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Influence of a large commercial airport on the ultrafine particle number concentration in a distant residential area under different wind conditions and the impact of the COVID-19 pandemic☆

Janis Dröge *, Doris Klingelhöfer, Markus Braun, David A. Groneberg

Goethe University Frankfurt, Institute of Occupational, Social and Environmental Medicine, Frankfurt am Main, Germany

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A B S T R A C T

Exposure to ultrafine particles has a significant influence on human health. In regions with large commercial airports, air traffic and ground operations can represent a potential particle source. The particle number concentration was measured in a low-traffic residential area about 7 km from Frankfurt Airport with a Condensation Particle Counter in a long-term study. In addition, the particle number size distribution was determined using a Fast Mobility Particle Sizer.

The particle number concentrations showed high variations over the entire measuring period and even within a single day. A maximum 24 h-mean of 24,120 cm^{-3} was detected. Very high particle number concentrations were in particular measured when the wind came from the direction of the airport. In this case, the particle number size distribution showed a maximum in the particle size range between 5 and 15 nm. Particles produced by combustion in jet engines typically have this size range and a high potential to be deposited in the alveoli. During a period with high air traffic volume, significantly higher particle number concentrations could be measured than during a period with low air traffic volume, as in the COVID-19 pandemic.

A large commercial airport thus has the potential to lead to a high particle number concentration even in a distant residential area. Due to the high particle number concentrations, the critical particle size, and strong concentration fluctuations, long-term measurements are essential for a realistic exposure analysis.

1. Introduction

Ultrafine particles (UFPs) are particles with a diameter of less than 100 nm. Compared to coarser particles, they represent a comparatively small mass, but dominate the number concentration (Morawska et al., 2008). Because of the low weight fraction for the quantification, the particle number concentration (PNC) is usually measured. Their chemical and physical properties vary greatly depending on the source. They are either emitted directly or formed secondarily from emitted precursors such as sulfates, organic components, or metals through chemical reactions in the ambient air (Westerdahl et al., 2008; Guo et al., 2020; Kwon et al., 2020). The main sources of UFPs are combustion-related processes from industrial plants, power plants, and the transport sector. In urban regions, the transport sector is the dominant source of UFPs (Aalto et al., 2005; Hasegawa et al., 2004). In addition to combustion engines from motor vehicles, airports also represent significant sources of UFPs. Increased PNCs have already been measured in the surroundings of airports in numerous studies and linked to air traffic (Fritz et al., 2022; Hudda et al., 2018; Keuken et al., 2015; Rose and Jacobi, 2019; Ditas et al., 2022; Ungeheuer et al., 2022). The particulate emissions are caused by the aircraft engines and auxiliary power units during taxiing, takeoff, and landing. However, vehicle traffic on the airport site as well as heating, maintenance, and repair work on the ground are also responsible for the total particulate emission (Amin, 2001; Mazaheri et al., 2011; Masiol and Harrison, 2014; Jasinski and Przylebska, 2018). Emitted particles from flying aircrafts also have the potential for vertical dispersion. In particular, wake turbulences generated by fast air movements on the upper side of the wings are capable of transporting particulate aircraft emissions to the ground (Riley et al., 2016; Unterstrasser et al., 2014; Westerdahl et al., 2008).

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* Corresponding author. Goethe University Frankfurt, Institute of Occupational, Social and Environmental Medicine, Theodor-Stern-Kai 7, 60590, Frankfurt am Main, Germany.

E-mail address: droege@med.uni-frankfurt.de (J. Dröge).

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Exposure to UFPs is associated with numerous negative consequences for human health. These include hypertension and damage to the cardiovascular system, the respiratory tract, and the central nervous system (Belleudi et al., 2010; Heusinkveld et al., 2016; He et al., 2020).

Compared to coarser particles, a high surface-to-mass ratio and the ability to disperse in the body and act systemically seem to be particularly responsible for increased toxicity (Heusinkveld et al., 2016; Nemmar et al., 2002; Kreyling et al., 2006; Araujo et al., 2008). In contrast to data of coarser particles (Pope et al., 2002; Creason et al., 2001; Liao et al., 1999), the data for long-term health-effects of UFPs are poor. One reason is the missing international standards on measurement protocols for UFPs. Information on the personal exposure is limited. Due to the lack of environmental epidemiological data, it is difficult to establish limit values. On the other side, the lack of valid limit values leads to the fact that exposure data are not routinely collected (Schraufnagel, 2020; Marval and Tronville, 2022; Umweltbundesamt, 2018). Even though long-term measurements, e.g. by authorities or institutes, are increasingly being carried out and networks have formed, comprehensive monitoring is currently not given (TROPOS, 2023; HLNUG, 2023).

With 513,912 takeoffs and landings in 2019, immediately before the COVID-19 pandemic, Frankfurt Airport is one of the airports with the most aircraft movements in Europe (Fraport AG, 2020). Frankfurt thus represents an ideal study site for investigating the effects of air traffic on the PNC in a residential area in a long-term study. Various individual analyses were carried out and evaluated in their entirety. In particular, wind direction-dependent and air traffic-dependent variations of the PNC were characterized. Also analyzed was whether passing aircrafts have an influence on the PNC at the study site and what kind of particle number size distribution is present in the ambient air. The data may serve as a basis for a realistic exposure analysis.

2. Material and methods

2.1. Study site

The study site is located on a roof over the entrance of a residential building in a low-traffic residential area in the south of Frankfurt (Lerchesberg, district Sachsenhausen). The distance between the study site and the closest point of the airport is 7 km. The distance to the center of the airport is approximately 10 km (compass heading 240°). Fig. 1 shows the geographical positions of the study site and the airport.

Frankfurt Airport has four runways. Runway Center and Runway South can be used for both takeoffs and landings. Runway Northwest can be used exclusively for landings and Runway West exclusively for takeoffs. There are two different operation directions for the airport. With the operation direction west, the aircrafts take off and land facing west (compass heading 250°) (Fraport AG, 2023a). In this case, all arriving aircrafts fly on three parallel approach paths. The landing aircrafts approaching on Runway Northwest fly almost directly over the study site with a height of approximately 600 m above ground level. Aircrafts landing on Runway Center/South pass the study site in the south with a horizontal offset of 1.2 km (Runway Center) and 1.7 km (Runway South) with a height of approximately 400 m above the level of the study site.

With the operation direction east, the aircrafts take off and land facing east (compass heading 70°). A certain proportion of the aircrafts taking off overfly the study site and the surrounding area.

Due to the steeper angle during climbing, the crossing altitude is comparatively high. Also, they do not fly in narrow parallel corridors over the study site, but fan out broadly (Fraport AG, 2022).

The decision for an operation direction depends mainly on the wind conditions. Headwind shortens both the distance required for takeoff and the distance required for landing. A prevailing headwind is thus preferred for flight operations. A westerly wind direction dominated in the region during the time of the study, so the operation direction west was used more frequently. For reasons of noise protection, no scheduled flights are allowed between 23:00 and 05:00 at Frankfurt Airport.

