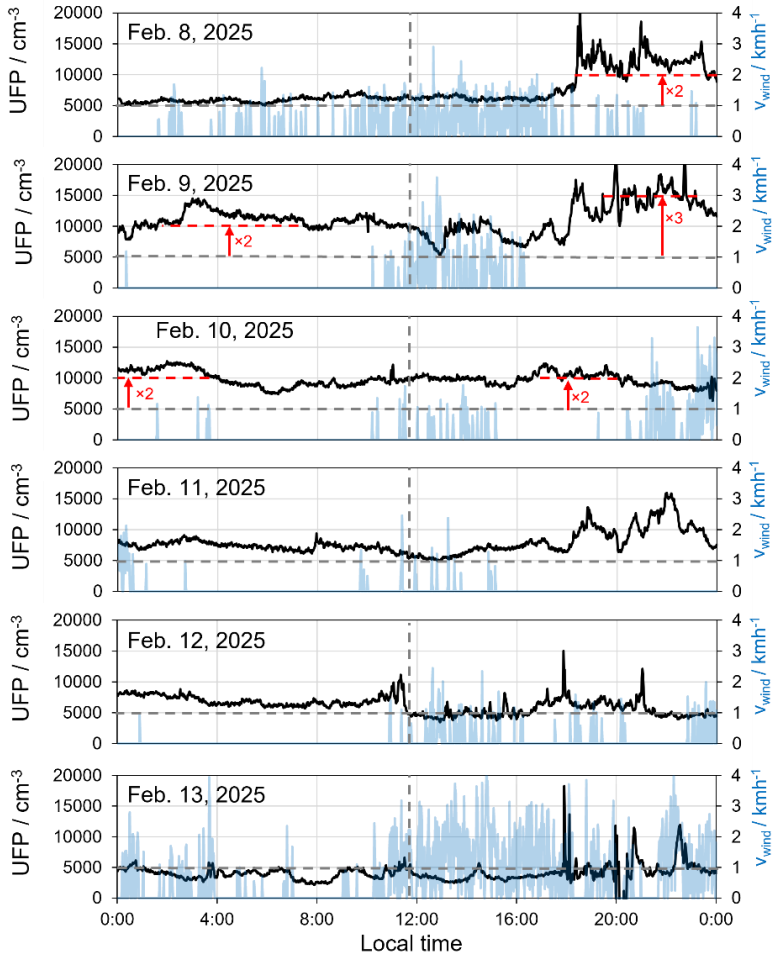


Figure 7 – UFP number concentration and dispersion conditions during prevalence of a high pressure area / stationary temperature inversions in February 2025

Increased wood-stove operation led to an increase in UFP concentration during the evening hours of Feb. 8. Due to poor pollutant dispersion and the beginning of the impact of the high-pressure-area, this level remained constant up to the lunch hours of the next day. In the evening of Feb. 9, concentrations again increased up to three times the background concentration and remained at a level of 10 000 cm^{-3} (high concentration according to WHO good practice statement) for the entirety of Feb. 10. On Feb. 11, the concentration slowly decreased to the background level up to the evening hours, where wood-stove operation again contributed to air pollution. Towards the end of the effective duration of the high-pressure-area on Feb. 12 and 13, the concentration decreased and, especially on Feb. 13, the concentration was at or below the background level and significant wind speeds were measured for the majority of the day. Noise in the data of Feb. 13 is again an indication for source activity and simultaneous dispersion / dilution.

3.3 UFP concentration levels in the context of pollutant dispersion during the entire measurement period

To give a direct correlation between ultrafine particles and wind speed, a scatterplot is drawn for the 15-minute average UFP concentrations and the corresponding average wind speed in Figure 8. Correlations for different ambient conditions can be found in the supplementary information – although no clear trends could be derived from this evaluation. In Figure 8, different sectors can be identified that illustrate the main conclusions drawn from the previously discussed measurements of UFP in the context of wind speeds / pollutant dispersion.

