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Supplementary material for this article is available [online](#)

Abstract

Indoor air pollution contributes significantly as a world-wide environmental issue, impacting health and livelihood. To quantify benefits of filtration on indoor air quality, it is essential to understand the relationships between the various factors impacting the concentrations of indoor air pollutants. This work uses a mass-conserving 2-box model, high-frequency observations of aerosol number concentration, and a home-made, low-cost, 3-layer non-woven fabric filter, powered by a standard ventilation fan to quantify the effectiveness aerosol reduction in multiple indoor environments. The data shows that aerosol loading is effectively reduced under both steady-state and extreme event conditions, although there are significant and important differences between simultaneous observations both indoor and outside. To obtain a proper accounting, the following must be considered: the usage or not of the fan filter, whether windows are opened or closed, the state of outdoor air is pollution, and the strength and duration of indoor emissions. The experiments are applied in residential indoor environments in four cities in eastern (Xuzhou), central (Zhoukou), and southern (Zhuhai and Shunde) China. Photographic evidence of the altered fan filter state under both conditions show that while usually dark/black aerosols dominate, there are conditions when yellow aerosols also dominate. The observations are based on multiple, independent, continuous low-cost sensors which have been calibrated against a GRIMM-180 over the number concentration range from 0.3 to 1.0 microns, and yield a removal rate due to the fan-filter of 46%, 80%, 81%, and 36% respectively across the four cities. A corresponding rate to return from an extreme event to steady-state, is computed outdoors and indoors respectively from: 14.–44. minutes, 6.6–21. minutes, 16.–33. minutes, and 24.–58. minutes. The most important factors contributing to the removal efficiency and decay gradient are observed as keeping windows closed and reducing leakiness, the apartment/classroom size, and the outdoor air pollution loading.

1. Introduction

Over the past few decades, significant economic development has led to hundreds of millions of people being exposed to high levels of indoor air pollution (Samet 1987, Cohen 2011), while at the same time also increasing the knowledge among the public that this is a serious issue impacting people's health and livelihood (Tham 2018,

Brook *et al* 2010, Zhao *et al* 2020, Barkjohn *et al* 2021). One major source of indoor air pollution is the transport of aerosols and gasses from outdoors to inside via doors, windows, ventilation systems, and cracks/pores in various building materials (Ohura *et al* 2009, Uhde, Salthammer (2007), Chen and Zhao 2011). Another major source consists of emissions located inside, including but not limited to cooking and other open flames (Brasche and Bischof 2005, Schweizer *et al* 2007, Kassomenos *et al* 2014), intentional burning such as cigarette smoke and incense (Holcomb 1993, Dai *et al* 2016, Odeh and Hussein 2016), mosquito coils, evaporation of semi-volatiles like paint and varnish, and other sources (Escobedo *et al* 2014, Goyal and Khare 2011).