2.2. Measurement of ultrafine particles

The positioning of the measurement instruments at the study site is shown in Supplementary Figure F1. The continuous measurement of

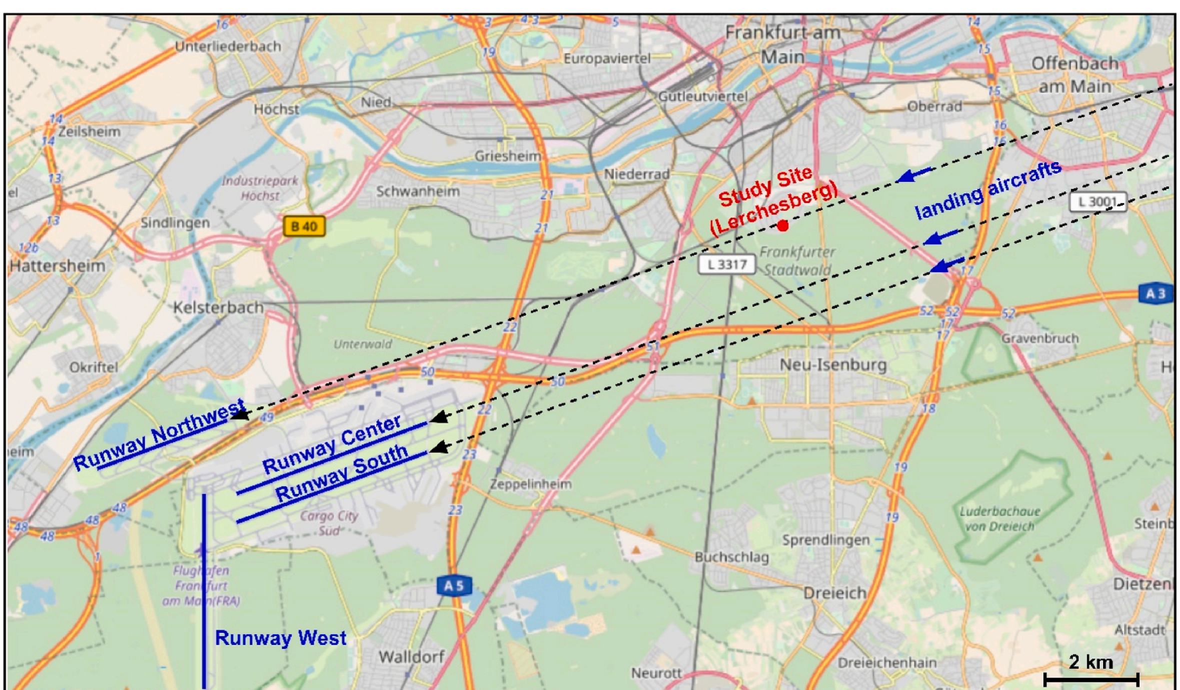

Fig. 1. Geographical position of the study site, the airport with its runways (blue lines) and the associated landing approach paths (dotted lines) during operation direction west. Geographical picture by *OpenStreetMap*. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

UFPs in ambient air was carried out with a Condensation Particle Counter (CPC) of the type Grimm EDM 465. The CPC detects particles with a diameter between 7 nm and 1 μm and indicates the PNC. The maximum temporal resolution is 5 s. The CPC was calibrated by the manufacturer.

To characterize the particle load in more detail and to perform a source analysis, the particle number size distribution (PNSD) was additionally determined with a Fast Mobility Particle Sizer (FMPS) type 3091 from TSI. Particles between 5.6 and 560 nm can be differentiated with a resolution of 32 channels. The maximum temporal resolution is 1 s.

Continuous measurements with the CPC took place in the period from 07-30–2020 to 06-30-2022. Due to maintenance, no data was generated between March and June 2021. A measurement with the FMPS was carried out on 09-06-2022 (airport operation direction west).

2.3. *Influence of the wind and the time of day on the particle number concentration*

To characterize the influence of the wind direction on the particle load at the study site, the mean PNCs measured for the respective wind directions were analyzed over the entire measurement period.

Since urban structures can strongly influence both wind speed and wind direction, it is difficult to determine the main wind direction responsible for particle transport at the study site. For this reason data for wind direction (10°-resolution) and wind speed were taken from the database of the German Weather Service (*Deutscher Wetterdienst*, DWD) for the station Frankfurt Airport (DWD, 2023), which carries out a continuous measurement in an open field at about 10 m height above the ground.

Due to the distance (13 km) of the study site from the weather station, a slight temporal offset of the wind field is still possible. Since a certain wind speed is necessary for particle transport, only the periods when the wind speed was ≥1 m/s were included in the analysis. With the limit value of 1 m/s, it can be assumed that a certain basic flow was present, even when using time-averaged wind speeds. As the periods in which wind speeds of less than 1 m/s occurred only account for a very small proportion, the choice of this limit value meant that almost all the data could be included in the analysis. A temporal resolution of 1 h was chosen for both the meteorological data and the data of the PNC. There was a differentiated characterization between the periods with and without flight operation. The period between 23:00 and 0:00 was also assigned to the period with flight operation, since airport-related high concentration levels would not drop abruptly after flight operation terminates.

For a wind direction-dependent source analysis of the particle load at the study site, its surroundings were divided into six sectors. This division ensured both high spatial resolution and sufficient data availability for the individual sectors. Fig. 2 shows the division of the individual sectors around the study site.

In addition, exemplary PNC variations during the course of the day are presented graphically. PNC data in a high temporal resolution (1 min) were used for this purpose.

2.4. *Influence of the air traffic volume on the particle number concentration*

Since there have been significant fluctuations in air traffic volume in recent years due to the COVID-19 pandemic, there is an opportunity to compare PNCs measured during a period of high air traffic volume with the PNCs measured during a period of low air traffic volume. In this way, it is possible to determine any relation between air traffic volume and PNC at the study site. The analysis was performed for each wind sector individually since the wind conditions were subject to strong variations during the study period which in turn can have a significant influence on the PNC. Due to data availability and seasonal variations in PNC (Sabaliauskas et al., 2012), the 7-month mean PNCs from the periods Aug 2020–Feb 2021 (low air traffic volume) and Aug 2021–Feb 2022 (high air traffic volume) were compared. The total of all aircraft movements (takeoffs and landings) that occurred in a month was used as a measure of air traffic volume. In the period with low air traffic volume the value varied between approximately 11,100 (Feb 2021) and 17,700

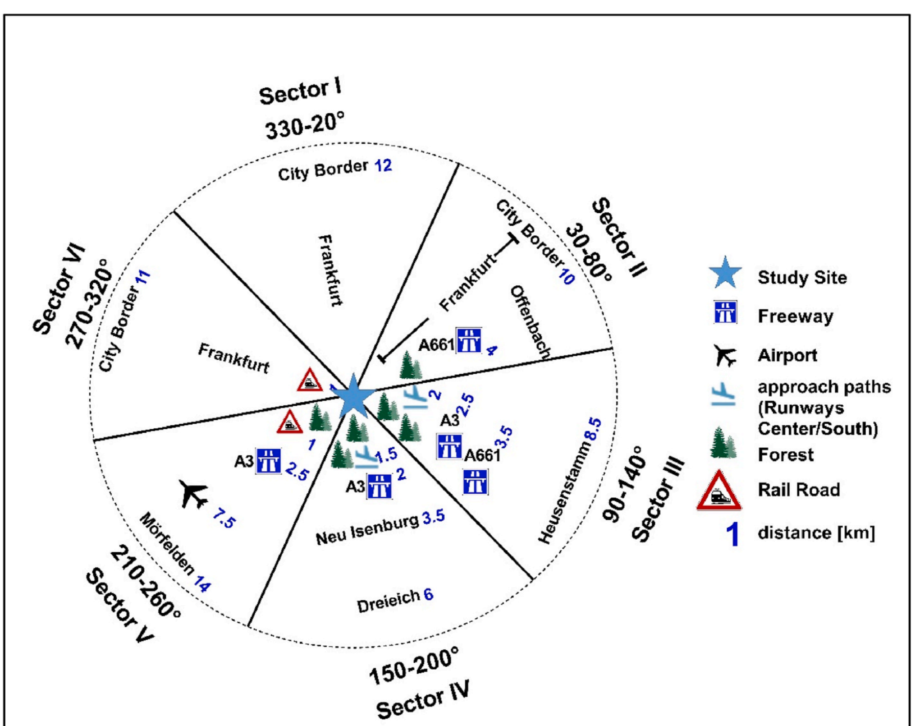

Fig. 2. Sectors around the study site with geographical feature, communities, and the distance to the study site.

(Aug 2020). In The period with high air traffic volume the value varied between approximately 22,300 (Feb 2022) and 30,000 (Oct 2021) (Fraport AG, 2023b).