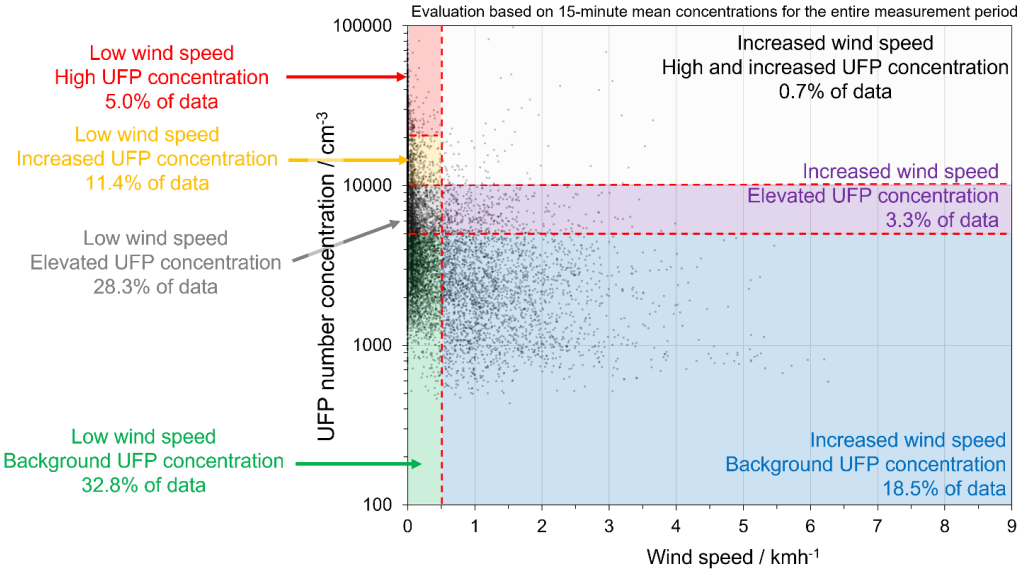


Figure 8 – Scatterplot of 15- minute mean UFP-concentrations and wind speeds for the entire measurement period

The highest UFP concentrations occur under conditions where pollutant dispersion is very low (red and yellow sector). The threshold wind speed was selected at 0.5 km/h as almost no concentrations above 10 000 cm^{-3} were measured at higher wind

speeds. Data above the background level at low wind speeds amounts to 44.7% of the total data and was likely caused by source activity and wood-smoke pollution.

For wind speeds above 0.5 km/h and concentrations above 5 000 cm^{-3} only a very limited amount of data can be found (4 % total) by comparison. With increasing pollutant dispersion, even under conditions with high source activity the effect on air quality is not as significant.

In the sector including wind speeds above 0.5 km/h and concentrations below 5 000 cm^{-3} a total of 18.5 % of the measurement data can be found. Pollutant dispersion dominates the overall particle concentration level so that even in case of source activity, the effect on ambient air quality is not measurable, impeding the generation of emission inventories (e.g. climate-damaging black carbon from incomplete combustion from wood-stoves). This data is predominantly obtained during the lunch hours with increased wind speeds.

Only for data below the background concentration and at low wind speeds source activity can be ruled out with high certainty. The amount of data in this quadrant amounts to 32.8%.

Summarizing, the dispersion conditions have a major impact on the measured air quality in the residential area. In case of low pollutant dispersion, increased concentration levels can persevere across multiple days. For higher wind speeds, pollutant dispersion can dominate the ambient air quality and low concentration can be measured, despite the possibility of wood-smoke emissions.

3.4 Evaluation of average UFP and particulate matter concentrations regarding ambient air quality limits and WHO recommendations

In the previous sections, the measured UFP concentrations were already discussed in the context of particle concentration levels introduced by the World Health Organizations' "good practice statements". Particle concentrations above 10 000 cm^{-3} (24-hour mean) are considered a high concentration. Furthermore, a daily maximum 1-hour mean concentration of 20 000 cm^{-3} should also not be exceeded. In Figure 9, the daily mean UFP concentration as well as the maximum 1-hour mean concentration for the entire measurement period ranging from Nov. 20, 2024 up to Mar. 30, 2025 are calculated and set into the context of the WHO "good practice statements".

