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Significant reduction of ultrafine particle emission fluxes to the urban atmosphere during the COVID-19 lockdown

Agnes Straaten ⁎, Fred Meier, Dieter Scherer, Stephan Weber

Abstract

The worldwide restrictions of social contacts that were implemented in spring 2020 to slow down infection rates of the SARS-CoV-2 virus resulted in significant modifications in mobility behaviour of urban residents. We used three-year eddy covariance measurements of size-resolved particle number fluxes from an urban site in Berlin to estimate the effects of reduced traffic intensity on particle fluxes. Similar observations of urban surface-atmosphere exchange of size-resolved particles that focus on COVID-19 lockdown-related effects are not available, yet. Although the site remained a net emission source for ultrafine particles (UFP, Dp < 100 nm), the median upward flux of ultrafine particles (FUFP) decreased from 8.78 × 10⁷ m⁻² s⁻¹ in the reference period to 5.44 × 10⁷ m⁻² s⁻¹ during the lockdown. This was equivalent to a relative reduction of −38 % for median FUFP, which was similar to −35 % decrease of road traffic intensity in the flux source area during that period. The size-resolved analysis demonstrated that, on average, net deposition of UFP occurred only during night when particle emission source strength by traffic was at its minimum, whereas accumulation mode particles (100 nm < Dp < 200 nm) showed net deposition also during daytime. The results indicate the benefits of traffic reductions as a mitigation strategy to reduce UFP emissions to the urban atmosphere.

1. Introduction

The outbreak of the coronavirus disease (COVID-19) in early 2020 resulted in a large number of infections and increased mortality rates worldwide. To not overload intensive care units and save human lives, many countries introduced measures to slow down infection rates. The measures were generally associated with an economic and social lockdown, which included travel restrictions, home-office recommendations, closings of restaurants, and department stores. These restrictions led to a modification in the people’s mobility and a worldwide decrease of pollutant and carbon dioxide emissions due to reductions in road transport, aviation as well as manufacturing and energy industry (Le Quéré et al., 2020; Guevara et al., 2021; Reifenberg et al., 2021). Several recent studies report improvements in regional air quality by reduced pollutant concentrations, such as for NO₂.
Road traffic is one of the dominant sources of urban air pollution being responsible for high emissions of ultrafine particles (UFP, \( D_p < 100 \text{ nm} \)) (Dorsey et al., 2002; Weber et al., 2013; Birmili et al., 2015; Hudda et al., 2020)) that are associated to acute and chronic adverse health effects (Nemmar et al., 2002; HEI Review Panel on Ultrafine Particles, 2020). However, we additionally looked into the variation in weather or atmospheric conditions as would be the case for surface-atmosphere exchange and do not need compensation for footprint, and turbulent transport. Hence, EC particle losses within the sampling system (including the NaCl mast allowing to transport particles with a flow rate of 10 L min \(^{-1} \)) downwards to the sonic anemometer. The sampling line was connected to a 10 m rooftop mast allowing to transport particles with a flow rate of 10 L min \(^{-1} \) downwards to the EEPS through a 0.01 m stainless steel tube. The sample air was dried using a Nafion dryer (MD-700, Perma Pure LLC, length 0.9 m).

Although the EEPS measured particles in the size range \( 5.6 \text{ nm} < D_p < 560 \text{ nm} \), the range for particle number flux calculation was limited to \( 10 \text{ nm} < D_p < 200 \text{ nm} \) due to increased uncertainties in the boundary regions of the particle number size distributions (PNSDs) caused by the necessity gap-filling procedure according to Meyer-Kornblum et al., (2019). Further details on the measurement setup and gap-filling procedure of PNSDs are reported in Straaten and Weber, (2021) and (Meyer-Kornblum et al., 2019).