In the analysis, a differentiation between PNCs measured during daytime (flight operation) and nighttime (no flight operation) was made. Since a certain wind speed is necessary for particle transport to the study site, the PNCs measured at wind speeds below 1 m/s were not included in the analysis.

2.5. Influence of landing aircrafts on the particle number concentration

Since landing aircrafts during operation direction west fly over the station directly or with a low horizontal offset, they thus represent potential particle sources at the study site. To detect the influence of these emitters, the course of the PNC at the transition to flight operations (04:00–06:00) was analyzed over the entire measurement period during operation direction west.

Aircraft-induced PNC-increases should be detected most sensitively during this period.

In addition, the average PNCs of the period 04:00–05:00 ($PNC_{4\text{-}5}$) without flight operation and 05:00–06:00 ($PNC_{5\text{-}6}$) with flight operation were compared with each other in a Wilcoxon-Signed-Rank test.

To characterize the influence of the aircrafts which pass the measuring station south (approaching on Runway Center/South), only those days were included in the analysis on which the wind blows constantly from directions 120–180° with a minimum speed of 1 m/s between 04:00 and 06:00. The wind direction was selected in such a way that the particle emissions from aircrafts have a short way as possible to the study site. At the same time, there is no signal overlap with particles emitted from the airport site, as a sufficient safety distance from its area of influence has been selected. Data for wind speed and wind direction with a high temporal resolution (10 min) were used to assume a constant wind field. To detect the emissions of the aircrafts flying directly overhead of the study site, calm conditions or wind from the east or west are necessary. With northerly or southerly wind directions, the emitted particles are transported away from the study site. When the wind is blowing from the east, the operating direction is almost exclusively east and no landing aircrafts fly over the study site. During west wind conditions, there is a signal overlap with particles emitted from the airport site, so an assignment to a particle source (overflying aircraft vs. airport) is difficult. Due to the low proportion of calm conditions (<1 m/s), the data availability for a comprehensive analysis is too low. Furthermore, the aircrafts directly flying over the measuring station have a comparatively high altitude. For these reasons, the influence of aircrafts landing on Runway Northwest was not initially analyzed. For a detailed analysis of temporal relations, the PNCs with a temporal resolution of 5 s were used.

3. Results

3.1. Variations of the particle number concentration

Fig. 3 shows the mean PNCs for the individual months in the entire measurement period. In addition, the maximum and minimum 24-h mean PNCs are presented for each individual month (data in Supplementary Table T1).

Over the entire measurement period, the monthly mean PNCs varied between 4707 cm^{-3} (Feb 2021) and 11,313 cm^{-3} (Oct 2021). Within the respective months, there were also large variations between the individual days. The highest 24 h-mean PNC was measured on a day in Oct 2021 (24,120 cm^{-3}). The lowest 24 h-mean PNC was measured on a day in Feb 2021 (2137 cm^{-3}).

Fig. 4 shows the mean PNCs measured for the respective wind directions over the entire measurement period (data in Supplementary Table T2).

During the operating time of the airport, a clear maximum of the PNC could be detected during wind from sector V (210–260°). The maximum PNC (18,492 cm^{-3}) was measured for the wind direction 240°, which matches with the center of the airport. During the night hours without flight operation, no clear wind direction-dependent trend could be observed.

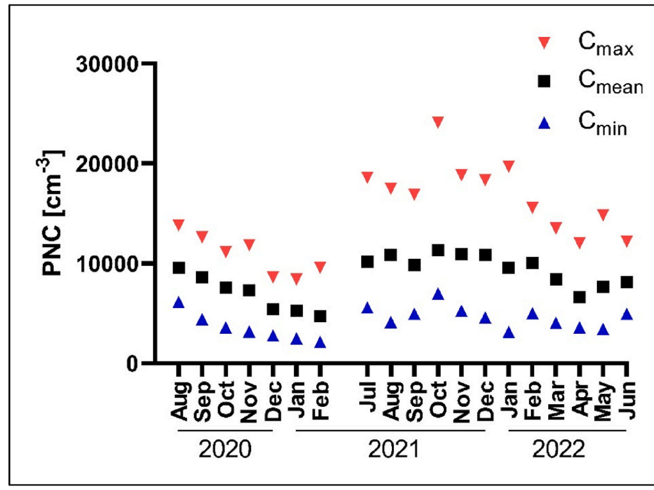

Fig. 3. Maximum, minimum, and mean 24-h particle number concentrations (PNCs) measured during different months from 2020 to 2022.

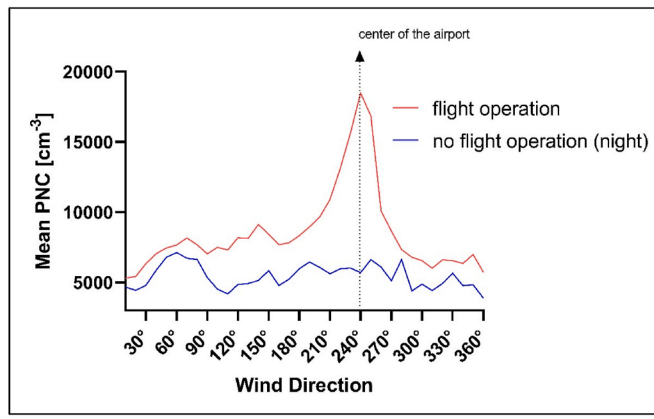

Fig. 4. Wind direction-dependent mean particle number concentrations (PNCs).

Fig. 5 shows the diurnal variations of the PNCs exemplarily for two different days.

With a stable wind situation from the airport sector, typical concentration profiles could be observed. On 11-18-2021 (Fig. 5a), at the beginning of flight operations in the early morning, a clear increase in PNC was evident with a short latency period. High PNCs persisted until the end of flight operation. In addition to this typical concentration profile, isolated high concentration peaks were observed during the course of the day. A maximum PNC of 59,940 cm^{-3} was reached. Also on 12-07-2021 (Fig. 5b), a clear concentration profile could be observed. There was an abrupt increase of the PNC at the beginning of flight operation around 5:00. The wind came from the direction of the airport with high intensity. A maximum PNC of 60,761 cm^{-3} was reached. At about 13:00, the wind direction changed to south and southeast. The wind speed also decreased significantly. The concentration profile shows an abrupt decrease at this time. The operation direction also changed on this day. However, the change in operation direction from west to east did not occur until 20:00, when the measured PNCs were already at a low level.

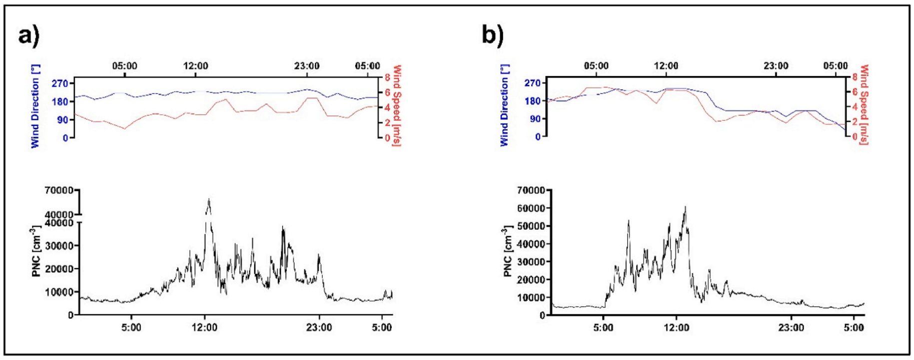

Fig. 5. Variations of the particle number concentrations (PNCs) on a) 11-18-2021 and b) 12-07-2021.

3.2. Influence of the air traffic volume on the particle number concentration

Fig. 6 shows the mean PNCs measured during wind from the individual sectors. There is a differentiated characterization between the periods with and without flight operation (data in Supplementary Table T3).