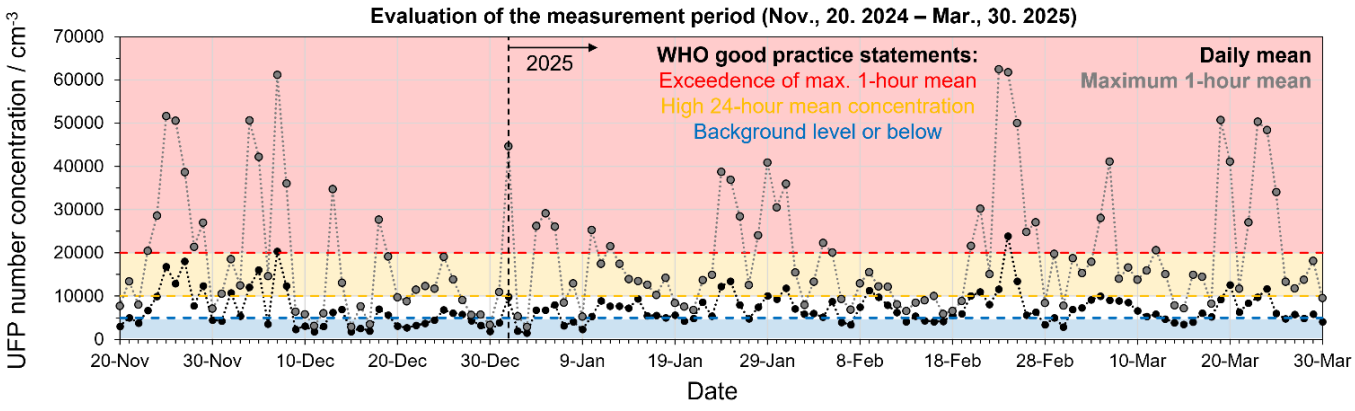


Figure 9 – Mean daily and maximum 1-hour UFP number concentration for the entire measurement period

Considering the 24-hour mean concentrations, only a total of 16 % of measurement days (21 / 131 days) exceed the 24-hour mean UFP concentration of 10 000 cm^{-3} (black data-points within yellow area). This is mainly caused by the diurnal pattern, where increased concentrations are only detected during the morning and evening hours so that these concentration spikes are not as significant in the context of 24-hour mean concentrations.

However, considering increased short-term exposure to high concentrations above 20 000 cm^{-3}, a total of 33.6 % of measurement days (44 / 131 days) exceed the daily maximum 1-hour mean concentration at least once during the day. Considering a total of 24 hours for each measurement day, the number of hours exceeding the 20 000 cm^{-3} threshold is 154 / 3144 which corresponds to 4.9% of hours during the measurement period. These increased concentration levels are very likely hazardous due to their origin from wood combustion and can contribute to long-term health effects and endanger high risk groups such as children and the elderly regarding short-term health effects.

3.5 UFP concentrations in the context of $PM_{2.5}$ measurements

To add further context to the increased UFP peak concentrations (Figure 9), the mean daily $PM_{2.5}$ concentrations obtained from scattered-light based measurements using the Fidas Smart 100 (compare Figure 1) are displayed in Figure 10. These measurements were indicative measurements and not government-official. For further information on the temporally resolved $PM_{2.5}$ behavior, a Heat Map similar to Figure 4 can be accessed in the supplementary information.