2.2. Data handling for flux calculation

To calculate particle fluxes, the PNSDs were corrected to account for diffusional particle losses within the sampling system (including the Nafion dryer) according to Hinds, (1999). Subsequently, the gap-filling procedure according to (Meyer-Kornblum et al., 2019) was applied to the size range \( 10 \text{ nm} < D_p < 200 \text{ nm} \) (cf. Section 2.1). This gap-filling method uses a natural spline interpolation approach to fill the gaps within the PNSDs resulting from low concentrations in some size channels (Straaten and Weber, 2021; Meyer-Kornblum et al., 2019). From a total of \( 1.74 \times 10^5 \) measured PNSDs, 82.2 % were gap-filled, 16.7 % had to be rejected due to not fulfilling the gap-filling requirements as defined by Straaten and Weber, (2021), and 1.1 % of the PNSDs were without any gaps (Straaten and Weber, 2021). The gap-filled PNSDs were used for the analysis of particle number concentrations and to calculate number fluxes. The half-hourly averaged particle fluxes were calculated using the software EddyPro® v6.2.2. The missing samples allowance was set to 20 %, wind and particle data were checked for plausibility referring to a realistic range of values and spikes were eliminated following the procedure as proposed by Vickers and Mahr, (1997). In addition, spectral corrections (Moncrieff et al., 1997; Moncrieff et al., 2004) and double coordinate rotation for tilt correction were applied. The time lag between particle and sonic data was corrected by covariance maximisation within a specified time lag window of \( 9 \pm 4.5 \text{ s} \). In case no maximisation was found, a time lag of 9 s was used. Furthermore, linear detrending and a correction concerning the response time for fast changes of the EEPS following (Horst, 1997) were applied. Finally, according to Foken et al., (2004), particle number fluxes with quality flags \( >6 \) were rejected (refer to Straaten and Weber, (2021) for further details on flux processing procedures as well as quality control and data assurance procedures).

Half-hourly particle number fluxes showing net emission are, by definition, positive whereas net deposition fluxes are defined by a negative sign. Finally, turbulent fluxes for aggregated particle size ranges were calculated, i.e. the total particle number flux \( (F_\text{TOT}, 10 \text{ nm} < D_p < 200 \text{ nm}) \), ultrafine particle flux \( (F_\text{UFF}, 10 \text{ nm} < D_p < 100 \text{ nm}) \) and for the three modes, i.e.
nucleation mode ($F_{\text{NOC}}$, 10 nm $< D_p < 30$ nm), Aitken mode ($F_{\text{AT}}, 30$ nm $< D_p < 100$ nm), and accumulation mode ($F_{\text{ACC}}, 100$ nm $< D_p < 200$ nm). For that, the number concentrations of the specific size channels in the diameter ranges as given above were summed up from gap-filled PNSDs and used for flux calculation.

Flux footprints were estimated using the two-dimensional parameterization of Kljun et al., (2015). To analyse the spatially varying impact of traffic intensity on different roads within the flux footprint such as minor and major roads, we calculated a footprint-weighted ADT for both periods (lockdown and reference period; data source: (Geoportal Berlin, 2021a)). For this purpose, the ADT shapefile was converted into a raster (4 km $\times$ 4 km, 4 m spatial resolution, based on the footprint climatology raster) and weighted with the footprint climatology to calculate a mean ADT (Straaten and Weber, 2021). Hence, this quantity indicates the spatial variation of traffic intensity in the flux footprint on a theoretical basis as estimated from the static data of spatially varying ADT on different roads in the year 2019. It does not, however, account for temporally varying traffic intensity as measured at traffic counting sites.

2.3. Lockdown and reference period

The German lockdown was set to start on 16 March 2020 with the nationwide closure of schools, day-care centres and numerous stores. A week later, contact restrictions were introduced so that social contacts should be kept to a minimum. The lockdown period was further characterized by travel restrictions, home-office recommendations, closing of restaurants, department stores, and coiffures. First relaxations took effect on 20 April 2020 continuing at the beginning of May with the gradual opening of schools and stores as well as weaker social-distancing measures. Hence, the end of the lockdown period was set to 06 May 2020 defining the lockdown period in this study as from 16 March to 06 May 2020. This period coincides with a local maximum value of the ‘Oxford stringency index’ that is a composite measure of response indicators such as school closures, workplace closures, and travel bans to compare worldwide COVID-19 policies. The stringency index, which defines a value of 100 for the strictest response, estimates the German policy at a local maximum value of 77 between 22 March and 02 May 2020 (Hale et al., 2021). To compare the lockdown period with a reference value, the same periods from the three preceding years 2017, 2018, and 2019 were pooled and defined as the reference period. Particle number flux data availability for the different size ranges (cf. Section 2.2) was similar in both periods with 60–62 % for the reference and 57–60 % for the lockdown period, respectively. To check the statistical significance of the data in the two different periods (lockdown vs. reference), the Wilcoxon-Mann-Whitney rank sum test was applied. For further comparison, we defined a pre-lockdown period (i.e. 15 January to the end of February in 2020 vs. 2018/2019), which might offer the chance to somewhat ‘calibrate’ the applied method. However, since the pre-lockdown periods were associated with clearly different flux footprint climatologies and meteorological conditions (cf. Figs. S1, S2), the comparison was not suitable as a ‘calibration method’ for lockdown-related effects. Hence, the pre-lockdown analysis was not included in the present analysis but is documented in the supplementary materials.