In the first period and during the operation time of the airport (Fig. 6a), the mean PNC (averaging period Aug 2020–Feb 2021) measured while the wind came from sector II was comparable to those measured while the wind came from the sectors III and VI. For wind from sector I, the measured mean PNC was significantly lower. The highest mean PNC was measured while the wind came from sector V (airport sector). In period 2 and during the operation time of the airport, the mean PNC (averaging period Aug 2021–Feb 2022) measured with wind from sector VI corresponded approximately to the mean PNC with wind from sector VI measured in period 1.

With wind from the other sectors, the measured mean PNCs during period 2 exceeded the previous year's level. For wind from sectors IV and V, the measured mean PNCs deviated most strongly in between both periods. As in period 1, the highest mean PNC in period 2 was measured during wind from sector V. Potential particle sources, located in both sectors are, for example, the airport, freeways, and aircrafts flying in the approach paths to the Runways Center/South.

Outside the operating time of the airport (Fig. 6b), the measured PNCs were smaller than during the time of flight operation. However, especially during east and south wind conditions, the measured mean PNCs in period 2 were higher than in period 1.

Supplementary Figure F2 shows in additional the monthly wind direction-independent mean PNCs for the entire measurement period as well as the air traffic volume (data in Supplementary Table T4).

3.3. Influence of the aircrafts approaching on Runway Center and Runway South on the particle number concentration

A total of 14 measurement days complied with the criteria for the potential detection of particulate emissions from aircrafts passing to the south. The $PNC_{4\text{-}5}$ and $PNC_{5\text{-}6}$ measured on each day are listed in Supplementary Table T5.

Fig. 7 shows an example of two different PNC profiles on which 13 (12-31-2020) and 14 (01-08-2021) aircrafts passed the station between 05:00 and 06:00.

Despite similar wind direction, wind speed, and number of passing aircrafts, the PNC profiles do not show a similar pattern. On 01-08-2021, there was a clear increase in PNC from 05:10 onwards. In addition to an increase in the base concentration, numerous individual concentration peaks could be observed. On 12-31-2020 on the other hand, no trend in background concentration could be observed. Numerous moderate concentration peaks occurred throughout the entire period.

The Wilcoxon-signed-rank test shows no significant difference ($p = 0.2676$) between $PNC_{4\text{-}5}$ and $PNC_{5\text{-}6}$ of all included measurement days.

3.4. Analysis of the particle number size distribution

Fig. 8 shows the normalized PNCs and PNSDs with different temporal resolutions at the study site, measured with the FMPS on 09-06-2022.

Over the entire measurement period, particles with a size below 30 nm dominated the total PNC (Fig. 8 a). In particular, the concentration

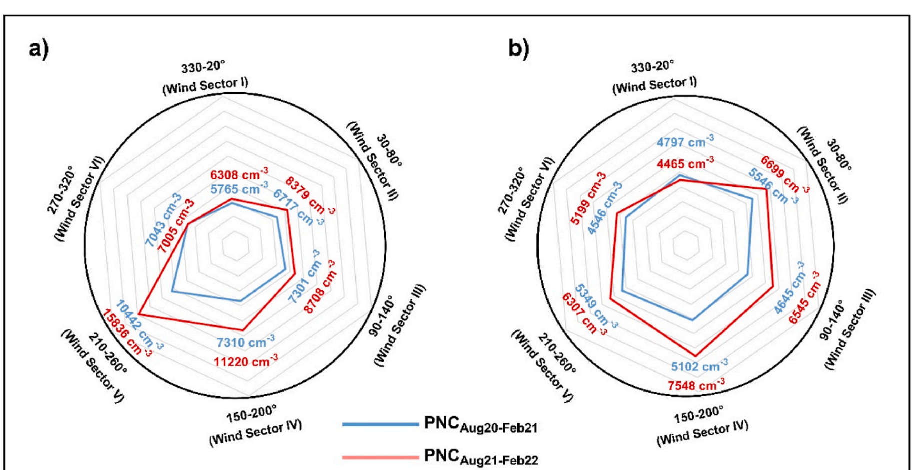

Fig. 6. Mean particle number concentrations (PNCs) for the different wind sectors and time intervals measured a) during operation time and b) during flight restriction (night).

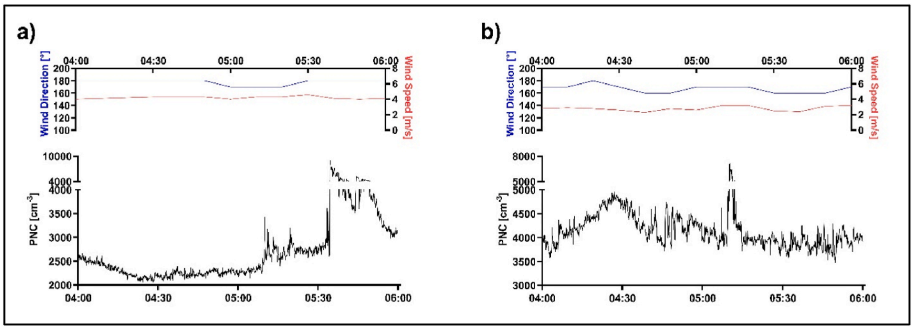

Fig. 7. Variations of the particle number concentrations (PNCs) measured between 04:00 and 06:00 on a) 01-08-2021 and b) 12-31-2020.

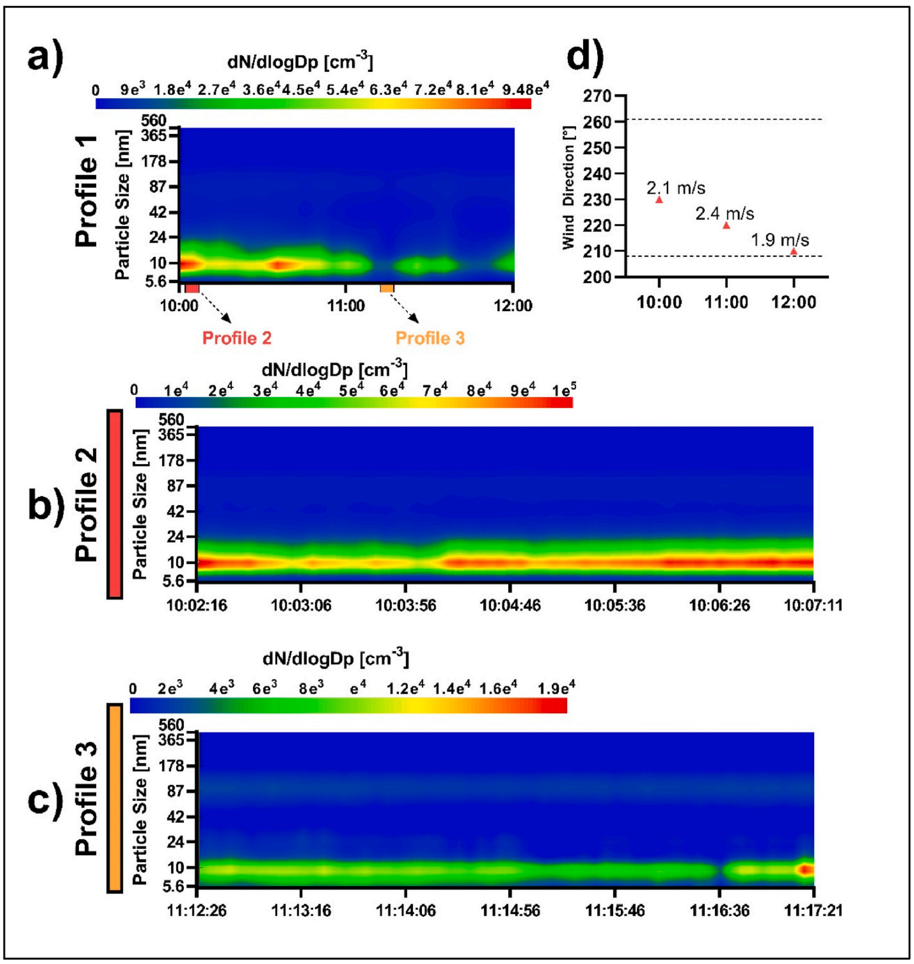

Fig. 8. Course of normalized (to the bin width) particle number concentrations (PNCs) and particle number size distributions (PNSDs) for a) the entire morning (10:00–12:00, 5-min resolution), b) a subsection of a) with high PNC (5-s resolution), c) a subsection of a) with low PNC (5-s resolution), and d) the variations within wind direction and wind speed during the measurement period.

of particles in the size range around 10 nm showed high variations over the course of the measuring period. The total PNC was high at the beginning of the measurement with some variation and decreased around 11:00. The wind direction showed only slight variations within the measurement period and shifted from the center to the edge of the airport wind sector. The wind speed showed only little variation.