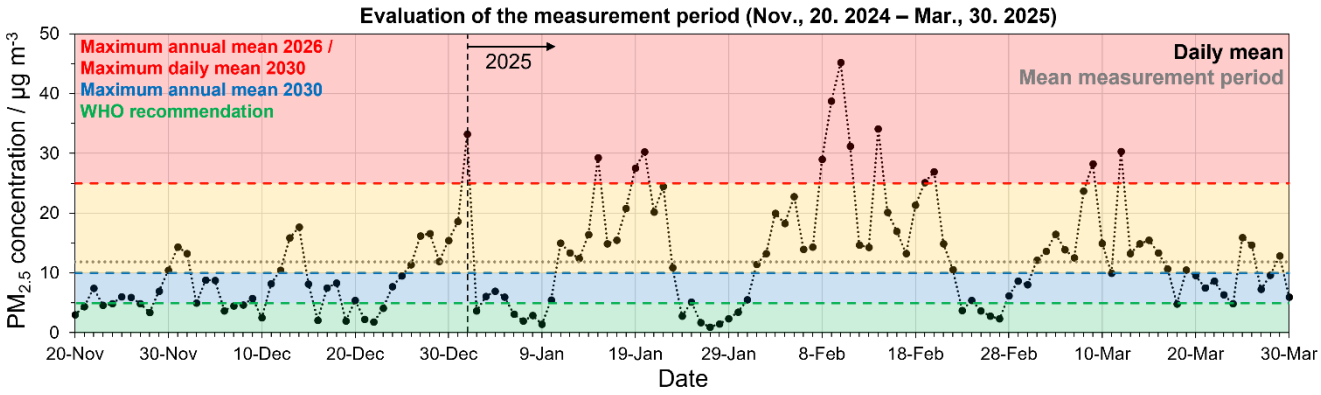


Figure 10 – Mean daily $PM_{2.5}$ concentration for the entire measurement period within the scope of the limits specified in the revised Ambient Air Quality Directive (indicative measurement – no government-official data)

The average $PM_{2.5}$ concentration of the measurement period (11.9 µg/m³) is close to the future annual limit values for the year 2030. Therefore, the current mean annual concentration limit of 25 µg/m³ is easily kept. As the measurement period was performed during the heating season, where higher PM concentrations are expected, there will likely be no (or no significant) exceedance of the future 10 µg/m³ limit in case of the year 2025. When it comes to the future number of 18 exceedance days of a concentration of 25 µg/m³, which will be relevant starting in 2030, there were a total of 13 exceedance days during the measurement period (all of which occurred in 2025). Several of these exceedance days were obtained during the impact of the high-pressure-area discussed in sect. 3.2.2. so that the concentration itself is not directly linked to the emission of pollutants but rather the dispersion conditions that may dictate whether or not the number of exceedance days can be complied with.

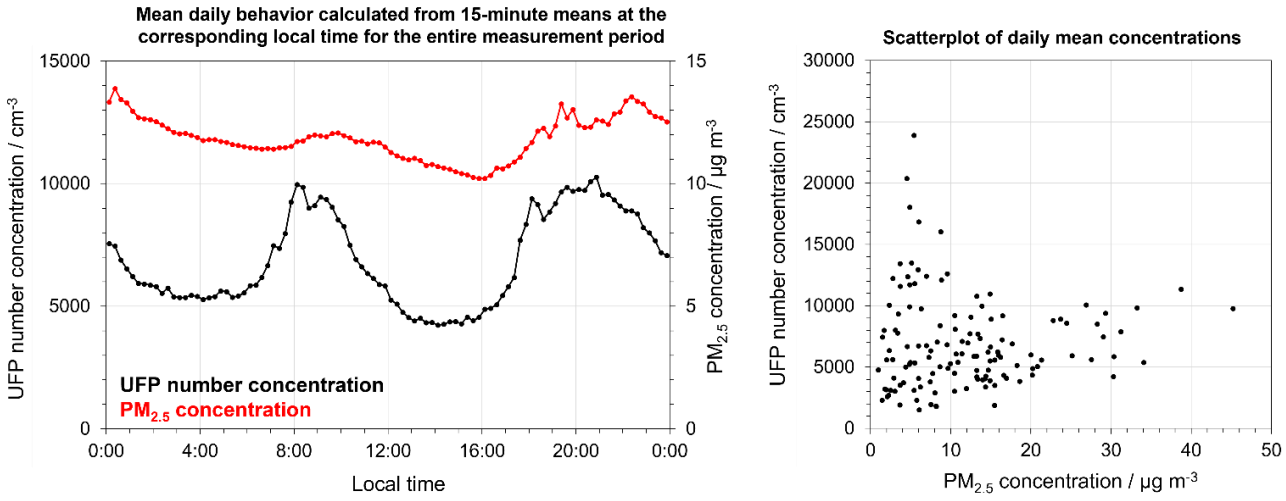


Figure 11 – 15- minute mean diurnal UFP (compare Figure 4 regarding UFP concentrations) and $PM_{2.5}$ pattern for the entire measurement period and scatterplot of UFP and $PM_{2.5}$ concentrations (compare Figure 9 and Figure 10)