Fig. 1. Measurement site in Berlin at the rooftop of the main building of Technische Universität Berlin (data sources: (Geoportal Berlin, 2021a; Geoportal Berlin, 2014) (modified), and (Geoportal Berlin, 2021b)). The average daily traffic (Mon-Thu) is only shown for the major road network.
3. Results

3.1. Meteorological conditions

To compare particle number fluxes between the reference and the lockdown period, we analysed differences in meteorological quantities relevant for turbulent mixing and vertical exchange. This was important to ensure that potential reductions in particle number fluxes were not due to differences in meteorological drivers (Fig. 2). The quantities wind speed, friction velocity, the integral turbulence characteristic \( \sigma_w/u^* \), and stability parameter were in a similar range when comparing lockdown and reference periods. Horizontal wind speed, friction velocity and the integral turbulence characteristic did not indicate significant differences (p-values >0.05). The stability parameter for daytime hours, however, was significantly different between the two periods (p-value <0.001). While the lockdown period showed a smaller range for the stability parameter, the amount of unstable stratification was slightly higher in the lockdown compared to the reference period. However, since an unstable atmosphere tends to favour vertical exchange, we argue that particle fluxes should also tend to increase under more unstable situations. Hence, potential reductions in particle number fluxes should not be due to distinct differences in meteorological conditions between lockdown and reference period.

3.2. Footprint analysis

To be able to compare particle number fluxes from two different periods, it is vital that flux footprints of both periods are similar in their spatial extent and surface sources. The footprint climatologies of both lockdown and reference period each represent a surface area of around 4.8 km\(^2\) (referring to the 80 % contour line) with the peak contribution being situated at a distance of approximately 60 to 300 m to the northwest of the site (Fig. 3). In this direction a large share of traffic areas with high traffic intensities is located (cf. Fig. 1). The agreement of footprint climatologies is also reflected in the frequency distribution of land-use types that were extracted from a biotope type mapping as provided by the Berlin city authorities (Geoportal Berlin, 2014) and aggregated into five land-use types (built-up areas, vegetated areas, water surfaces, traffic areas, other areas). Finally, these land-use types were footprint-weighted for both time periods. The share of land use in the flux footprint is composed of built-up areas with 58.2 % (reference) vs. 57.4 % (lockdown), vegetated areas (11.1 % vs. 11.5 %), and water surfaces (3.3 % vs. 3.6 %) for the reference and lockdown period, respectively. Especially in terms of traffic areas (both 27.1 %), both periods cover nearly identical source areas. To quantify the impact of varying traffic intensity on different roads in the flux footprint, we calculated a footprint-weighted ADT for both periods. This resulted in a slightly higher footprint-weighted ADT of 32 420 vehicles day\(^{-1}\) for the lockdown period in contrast to 31 903 vehicles day\(^{-1}\) for the reference period (1.6 % difference), respectively. Hence, due to a potentially stronger impact from traffic related sources in the flux footprint during the lockdown period we argue that the observed particle number flux reduction is a rather conservative estimate which might be slightly underestimated.