Looking at profile 2 (high PNC), it could be observed that particles with a size between 8 and 20 nm were dominating the total PNC (Fig. 8 b). At particle size 14 nm, a maximum could be observed. Differences in the total PNC were mainly due to concentration changes of particles with a size between 12 and 16 nm. In this size range, significant concentration variations could be observed frequently. Isolated concentration peaks with wide particle spectra, did not occur in this period. A mean total PNC of 26,126 cm^{-3} was measured.

Looking at profile 3 (low PNC), particles <14 nm were dominating the total PNC (Fig. 8c). Individual concentration peaks showing wide particle spectra also did not appear in this period. A mean total PNC of 2899 cm^{-3} was measured.

4. Discussion

4.1. Variations of the particle number concentration and particle number size distribution

This study demonstrates that even low-traffic residential areas can be exposed to a high load of UFPs under certain circumstances. The PNCs were subject to strong variations throughout the year and even during a single day. There was a strong dependence on the wind direction. The highest PNCs during daytime appeared when the wind came from the direction of the airport, especially from its center. However, relatively high PNCs were also measured when the wind direction was east or south. Considering wind direction-dependent mean PNCs at night, lower values were measured than those measured during flight operation. Significant concentration differences (day vs. night) particularly appeared when the study site was downwind from the airport. A clear concentration peak could not be observed during nighttime. The air masses reaching the study site can also contain particles from other sources. However, the fact that by far the most distinctive day-night differences appeared when the study site was downwind from the airport is a strong indication that the airport is the determining particle source during daytime.

A further indication of the influence of the airport on the PNC at the study site is provided by characteristic curves of the PNC over the day, taking into account the wind direction and wind speed. If the study site was constantly downwind from the airport, a clear increase in PNC could be observed as soon as the airport started operations. From the beginning of the night flight restrictions, there was finally a clear drop. On days with these wind conditions, particularly high 24-h-mean PNCs were measured. The isolated concentration peaks during the course of the day are very likely due to extremely short-lasting gusts of wind, which are not reflected even in short averaging values of wind direction and wind speed. Other measurement campaigns in the vicinity of this and other airports could also link high PNCs with wind from the direction of the airport and demonstrated high temporal variations (Hudda et al., 2018; Fritz et al., 2022; Rose and Jacobi, 2019; Westerdahl et al., 2008). With the help of the FMPS, distinct variations in the PNC and PNSD could be observed with a high temporal resolution within a comparatively short measurement period. During this time, the wind came exclusively from the airport sector. The dominant particle size ranged from 8 to 20 nm, with a maximum at 14 nm. Particles in this size range can be produced by combustion in jet engines (Jasinski and Przylebska, 2018; Keuken et al., 2015; Ungeheuer et al., 2022). This is another indication that the airport represents the dominant particle source at the study site. Due to the lack of a broader particle spectrum and especially the very small share of particles with diameters between 30 and 100 nm, there are significant differences from a common urban particle spectrum with road traffic-related emissions (Costabile et al., 2009; Riley et al., 2016; Vu et al., 2015). The influence of single local point sources seems to have a minor impact at the study site. At high resolution, it became apparent that short-term concentration differences are mainly due to changes in the concentration of the very limited particle size range between 8 and 20 nm. It is likely that the vast majority of these concentration peaks lasting only seconds are related to short-term variations in the local wind direction and speed. It cannot be ruled out that isolated concentration peaks in this particle spectrum are related to landing aircrafts overflying the station. A final source attribution is generally difficult to realize due to the signal overlap of the particle sources (airport vs. overflying aircrafts) in the case of wind from the airport sector.

4.2. Influence of the air traffic volume on the particle number concentration

Significant differences between the period with a high air traffic volume and the period with a low air traffic volume were observed in the wind direction-dependent and time-of-day-dependent analysis of the PNCs. During the operation time of the airport, a clear concentration peak was evident within both periods when the wind was coming from the direction of the airport (sector V). However, the concentration was much lower in the first period. Outside the operating time of the airport, such differences in PNC could not be observed. This suggests that differences in the number of aircrafts taking off and landing, and general ground operations have a significant influence on the PNC. With prevailing wind directions east and especially south (sector III, IV), the PNCs differed clearly between the two periods during daytime. With winds from these directions, nearby freeways may be a source of particles. There were also differences in freeway traffic between the two periods (BAST, 2023). In addition to the freeways, aircrafts approaching on the runways Center and South can also be a potential source since they pass the study site at a comparatively short distance with a high frequency. The fact that there was also a PNC difference between both periods during nighttime (no flight operation) indicates that the freeways are significant sources of particles. At night, aircrafts do not pass the study site either in the first or the second period. Thus, PNC differences in this case cannot be linked to changes in air traffic volume. Traffic density on the highways at night, on the other hand, showed significant differences between the two periods. The traffic volume in the second period was higher (BAST, 2023) and thus the potential particle emissions.

4.3. Influence of landing aircrafts on the particle number concentration

The evaluation of the concentration profiles in the early morning hours showed in some cases an abrupt increase in PNC parallel to the first aircrafts flying over the area. Since the influence of the airport as a particle source could be largely excluded, these PNC increases could potentially be linked to emissions of the aircrafts. On the other hand, no characteristic profiles could be observed on many other days. In the statistical evaluation of all analysis days, no significant difference between the PNCs measured in the period 04:00–05:00 and 05:00–06:00 was found. Even though the aircrafts are much closer to the study site than the airport, their particle emissions are comparatively low. Aircraft turbines often run at only 20–30% of maximum power during landing, which limits particulate emissions. At the airport itself, emissions are significantly higher due to the totality of aircrafts taking off and landing as well as ground operations (Mazaheri et al., 2009; ICAO, 2021; Mazaheri et al., 2011; Petzold and Schröder, 1998; Freund, 2019). Aircrafts taking off have the highest emissions here. In addition, the dispersion of particles and thus the dilution process takes twice as long for aircrafts taking off as for aircrafts landing (Stafoggia et al., 2016; Jasinski and Przylebska, 2018). The fact that approaching aircrafts can potentially make a certain contribution to the PNC in neighborhoods beneath the approaching paths has already been proven in isolated studies and measurement campaigns. However, this was mostly limited to the immediate vicinity of the landing point (Riley et al., 2016; Westerdahl et al., 2008; Stacey, 2019; Freund, 2019; Maron and Schönfeld, 2020). It can be assumed that the particles emitted by the aircrafts only lead to increasing PNCs at the study site under certain circumstances. Here, the condition of the atmospheric boundary layer is the determining factor. Variable vertical gradients in wind, temperature, and humidity profiles occur in this layer. The strength of turbulent mixing subjects to strong fluctuations. This has a direct influence on the transport of the individual exhaust plumes (Nieuwstadt and Duynkerke, 1996; Salmond et al., 2010; Tait et al., 2022). Unfortunately, the determination of condition parameters is only possible to a limited extent and at great expense within individual research programs.

In addition to landing aircrafts, the freeways also represent potential sources. A final separation of these signals is not possible conclusively. To further characterize the particle sources, an extension of temporally high-resolution measurements of the PNSD in the early morning hours at different wind directions is necessary.