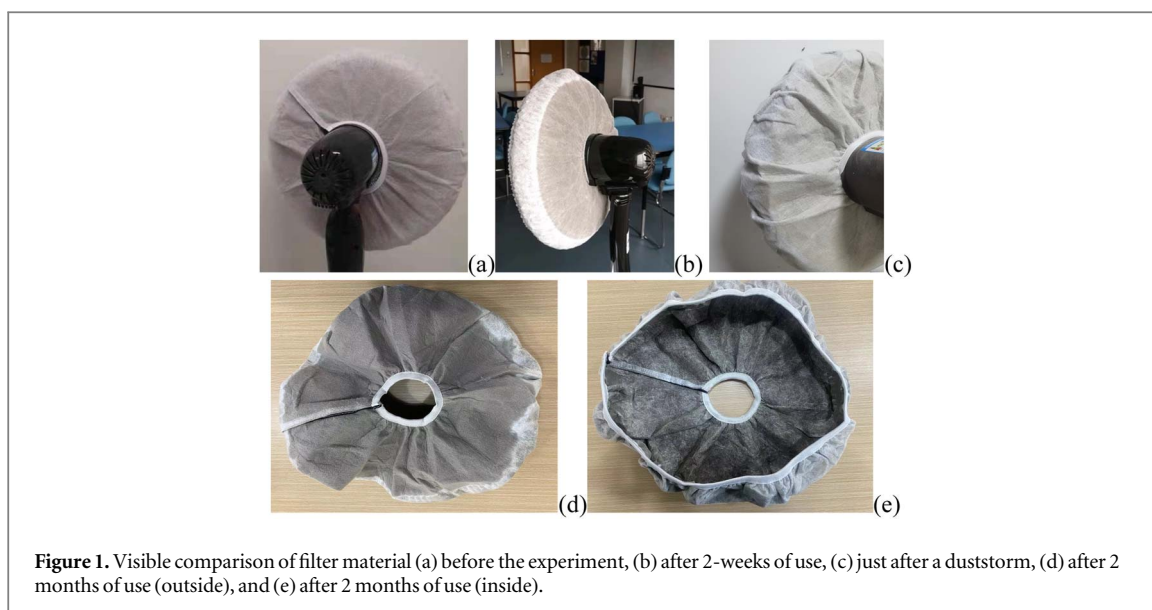
For these reasons, there has been a considerable amount of time and effort put into ways to reduce the loading of aerosols in the indoor environment (Abt *et al* 2000, Zheng *et al* 2018). One of these methods is to reduce the source of emissions inside. A second of these methods is to reduce the transport of sources from outside to inside, or from another perspective, increase the dilution of dirty indoor air with cleaner outdoor air (Gao *et al* 2013, Xiang *et al* 2021). A third method is to find filters, materials, paints, plants, etc which are capable of removing these aerosols and gasses *in situ* (Liang *et al* 2021).

A common misconception is that any material with a high level of filtration (i.e., how much aerosol is removed from a given volume of air or a given puff directed at or through the filter) will be effective in cleaning indoor air. Supporting this misconception are many materials and standards (i.e., MERV and PFE) which have been developed (Scott *et al* 2009, Qian *et al* 1998). According to these standards, there are many such materials that claim to remove upwards of 99.97% of aerosols with a diameter of 2.5 microns and smaller (PM_{2.5}). These standards tend to be tested in environments contained within sealed boxes or other containers, under *in situ* concentrations which tend to have aerosol concentrations which are considerably lower than observed in highly polluted indoor environments, with the vast majority of the PM_{2.5} being tested composed of mostly sea salt and other ionizable aerosols, and with the exposure to the filter material taking place over an extended period of time with respect to the actual residence time in a typical indoor environment (Morawska 2020, Bałazy *et al* 2006, Bouilly *et al* 2005, Lam *et al* 2020).

However, inside a real indoor location where people live, work, and go about life, such idealized tests do not offer a fair representation of reality (Alves *et al* 2013, Batterman *et al* 2005). There is always air exchange between the indoor and outdoor environment (Rim *et al* 2010), otherwise there would be a buildup of CO₂ and death would surely follow. In fact, most residential buildings are both quite large and have a relatively rapid overturning flow time on the order of an hour at most (Chambers *et al* 2001). Furthermore, the aerosol loadings in polluted regions of the world, with southern and central China being good examples, can typically far exceed those of the WHO standard on a regular basis (Prüss-Üstün *et al* 2016), and frequently contain significant amount of non-ionizable organic carbon (OC) and black carbon (BC) aerosols (Cohen 2011, Cohen and Wang 2014, Wang *et al* 2021a). Therefore, environmental testing under realistic conditions where people live, work, and tend to spend their time necessitates a step over and beyond the idealized conditions considered by the present generation of studies (Zhou 2016), especially so under actual indoor environmental conditions, and over extended continuous periods of time from hours through days.

To address these issues, a new systems approach is introduced to comprehensively analyze the loadings of aerosols, their size distribution, and their time-rate of their change, as they occur inside actual indoor residential environments under both filtered and non-filtered conditions. These measurements are designed to test the efficiency of a next-generation, home-made material, driven using a common household fan. The new material has both high filtration efficiency (MERV 17) including for particles as small as 300 nm, and low pressure drop (always measured at less than 13 Pa, sometimes as low as 11 Pa). This net combination of high filtration material and low pressure drop allows a high volume of air to be filtered. Furthermore, due to the relatively flat, perpendicular, and thin material surface, the air flow remains laminar, allowing more aerosols to follow the flow streams and be filtered by the material on each pass.