3.3. Differences in traffic intensity

During the first week of the lockdown period, mean diurnal traffic intensities decreased continuously at both traffic-counting stations (Fig. 4a). Subsequently, the traffic intensity remained on a low level before it increased after first lockdown relaxations were set into effect on 20 April 2020. However, until 06 May 2020 lockdown traffic intensity was lower than in the reference period. The daily average reduction of traffic intensity was −32 % at ‘Hardenbergstraße’ and −37 % at ‘Straße des 17. Juni’, resulting in an average reduction of −35 % (Fig. 4b).
3.4. Lockdown effects on size-resolved particle number fluxes

Particle number fluxes showed significant reductions over the entire size range during the lockdown period (Fig. 5a). The median reference FTNC of $9.15 \times 10^7 \text{ m}^{-2} \text{s}^{-1}$ dropped by about 38% to $5.64 \times 10^7 \text{ m}^{-2} \text{s}^{-1}$ in the lockdown period (reduction of average FTNC = 34%). The largest reduction of 50.5% was observed for average FACC (Table 1). The decrease in particle number fluxes agreed with the decline in traffic intensity as both dropped by roughly the same magnitude (~35%). We further observed a shift in the relative frequency of emission fluxes that is from higher to lower emission fluxes (Fig. 5b). Due to the reduction in particle emission strength during the lockdown period, stronger emission fluxes occurred less frequently whereas a higher frequency of deposition fluxes occurred, which were not compensated by the reduced particle emission. Thus, deposition events occurred at a higher frequency of 8.9% during lockdown than in the reference period (5.7%). Nevertheless, emission events clearly outweighed deposition events in frequency and strength during the lockdown period, such that the city remained a net source of particles.

Mean diurnal cycles of the particle number fluxes were characterized by a lower amplitude and lower average fluxes during the lockdown (Fig. 6). At nearly any time of day, lockdown fluxes were lower than the reference. Additionally, relative average diurnal flux reductions increased with particle diameter as indicated by the particle mode fluxes (Fig. 6b). The reduction of number fluxes was evident in every size bin of the particle size spectrum, but was in terms of absolute fluxes most pronounced in the ultrafine size range (Fig. 7). Deposition events which increased in frequency during the lockdown period could be assigned to certain periods on the diurnal cycle and particle diameters. On the mean diurnal cycle, UFP deposition events were evident only during night, whereas ACC particles were also deposited during daytime. Non-evident daytime UFP deposition probably was due to the higher daytime particle emission fluxes, which overcompensated particle deposition. In contrast, ACC emission fluxes were significantly lower than NUC fluxes so that in ACC mode net deposition fluxes could occur during the day (cf. Fig. 7a). The reference period, however, was characterized by average emission fluxes in all size ranges at any time of day.

3.5. Particle number concentrations during the lockdown period

To quantify lockdown-related effects on number concentrations of particles, the variation in weather and atmospheric background conditions between lockdown and reference period has to be taken into account, e.g. by
Fig. 5. (a) Comparison of $F_{\text{TNC}}, F_{\text{UFP}}, F_{\text{NUC}}, F_{\text{AIT}},$ and $F_{\text{ACC}}$ of the reference (R) and lockdown (L) period. The percentage reductions of median fluxes are shown in blue and significant differences are highlighted (significance level of 0.001 ***). (b) Frequency distributions of $F_{\text{UFP}}$ of the reference and lockdown period.

Table 1
Average, standard deviation, median as well as minimum and maximum particle number fluxes of the reference and lockdown period. In addition, the percentage reductions with regard to the average and median values are given.