4.4. Results of medical studies and particle uptake

Whereas there is a limited amount of data on short-term effects, the assessment of health risks from long-term UFP exposure is very limited. There are also differences in the results of the available studies, and the effects often relate to road transport or mixtures of pollutants, which complicates the individual contribution of UFPs to health effects (Ohlwein et al., 2018; Lanzinger et al., 2016; Evans et al., 2014; Samoli et al., 2016; Ostro et al., 2015; Laurent et al., 2016; Downward et al., 2018; Corlin et al., 2018; Li et al., 2016; Chung et al., 2015). The different chemical and physical properties limit direct transferability to our study. In the case of particle exposures in the immediate vicinity of the airport, short-term negative effects on human health have already been demonstrated (Lammers et al., 2020; Habre et al., 2018). The exposure concentrations in these cases were mostly above the concentrations measured at our study site. However, several studies in urban environments suggest that a higher 24 h-mean PNC of 10,000 cm^{-3} could have negative effects on the cardiovascular and respiratory system under certain conditions (Samoli et al., 2016; Chung et al., 2015). Variations in this magnitude occurred during our study both for short periods and for longer periods. A study by Bos et al. found evidence that the positive effects of exercise on cognitive performance are already significantly reduced at short-term PNCs of 28,120 cm^{-3} in ambient air in comparison to a low-particle environment (Bos et al., 2011).

With the help of inhalation dosimetry, it is possible to estimate what proportion of the inhaled particles is ultimately deposited in the alveoli or passes into the pulmonary vessels and thus has a relevant impact on human health. The extent of deposition depends directly on the particle size and also differs significantly in the size range of UFPs. Where particles with a diameter of 5 nm are 91% deposited, the proportion decreases to 63% for particles sized 30 nm. Particles with a size of 100 nm are only deposited to a share of 13%. (International Commission on Radiological Protection, 1994; Kumar et al., 2014). Besides the PNC, the knowledge about the PNSD is therefore of high relevance to assess the medical relevance. The FMPS measurement could show that at very high PNCs, which are quantified at the wind direction of the airport, the particles with a small diameter below 30 nm dominated. Especially these particles are deposited to a large extent.

In comparison to the majority of previous studies that have investigated the PNSD in the vicinity of airports, the measurement in this study was carried out with a very high temporal resolution (FMPS measurement). Only with such a high resolution, the number and the particle spectrum of the very short-lasting and extremely high concentration peaks with potential medical relevance can be analyzed. These concentration peaks showed the PNSD profile of typical airport emissions.

5. Conclusion

In this study, the importance of continuous long-term measurements of the PNC was demonstrated. The concentration of UFPs at the study site was subject to high variations. Differences between the individual months and days, as well as within a single day, were shown. Wind direction dependent-concentration patterns could be detected. A clear dependence of the PNC on the air traffic volume could also be demonstrated. Considering these results and the results from the analysis of the PNSD, the airport could be identified as the main particle source at the study site and thus in a distant residential area. It is possible that passing aircrafts also contribute to the total PNC at the study site. However, their influence is lower than the influence of the airport and can only be detected irregularly. Further size-resolved measurements are needed to characterize this relationship more precisely. The current data availability of effects of UFP on human health is limited.

However, isolated studies in urban environments have found evidence that negative effects on human health may be observed at similar concentration levels under certain conditions.

Since the PNC at the study site only increases strongly under certain wind conditions, strategies can be developed to reduce the particle exposure of the local population. This requires further knowledge about individual exposure profiles.

CRediT authorship contribution statement

Janis Dröge: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Doris Klingelhöfer:** Writing – review & editing, Visualization, Validation, Formal analysis. **Markus Braun:** Writing – review & editing, Visualization, Validation, Formal analysis. **David A. Groneberg:** Writing – review & editing, Validation, Resources, Project administration, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Janis Dröge reports financial support was provided by Dr. Senckenbergische Stiftung. Janis Dröge reports financial support was provided by Alfons und Gertrund Kassel-Stiftung.

Data availability

All data generated or analyzed during this study are included in the supplementary material of this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2024.123390.

References

Aalto, Pasi, Hämeri, Kaarle, Paatero, Pentti, Kulmala, Markku, Bellander, Tom, Berglind, Niklas, et al., 2005. Aerosol particle number concentration measurements in five European cities using TSI-3022 condensation particle counter over a three-year period during health effects of air pollution on susceptible subpopulations. J. Air Waste Manag. Assoc. 55 (8), 1064–1076. https://doi.org/10.1080/10473289.2005.10464702, 1995.

Amin, Ratna, 2001. Airports and the general Conformity process. In: Institute of Transportation Studies, UC Berkeley, Institute of Transportation Studies, Research Reports, Working Papers, Proceedings.

Araujo, Jesus A., Barajas, Berenice, Kleinman, Michael, Wang, Xuping, Bennett, Brian J., Gong, Ke Wei, et al., 2008. Ambient particulate pollutants in the ultrafine range promote early atherosclerosis and systemic oxidative stress. Circ. Res. 102 (5), 589–596. https://doi.org/10.1161/CIRCRESAHA.107.164970.

BAST, 2023. Infrastruktur-, Verkehrs- und Unfalldaten (Infrastructure, traffic and accident data). Straßenverkehrszählungen (Traffic Census). Bundesanstalt für Straßenwesen Federal Highway Research Institute checked on 5/19/2023.

Belleudi, Valeria, Faustini, Annunziata, Stafoggia, Massimo, Cattani, Giorgio, Marconi, Achille, Perucci, Carlo A., Forastiere, Francesco, 2010. Impact of fine and ultrafine particles on emergency hospital admissions for cardiac and respiratory diseases. Epidemiology (Cambridge, Mass 21 (3), 414–423. https://doi.org/10.1097/EDE.0b013e3181d5c021.

Bos, I., Jacobs, L., Nawrot, T.S., Geus, B. de, Torfs, R., Int Panis, L., et al., 2011. No exercise-induced increase in serum BDNF after cycling near a major traffic road. Neurosci. Lett. 500 (2), 129–132. https://doi.org/10.1016/j.neulet.2011.06.019.

Chung, Mei, Wang, Ding Ding, Rizzo, Amanda M., Gachette, Darrel, Delnord, Marie, Parambi, Ron, et al., 2015. Association of PNC, BC, and PM2.5 measured at a central monitoring site with blood pressure in a predominantly near highway population. Int. J. Environ. Res. Publ. Health 12 (3), 2765–2780. https://doi.org/10.3390/ijerph120302765.

Corlin, Laura, Woodin, Mark, Hart, Jaime E., Simon, Matthew C., Gute, David M., Stowell, Joanna, et al., 2018. Longitudinal associations of long-term exposure to ultrafine particles with blood pressure and systemic inflammation in Puerto Rican adults. Environ. Health Global Access Sci. Source 17 (1), 33. https://doi.org/10.1186/s12940-018-0379-9.

Costabile, F., Birmili, W., Klose, S., Tuch, T., Wehner, B., Wiedensohler, A., et al., 2009. Spatio-temporal variability and principal components of the particle number size distribution in an urban atmosphere. Atmos. Chem. Phys. 9 (9), 3163–3195. https://doi.org/10.5194/acp-9-3163-2009.

Creason, J., Neas, L., Walsh, D., Williams, R., Sheldon, L., Liao, D., Shy, C., 2001. Particulate matter and heart rate variability among elderly retirees: the Baltimore 1998 PM study. J. Expo. Sci. Environ. Epidemiol. 11 (2), 116–122. https://doi.org/10.1038/sj.jea.7500154.

Ditas, F., Rose, D., Jacobi, S., 2022. Bericht zur Untersuchung der regionalen Luftqualität auf ultrafeine Partikel im Bereich des Flughafens Frankfurt. In: Hessian Agency for Nature Conservation, Environment and Geology (Hessisches Landesamt für Naturschutz, Umwelt und Geologie), p. 4.