This work introduces a new analytic approach to quantify the air quality improvement in real time offered by a next-generation air filtration material. The analysis techniques specifically account for the large variations in observed indoor and outdoor aerosol loadings at high temporal frequency. One major point is that the flux from indoor to outdoor and visa-versa are explicitly considered, in terms of their impact on the indoor residential environment. The data collected has been analyzed continuously at each site over weeks to months, allowing consideration of impacts from variations observed across meteorological, geographical and other environmental factors. Specific consideration is made to when the flow between the indoor and outdoor environment (i.e., the building quality as well as active state of open/closed windows and ventilation systems), as well as the impact of indoor air mixing rates. The methods and results provided herein aim to provide a best practice approach to quantifying the effectiveness of in-home solution to air pollution reduction, both in terms of long-term impacts, impacts under extreme conditions, and impacts over 5-minute-long time scales, in terms of reducing the *in situ* loadings of aerosols that actually occurs in a real indoor environment.



2. Data and methods

This study has made continuous measurements in typical indoor environments across 4 different geographical regions in China. The experimental design allows the impact of a new generation of air pollution reduction materials to be tested in the real environment, including the impacts of variations in the real atmosphere, including those of a short-lived nature, those associated with the daily meteorological cycles, those related to longer-term variation in atmospheric conditions, and those induced by real-world indoor air circulation patterns and emissions (Shaughnessy, Sextro (2006)).

All tests were performed using new filters, applied in the same way, using the same materials and fitting procedures, the same standard 20-inch ventilation fans, oriented in the same direction so that air flows through the filter into the fan, and then subsequently out the front of the fan. This procedure allows for a portion of the redirected flow to pass through the filter a second time around the portions of the fan's rim that are covered on the front-facing side. The air passing through the fan-filter subsequently enters into the room in a cone-shape, with a variable rate and speed which depends on the air pressure, porosity of the indoor space being investigated, power flow to the fan, and other local meteorological properties as explained in. In the real rooms observed, there is air exchange between the inside and the outside, and there is turbulence in the air on the inside, which causes this variable to not necessarily match with the rate of decay of the aerosols in the real indoor environment. This is the underlying reason why this work introduces two new quantities to describe the steady and extreme states of aerosol loading and the effectiveness of the filter. The configuration of the filter, how it was applied to the fan, and the observed intense color change after 14-days of continuous use, are given in figure 1.

Across all experiments, measurement data was separated into two parts, those representing 'pseudo-steady-state' or typical conditions (i.e., those that are representative of the climatological background that the people living inside of the environment are exposed to) and 'events' (short-term atmospheric conditions representative of locally enhanced aerosol concentrations). Statistics are computed separately over these two categories, so as to account for the fact that in the real environment, there are short-term spikes frequently associated with turbulence, short-term but intense emissions (i.e. smoking, cooking, the start of large-scale vehicular traffic, rapid changes in the boundary layer or other atmospheric disturbances etc) which are not typical of the long-term conditions, but which have a significant short-term effect on the concentrations. The removal efficiency of the air pollution materials in terms of reduction of both the size-segregated number concentrations were computed for the 'pseudo-steady-state' condition. The decay time and the drop magnitude of the associated decay were computed for the 'events' conditions, consistent with quantifying the time it takes for extreme conditions to return to the normal conditions when the fan filter is in use. Furthermore, the impacts of different room porosities and indoor and outdoor aerosol loadings are characterized and explained.

2.1. Experimental design

A comparison between the aerosol number concentrations in the outdoor environment and the indoor environment is essential to quantify the effects of the air filters. The setup places two (or three) sensors in close proximity to each other. One is (or two are) placed inside the room being sampled, far from primary emissions sources (i.e., not near the kitchen or water heater). The remaining sensor is placed just outdoors on the balcony