|                  | $F_{\text{TNC}}$ | $F_{\text{UFP}}$ | $F_{\text{NUC}}$ | $F_{\text{AIT}}$ | $F_{\text{ACC}}$ |
|------------------|------------------|------------------|------------------|------------------|------------------|
| Reference (m$^{-2}$ s$^{-1}$) |                  |                  |                  |                  |                  |
| Average          | $1.28 \times 10^8$ | $1.23 \times 10^8$ | $8.25 \times 10^7$ | $4.25 \times 10^7$ | $5.09 \times 10^6$ |
| Standard deviation | $1.64 \times 10^8$ | $1.62 \times 10^8$ | $1.20 \times 10^8$ | $5.59 \times 10^7$ | $7.59 \times 10^6$ |
| Median           | $9.15 \times 10^7$ | $8.78 \times 10^7$ | $5.65 \times 10^7$ | $3.36 \times 10^7$ | $4.84 \times 10^6$ |
| Minimum          | $-8.92 \times 10^8$ | $-8.96 \times 10^8$ | $-8.55 \times 10^8$ | $-8.35 \times 10^8$ | $-7.15 \times 10^7$ |
| Maximum          | $2.68 \times 10^9$ | $2.67 \times 10^9$ | $2.35 \times 10^9$ | $1.33 \times 10^9$ | $5.81 \times 10^7$ |
| Lockdown (m$^{-2}$ s$^{-1}$) |                  |                  |                  |                  |                  |
| Average          | $8.44 \times 10^7$ | $8.22 \times 10^7$ | $5.61 \times 10^7$ | $2.75 \times 10^7$ | $2.52 \times 10^6$ |
| Standard deviation | $1.22 \times 10^8$ | $1.21 \times 10^8$ | $8.83 \times 10^7$ | $4.29 \times 10^7$ | $5.65 \times 10^6$ |
| Median           | $5.64 \times 10^7$ | $5.44 \times 10^7$ | $3.39 \times 10^7$ | $2.09 \times 10^7$ | $3.09 \times 10^6$ |
| Minimum          | $-1.07 \times 10^9$ | $-1.07 \times 10^9$ | $-8.03 \times 10^8$ | $-2.70 \times 10^8$ | $-2.58 \times 10^7$ |
| Maximum          | $1.06 \times 10^9$ | $1.05 \times 10^9$ | $6.81 \times 10^8$ | $4.52 \times 10^8$ | $4.64 \times 10^7$ |
| Difference (%)   |                  |                  |                  |                  |                  |
| Average          | $-33.9 \%$       | $-33.2 \%$       | $-31.9 \%$       | $-35.4 \%$       | $-50.5 \%$       |
| Median           | $-38.4 \%$       | $-38.1 \%$       | $-40.0 \%$       | $-37.8 \%$       | $-36.2 \%$       |

Fig. 6. (a) Mean diurnal cycles of particle number fluxes concerning TNC, UFP, and (b) the three modes NUC, AIT, and ACC. In addition, the percentage reductions of the daily average particle number fluxes are shown. Please note the secondary ordinate axis for $F_{\text{ACC}}$. 
weather normalisation procedures as reported in Petetin et al., (2020) or Shi et al., (2021). As the subject of the present study was to look into lockdown-related effects on particle fluxes, we did not apply any weather-normalisation procedures to particle number concentrations. However, we subsequently look into differences of observed number concentrations between the lockdown and reference period to highlight atmospheric particle transformation processes with implications for particle number fluxes.

While particle number concentrations in the ACC mode were significantly (p-value < 0.001) lower by −28.9 % in median concentration during the lockdown period, number concentrations in the NUC mode (+1.4 %) and AIT mode (+12.7 %) were higher in comparison to the reference period (Table 2). However, the mean diurnal cycle of the particle number size distribution shows that the concentration increase is mainly confined to the noon and afternoon hours whereas the morning rush hours and the evenings are characterized by concentration reductions (Figs. 8 and 9). The number concentration increase resembles a 'banana-like' shape starting at around noon in the lowest size channels. This feature is well-known from atmospheric new particle formation events (Heintzenberg et al., 2007; Kulmala et al., 2004). We argue that due to a lower condensation sink as a result of decreased aerosol loading within the urban boundary layer, a higher probability of new particle formation events and subsequent effects of particle growth may be responsible for the observed increase of number concentrations in the NUC and AIT mode during the lockdown period (red areas in Fig. 8b). The observed banana-shape in particle number concentrations between lockdown and reference period (Fig. 8) follows a growth rate of about 3–4 nm h⁻¹ which is at the lower end of typical urban particle growth rates (Kerminen et al., 2018). The higher noon and afternoon particle concentrations in the NUC mode (cf. Fig. 9b) likely trigger the observed relative increase in FNUC during that time (Fig. 6b).

### Table 2

Average, standard deviation, median as well as minimum and maximum of particle number concentrations of the reference and lockdown period. In addition, the percentage reductions with regard to the average and median values as well as the statistical significance of the differences are given (significance levels of 0.05 *, 0.01 **, and 0.001 ***). The concentrations are not weather-normalised and are thus not suitable to analyse lockdown-related reduction effects.