In this case, the actual pollution with hazardous nanoparticles from wood combustion is not properly represented by "conventional" air quality monitoring (Figure 11). There is no direct correlation between the $PM_{2.5}$ and UFP measurements, as UFP are below the detectable size range of the Fidas Smart 100 device and remain undetected (additionally, their contribution to mass concentrations is very small – see also scatterplot of 15-minute average UFP and $PM_{2.5}$ concentration in the supplementary information). While there is also a slight diurnal pattern considering average $PM_{2.5}$ concentrations – compared to the large differences during peak exposure times in the morning and evening hours for UFP concentrations (e.g. factor of 2 compared to background level), the absolute difference in PM is comparably low (factor 1.3 – 1.4). The (also mass based but non-size-resolved) BC-concentrations often increased from a close to zero-background level up to 5 µg m^{-3} during the evening hours by comparison (Figure 5).

Short-term exposures (e.g. covered by good practice statement for UFP in the form of 1-hour maximum concentration) are not considered in the limits of the Ambient Air Quality Directive due to the daily and annual averaging periods of particle concentrations.

These results demonstrate that UFP monitoring is especially relevant for regions where domestic heating using wood as combustion resource is used. While significant UFP-concentrations were measured in the residential area, the PM concentrations (mostly) comply with (or do not show a significant exceedance of) current and future PM-concentration limits. For areas where measurement stations do indeed register an exceedance of PM-concentration limits due to the emissions from wood-combustion for domestic heating as a main source, it has to be assumed that ambient air quality is likely affected by especially hazardous (black-carbon) nanoparticles.

4 Summary and Outlook

Measurements of ultrafine particle concentrations applying a diffusion charge based UFP-monitor were performed in a residential area in a small German town during a large fraction of the heating period of 2024 / 2025. The major source for air pollution in the residential area during this time was wood-stove exhaust for domestic heating. Especially during the morning and evening hours, significant UFP concentration spikes were measured, causing a characteristic diurnal pattern. Here, average concentrations of approx. 10 000 cm^{-3} (corresponds to twice the typical background level) were measured averaging the entire measurement period. The dispersion conditions have a large impact on the measured concentrations, as during daytime increased wind speeds occur and were measured at a reference wind measurement site and in the residential area. Higher wind speeds are linked to lower / decreasing UFP concentrations and only for low (or non-detectable) wind speeds large UFP-concentrations (e.g. exceeding 10 000 cm^{-3} were measured. On approx. 33.6% of days during the measurement period a maximum daily 1-hour mean concentration of 20 000 cm^{-3} was exceeded according to the WHO "good practice statements" on ultrafine particles. During these periods with increased wood-smoke pollution (morning and evening hours) people are more likely to spend time at their homes (indoors). Depending on ventilation / air exchange between interior and exterior, they may or may not be exposed to this outdoor air pollution. How much individual homes are affected can thus vary significantly.

Due to the small particle size, these UFP from wood-smoke are not contributing significantly to legally-relevant PM-concentrations, where a less pronounced diurnal pattern was shown with a scattered-light based Fidas Smart 100. This research highlights the dissonance between the size distribution of wood-smoke particle emissions from domestic heating (nanometer region) and conventional air quality measurements (mass based PM-concentrations). A follow-up publication will further discuss explorative (temporally resolved) Black-Carbon measurements and the link to UFP and PM concentration dynamics during this measurement period. Further research will aim to expand the setup to perform further characterization of the air pollutants measured in the residential area.

Data availability

The data that support the findings of this study are openly available in the KITOpen Repository under the doi:10.35097/2aab6yjdyfg4nr69.

Author contribution

P.B. : Conceptualization, Methodology, Investigation, Resources, Writing – Original Draft, Writing – Review & Editing
F. W.: Conceptualization, Validation, Resources, Data Curation, Writing – Review & Editing
S. K.: Validation, Data Curation, Writing – Review & Editing
A. D.: Conceptualization, Methodology, Validation, Resources, Supervision, Writing – Review & Editing.

Competing interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Frederik Weis and Sebastian Kohler are currently employed by Palas GmbH and worked on the development of the measurement device.

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