Downward, George S., van Nunen, Erik, J.H.M., Kerckhoffs, Jules, Vineis, Paolo, Brunekreef, Bert, Boer, Jolanda, M.A., et al., 2018. Long-term exposure to ultrafine particles and Incidence of cardiovascular and Cerebrovascular disease in a prospective study of a Dutch cohort. Environ. Health Perspect. 126 (12), 127007 https://doi.org/10.1289/EHP3047.

DWD, 2023. Climate data center. Edited by deutscher Wetterdienst (German weather Service). https://www.dwd.de/DE/klimaumwelt/cdc/cdc_node.html checked on 6/27/2023.

Evans, Kristin A., Halterman, Jill S., Hopke, Philip K., Fagnano, Maria, Rich, David Q., 2014. Increased ultrafine particles and carbon monoxide concentrations are associated with asthma exacerbation among urban children. Environ. Res. 129, 11–19. https://doi.org/10.1016/j.envres.2013.12.001.

Fraport, A.G., 2020. Fraport-Verkehrszahlen 2019: Über 70,5 Millionen Passagiere Am Flughafen Frankfurt. Fraport AG.

Fraport, A.G., 2022. Infoservice Fluglärm V 2.0. Edited by Fraport AG. Available online at: https://framap.fraport.de/framap/main/r/isfl/go. (Accessed 31 March 2023). checked on.

Fraport AG, 2023a. Easterly and westerly operations. https://www.fraport.com/en/business-areas/operations/airside-and-terminal-operations/easterly-and-westerly-operations.html checked on 2/22/2023.

Fraport AG, 2023b. Verkehrszahlen. 2020-2022. With assistance of Fraport AG. https://www.fraport.com/de/investoren/verkehrszahlen.html. checked on 6/27/2023.

Freund, J., 2019. Einfluss von Flugzeugemissionen auf die bodennahe Konzentration von Ultrafeinstaubpartikeln. Master's thesis. Institut für Atmosphäre und Umwelt - Goethe Universität Frankfurt am Main.

Fritz, Sabine; Grusdat, Felix; Sharkey, Rowan; Schneider, Christoph (2022): impact of airport operations and road traffic on the particle number concentration in the vicinity of a suburban airport. In Front. Environ. Sci. 10, Article 887493. DOI: 10.3389/fenvs.2022.887493..

Guo, Song, Hu, Min, Peng, Jianfei, Wu, Zhijun, Zamora, Misti L., Shang, Dongjie, et al., 2020. Remarkable nucleation and growth of ultrafine particles from vehicular exhaust. Proc. Natl. Acad. Sci. U. S. A. 117 (7), 3427–3432. https://doi.org/10.1073/pnas.1916366117.

Habre, Rima, Zhou, Hui, Eckel, Sandrah P., Enebish, Temuulen, Fruin, Scott, Bastain, Theresa, et al., 2018. Short-term effects of airport-associated ultrafine particle exposure on lung function and inflammation in adults with asthma. Environ. Int. 118, 48–59. https://doi.org/10.1016/j.envint.2018.05.031.

Hasegawa, Shuichi, Hirabayashi, Motohiro, Kobayashi, Shinji, Moriguchi, Yuichi, Kondo, Yoshinori, Tanabe, Kiyoshi, Wakamatsu, Shinji, 2004. Size distribution and characterization of ultrafine particles in roadside atmosphere. J Environ Sci Health A Tox Hazard Subst Environ Eng 39 (10), 2671–2690. https://doi.org/10.1081/LESA-200027025.

He, Rui-Wen, Gerlofs-Nijland, Miriam, E., Boere, John, Fokkens, Paul, Leseman, Daan, Janssen, Nicole A.H., Cassee, Flemming R., 2020. Comparative toxicity of ultrafine particles around a major airport in human bronchial epithelial (Calu-3) cell model at the air-liquid interface. Toxicol. Vitro : an international journal published in association with BIBRA 68, 104950. https://doi.org/10.1016/j.tiv.2020.104950.

Heusinkveld, Harm J., Wahle, Tina, Campbell, Arezoo, Westerink, Remco H.S., Tran, Lang, Johnston, Helinor, et al., 2016. Neurodegenerative and neurological disorders by small inhaled particles. Neurotoxicology 56, 94–106. https://doi.org/10.1016/j.neuro.2016.07.007.

HLNUG, 2023. Messdatenportal. Edited by Hessisches Landesamt für Naturschutz, Umwelt. Available online at: https://www.hlnug.de/messwerte/datenportal. (Accessed 21 January 2023).

Hudda, N., Simon, M.C., Zamore, W., Durant, J.L., 2018. Aviation-related impacts on ultrafine particle number concentrations outside and inside residences near an airport. Environ. Sci. Technol. 52 (4), 1765–1772. https://doi.org/10.1021/acs.est.7b05593.

ICAO, 2021. Aircraft engine emissions databank. Available online at: https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank, 7/4/2022.

International Commission on Radiological Protection, 1994. Human respiratory tract model for radiology protection. In: A Report of a Task Group of the International Commission on Radiological Protection. 1, vol. 24. Pergamon (Radiation protection, Oxford, pp. 1–3.

Jasinski, R., Przylebska, K., 2018. Analysis of the particle size distribution near the civil airport runway. IOP Conf. Ser. Mater. Sci. Eng. 421, 42030 https://doi.org/10.1088/1757-899X/421/4/042030.

Keuken, M.P., Moerman, M., Zandveld, P., Henzing, J.S., Hoek, G., 2015. Total and size-resolved particle number and black carbon concentrations in urban areas near Schiphol airport (The Netherlands). Atmos. Environ. 104, 132–142. https://doi.org/10.1016/j.atmosenv.2015.01.015.

Kreyling, Wolfgang G., Semmler-Behnke, Manuela, Möller, Winfried, 2006. Ultrafine particle-lung interactions: does size matter? J. Aerosol Med. : the official journal of the International Society for Aerosols in Medicine 19 (1), 74–83. https://doi.org/10.1089/jam.2006.19.74.

Kumar, Prashant, Morawska, Lidia, Birmili, Wolfram, Paasonen, Pauli, Hu, Min, Kulmala, Markku, et al., 2014. Ultrafine particles in cities. Environ. Int. 66, 1–10. https://doi.org/10.1016/j.envint.2014.01.013.

Kwon, Hyouk-Soo, Ryu, Min Hyung, Carlsten, Christopher, 2020. Ultrafine particles: unique physicochemical properties relevant to health and disease. Exp. Mol. Med. 52 (3), 318–328. https://doi.org/10.1038/s12276-020-0405-1.

Lammers, A., Janssen, N.A.H., Boere, A.J.F., Berger, M., Longo, C., Vijverberg, S.J.H., et al., 2020. Effects of short-term exposures to ultrafine particles near an airport in healthy subjects. Environ. Int. 141, 105779 https://doi.org/10.1016/j.envint.2020.105779.

Lanzinger, Stefanie, Schneider, Alexandra, Breitner, Susanne, Stafoggia, Massimo, Erzen, Ivan, Dostal, Miroslav, et al., 2016. Associations between ultrafine and fine particles and mortality in five central European cities - results from the UFIREG study. Environ. Int. 88, 44–52. https://doi.org/10.1016/j.envint.2015.12.006.

Laurent, Olivier, Hu, Jianlin, Li, Lianfa, Kleeman, Michael J., Bartell, Scott M., Cockburn, Myles, et al., 2016. Low birth weight and air pollution in California: which sources and components drive the risk? Environ. Int. 92–93, 471–477. https://doi.org/10.1016/j.envint.2016.04.034.

Li, Ya-Ru, Feng, Li-Ting, Chen, Bing-Yu, Kim, Ho, Yi, Seung-Muk, Guo, Yue Leon, Wu, Chang-Fu, 2016. Association of urban particle numbers and sources with lung function among children with asthma or allergies. Sci. Total Environ. 542 (Pt A), 841–844. https://doi.org/10.1016/j.scitotenv.2015.10.098.