|                  | TNC | UFP | NUC  | AIT  | ACC  |
|------------------|-----|-----|------|------|------|
| Reference (cm⁻³) |     |     |      |      |      |
| Average          | 8649| 7827| 4225 | 3602 | 823  |
| Standard deviation| 4193| 4019| 2968 | 2060 | 521  |
| Median           | 7650| 6750| 3206 | 3079 | 721  |
| Minimum          | 3292| 2958| 1732 | 801  | 82   |
| Maximum          | 41553| 39779| 28583| 19819| 4381 |
| Lockdown (cm⁻³) |     |     |      |      |      |
| Average          | 8543| 7862| 4161 | 3701 | 681  |
| Standard deviation| 3356| 3281| 2674 | 1742 | 497  |
| Median           | 7926| 7118| 3250 | 3471 | 513  |
| Minimum          | 3286| 2895| 1741 | 716  | 89   |
| Maximum          | 30559| 29749| 25645| 13246| 2777 |
| Difference (%)   |     |     |      |      |      |
| Average          | −1.2 %| +0.5 %| −1.5 %| +2.7 %| −17.3 %|
| Median           | +3.6 %| +5.5 %| +1.4 %| +12.7 %| −28.9 %|
| Significance     | **  | *** | *** | *** | *** |

4. Discussion

This study reports a significant reduction of −38 % in median ultrafine particle number fluxes in Berlin during the lockdown period which was associated with a decrease in road traffic of about −35 % (cf. Table 1). The relationship between particle mode fluxes and traffic varies with particle size (Straaten and Weber, 2021), as particle emission from road traffic is mainly in the ultrafine size range, especially in the nucleation mode (Dₚ < 30 nm). Hence, the highest percentage reduction during the lockdown was expected to occur in the NUC mode. This behaviour was evident for median fluxes with the highest reductions of −40 % for FNUC and lowest reductions of −36 % for FACC (cf. Table 1). In contrast, the reductions of average mode fluxes were highest in FACC (−51 %) but lowest in FNUC (−32 %; cf. Table 1). We argue that this might be an effect of an enhanced
occurrence of new particle formation events (Kerminen et al., 2018; Shen et al., 2021a), as these events have a stronger influence on average than on median fluxes. The average value reacts more sensitive to outliers, which results in lower reductions in average than in median fluxes. Recent studies from urban and suburban sites give evidence for an increased probability of new particle formation events under conditions of low or decreased condensation sinks (Brines et al., 2015; Zimmerman et al., 2020), i.e. due to reduced emission of particles. An increase of new particle formation events during the lockdown period was previously observed in Beijing, China (Shen et al., 2021a; Yan et al., 2022) as well as in the Po-Valley, northern Italy (Shen et al., 2021b). An average particle growth rate of about 3 nm h$^{-1}$ as found for particles $>10$ nm during the lockdown period in Beijing (Shen et al., 2021a) fits well to our data from Berlin (cf. Fig. 8). At the present site, growth of particles in NUC and ATI modes were observed that likely increased particle number emission fluxes of FNUC and FAIT compensating some of the reduction due to reduced traffic intensity.

The source strength of other particle emission sources due to anthropogenic activity such as biomass burning, food-cooking or domestic heating (e.g. (Robinson et al., 2018; Casquero-Vera et al., 2021)) might have varied during the lockdown period. However, a previous land-use regression analysis indicated traffic areas as the dominating land-use type influencing particle number fluxes at the site (Straaten and Weber, 2021). The influence of other sources that are associated with built-up areas such as domestic heating or cooking, is significantly lower compared to the traffic influence at this site. Thus, we argue that the reduction in particle number fluxes in mainly caused by the reduction in traffic intensity. This assumption is
supported by Nicolini et al., (2022) who studied CO2 flux variation during the COVID-19 lockdown. For some European cities they found that CO2 emissions from residential areas did not increase significantly during the COVID-19 lockdown even though people spend on average 20 % more time at home. Hence, vehicular traffic was assumed to be the main factor driving CO2 fluxes at the respective sites (Nicolini et al., 2022).

To the authors’ knowledge, there is only one other particle number flux study investigating COVID-19 lockdown effects that was conducted in suburban Lecce, Italy (Donateo et al., 2021). The impact of road traffic at this site was limited in comparison to our urban site in Berlin, so that the suburban site became a minor sink during the lockdown period. In contrast, the urban site in Berlin remained a net particle source even as the frequency of deposition fluxes increased. Nevertheless, significant reductions were observed in all particle size ranges. The comparison of these two locations indicates that suburban and urban sites may react differently to reductions in traffic activity.

With exception of the study of Donateo et al., (2021) no other particle number flux studies are available that investigate lockdown effects. However, surface-atmosphere exchange measurements of traffic-related gaseous pollutants report significantly lower emission fluxes of NO2, CO2 and aromatic non-methane volatile organic compounds (NMVOC) during the lockdown in Innsbruck, Austria (Lamprecht et al., 2021). Lockdown period integrated emissions of NO2 and aromatic NMVOCs were lower by −59 % and −56 %, whereas traffic intensity declined by −64 %. In several European cities, Nicolini et al., (2022) found strong variation in lockdown-related reductions in CO2 emission of between 5 % and 87 %. Additionally, a number of recent studies point to a causal relationship between lockdown-related reduction in traffic intensity (37–71 %) and significant reductions of air pollutant concentrations such as NO2 (reduction of 29–54 %), BC (22–56 %) or PM2.5 (29–33 %), respectively (Li and Tartarini, 2020; Xiang et al., 2020; Lovrić et al., 2021; Hudda et al., 2020). For traffic sites in Berlin, von Schneidemesser et al., (2021) found a 40 % decrease in NO2 concentrations during the lockdown period. Hence, the findings of the present study strongly agree with other observation-based results of COVID-19 lockdown effects from studies around the globe.

5. Conclusions

Size-resolved particle number fluxes were measured in central Berlin to investigate the effects of the first German wide COVID-19 lockdown on urban surface-atmosphere exchange. We showed that a reduction of particle number fluxes was not due to differences in the flux source area, boundary layer turbulence, or atmospheric stratification (cf. Sections 3.1 and 3.2) but due to lower surface emission strength by urban road traffic.

The present study demonstrates a causal relationship between traffic reduction and the decrease of particle number fluxes, i.e. −35 % traffic reduction, −34 % average F_{TNCS} and −33 % average F_{IPP}, respectively. Lower lockdown particle number fluxes were evident in each size bin of the particle size spectrum. Additionally, the frequency of particle deposition events increased due to the decline of traffic. As previous findings indicated traffic to be the main source of particles at this site (Straaten and Weber, 2021), lockdown effects in other particle source categories such as residential heating or industrial combustion were not evident in the present data. The findings highlight the benefits of traffic reduction as an air-quality mitigation strategy to lower the emission of ultrafine particles to the urban atmosphere and that eddy-covariance observations are a powerful tool to monitor longer-term variation of urban ultrafine particle fluxes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Aubinet, M., Vesala, T., Papale, D. (Eds.), 2012. Eddy Covariance. A Practical Guide to Measurement and Data Analysis. Springer Netherlands, Dordrecht https://doi.org/10.1007/978-90-047-2351-1.

Baldocchi, D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Rev. Glob. Chang. Biol. 9, 479–492.

Barr, J., Petrin, H., Colette, A., Guevara, M., Feuch, V.-H., Roux, L., Engelsen, R., Inness, A., Deventer, J., Pérez Grañeda-Pando, C., et al., 2021. Estimating lockdown-induced European NO2 changes using satellite and surface observations and air quality models. Atmos. Chem. Phys. 21 (9), 7373–7394. https://doi.org/10.5194/acp-21-7373-2021.

Birnili, W., Sun, J., Weinhold, K., Mekel, M., Rasch, F., Spindler, G., Wiedensohler, A., Bastian, S., Lischeid, G., Schlacht, A., et al., 2015. Atmospheric aerosol measurements in the German Ultrafine Aerosol Network (GUAN). Part 3: black carbon mass and particle number concentrations 2009 to 2014. Gefahrstoffe - Reinhalt. Luft 75 (11–12), 479–488.

Biondini, C., Ventura, V., Zino, M., Bitacorda, A., Pianosi, F., Ganesan, A.S., Jones, N.P., L’Ecuyer, T., 2019. A framework to evaluate ultrafine particle data from two counting stations. We thank the four anonymous reviewers for their constructive critics on the earlier version of the manuscript.

Agnieszka Straaten: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. Fred Meier: Writing – review & editing. Dieter Scherer: Writing – review & editing. Stephan Weber: Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

CRediT authorship contribution statement

Agnieszka Straaten: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. Fred Meier: Writing – review & editing. Dieter Scherer: Writing – review & editing. Stephan Weber: Conceptualization, Funding acquisition, Supervision, Writing – review & editing.