Liao, D., Creason, J., Shy, C., Williams, R., Watts, R., Zweidinger, R., 1999. Daily variation of particulate air pollution and poor cardiac autonomic control in the elderly. Environ. Health Perspect. 107 (7), 521–525. https://doi.org/10.1289/ehp.99107521.

Maron, C., Schönfeld, F., 2020. Zusammenhang von Ultrafeinstaub- konzentration und Flugverkehr. Auswertung von Langzeitmessungen in Raunheim, nahe des Flughafens Frankfurt am Main. Gefahrstoffe 80 (10), 405–414.

Marval, Jesus, Tronville, Paolo, 2022. Ultrafine particles: a review about their health effects, presence, generation, and measurement in indoor environments. Build. Environ. 216, 108992 https://doi.org/10.1016/j.buildenv.2022.108992.

Masiol, Mauro, Harrison, Roy M., 2014. Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution: a review. Atmos. Environ. 95, 409–455. https://doi.org/10.1016/j.atmosenv.2014.05.070.

Mazaheri, M., Johnson, G.R., Morawska, L., 2009. Particle and gaseous emissions from commercial aircraft at each stage of the landing and takeoff cycle. Environ. Sci. Technol. 43 (2), 441–446. https://doi.org/10.1021/es8013985.

Mazaheri, M., Johnson, G.R., Morawska, L., 2011. An inventory of particle and gaseous emissions from large aircraft thrust engine operations at an airport. Atmos. Environ. 45 (20), 3500–3507. https://doi.org/10.1016/j.atmosenv.2010.12.012.

Morawska, L., Ristovski, Z., Jayaratne, E.R., Keogh, D.U., Ling, X., 2008. Ambient nano and ultrafine particles from motor vehicle emissions: characteristics, ambient processing and implications on human exposure. Atmos. Environ. 42 (35), 8113–8138. https://doi.org/10.1016/j.atmosenv.2008.07.050.

Nemmar, A., Hoet, P.H.M., Vanquickenborne, B., Dinsdale, D., Thomeer, M., Hoylaerts, M.F., et al., 2002. Passage of inhaled particles into the blood circulation in humans. Circulation 105 (4), 411–414. https://doi.org/10.1161/hc0402.104118.

Nieuwstadt, F.T.M., Duynkerke, P.G., 1996. Turbulence in the atmospheric boundary layer. Atmos. Res. 40 (2–4), 111–142. https://doi.org/10.1016/0169-8095(95)00034-8.

Ohlwein, S., Hoffmann, B., Kappeler, R., Joss, M.K., Künzli, N., 2018. Health Effects of Ultrafine Particles. Systematic literature search and the potential transferability of the results to the German setting. In: Umwelt & Gesundheit.

Ostro, Bart, Hu, Jianlin, Goldberg, Debbie, Reynolds, Peggy, Hertz, Andrew, Bernstein, Leslie, Kleeman, Michael J., 2015. Associations of mortality with long-term exposures to fine and ultrafine particles, species and sources: results from the California teachers study cohort. Environ. Health Perspect. 123 (6), 549–556. https://doi.org/10.1289/ehp.1408565.

Petzold, A., Schröder, F.P., 1998. Jet engine exhaust aerosol characterization. Aerosol. Sci. Technol. 28 (1), 62–76. https://doi.org/10.1080/02786829808965512.

Pope, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. JAMA 287 (9), 1132. https://doi.org/10.1001/jama.287.9.1132.

Riley, Erin A., Gould, Timothy, Hartin, Kris, Fruin, Scott A., Simpson, Christopher D., Yost, Michael G., Larson, Timothy, 2016. Ultrafine particle size as a tracer for aircraft turbine emissions. Atmos. Environ. 139, 20–29. https://doi.org/10.1016/j.atmosenv.2016.05.016.

Rose, D., Jacobi, S., 2019. Zwischenbericht zur Untersuchung der regionalen Luftqualität auf ultrafeine Partikel im Bereich des Flughafens Frankfurt. Hessisches Landesamt für Naturschutz, Umwelt, p. 2.

Sabaliauskas, K., Jeong, C., Yao, X., Jun, Y., Jadidian, P., Evans, G.J., 2012. Five-year roadside measurements of ultrafine particles in a major Canadian city. In *Atmospheric*. Environment 49, 245–256. https://doi.org/10.1016/j.atmosenv.2011.11.052.

Salmond, J.A., Pauscher, L., Pigeon, G., Masson, V., Legain, D., 2010. Vertical transport of accumulation mode particles between two street canyons and the urban boundary layer. Atmos. Environ. 44 (39), 5139–5147. https://doi.org/10.1016/j.atmosenv.2010.09.002.

Samoli, Evangelia, Andersen, Zorana Jovanovic, Katsouyanni, Klea, Hennig, Frauke, Kuhlbusch, Thomas A.J., Bellander, Tom, et al., 2016. Exposure to ultrafine particles and respiratory hospitalisations in five European cities. Eur. Respir. J. 48 (3), 674–682. https://doi.org/10.1183/13993003.02108-2015.

Schraufnagel, Dean E., 2020. The health effects of ultrafine particles. Exp. Mol. Med. 52 (3), 311–317. https://doi.org/10.1038/s12276-020-0403-3.

Stacey, Brian, 2019. Measurement of ultrafine particles at airports: a review. Atmos. Environ. 198, 463–477. https://doi.org/10.1016/j.atmosenv.2018.10.041.

Stafoggia, M., Cattani, G., Forastiere, F., Di Menno Bucchianico, A., Gaeta, A., Ancona, C., 2016. Particle number concentrations near the Rome-Ciampino city airport. Atmos. Environ. 147, 264–273. https://doi.org/10.1016/j.atmosenv.2016.09.062.

Tait, Kieran N., Khan, Mohammad Anwar H., Bullock, Steve, Lowenberg, Mark H., Shallcross, Dudley E., 2022. Aircraft emissions, their plume-scale effects, and the spatio-temporal sensitivity of the atmospheric response: a review. Aerospace 9 (7), 355. https://doi.org/10.3390/aerospace9070355.

TROPOS, 2023. German Ultrafine Aerosol Network (GUAN). Edited by Leibniz-Institut für Troposphärenforschung. Available online at: https://www.tropos.de/forschung/atmosphaerische-aerosole/langzeit-prozess-und-trendanalysen/langzeitstudien-regionaler-bedeutung-und-luftqualitaet/guan, 1/21/2023.

Umweltbundesamt, 2018. Fragen und Antworten: Ultrafeine Partikel. Edited by Internetpräsenz Umweltbundesamt (German Environment Agency). Available online at: https://www.umweltbundesamt.de/themen/luft/luftschadstoffe-im-ueberblick/feinstaub/fragen-antworten-ultrafeine-partikel, 1/21/2023.

Ungeheuer, F., Caudillo, L., Ditas, F., Simon, M., van Pinxteren, D., Kılıç, D., et al., 2022. Nucleation of jet engine oil vapours is a large source of aviation-related ultrafine particles. Commun Earth Environ 3 (1). https://doi.org/10.1038/s43247-022-00653-w.

Unterstrasser, S., Paoli, R., Sölch, I., Kühnlein, C., Gerz, T., 2014. Dimension of aircraft exhaust plumes at cruise conditions: effect of wake vortices. Atmos. Chem. Phys. 14 (5), 2713–2733. https://doi.org/10.5194/acp-14-2713-2014.

Vu, Tuan V., Delgado-Saborit, Juana Maria, Harrison, Roy M., 2015. Review: particle number size distributions from seven major sources and implications for source apportionment studies. Atmos. Environ. 122, 114–132. https://doi.org/10.1016/j.atmosenv.2015.09.027.

Westerdahl, D., Fruin, S., Fine, P., Sioutas, C., 2008. The Los Angeles International Airport as a source of ultrafine particles and other pollutants to nearby communities. Atmos. Environ. 42 (13), 3143–3155. https://doi.org/10.1016/j.atmosenv.2007.09.006.