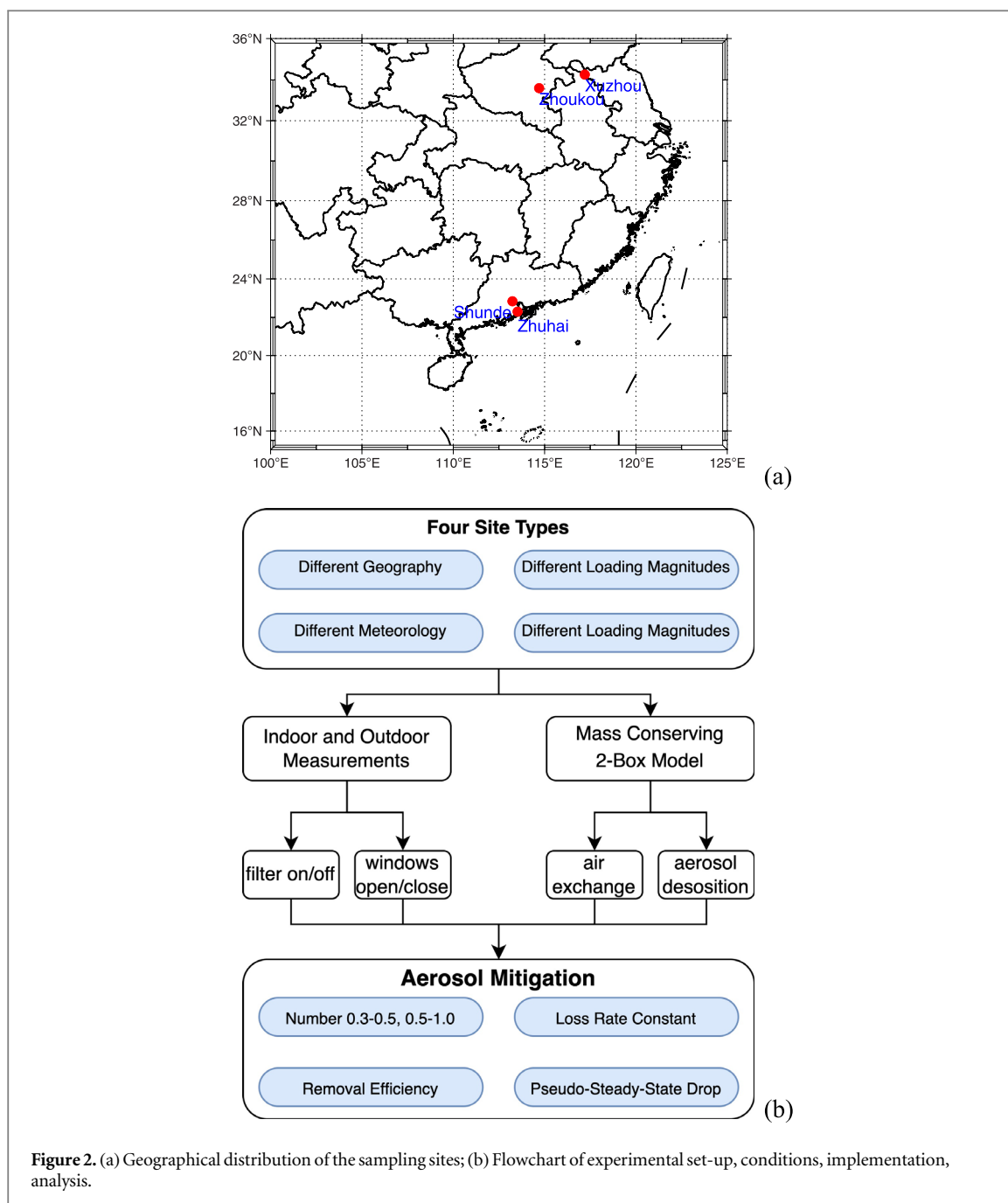


Figure 2. (a) Geographical distribution of the sampling sites; (b) Flowchart of experimental set-up, conditions, implementation, analysis.

or other outlying extension in a way as to be representative of the outdoor air which is in contact with the building's surface. The flowchart of experiment, as well as the locations of the four geographic regions in which testing was done are shown in figures 2(a) and (b).

In Zhuhai, the indoor space is approximately 105 m^2 and the doors and windows are usually kept closed and in double-rubber seal lock mode, due to special construction meant to address the frequent typhoons in this urban area each summer (this system successfully kept all debris out from the 2018 Typhoon Mangkhut which hit Zhuhai with 65 m/s maximum winds). The Zhuhai site is located near the Zhujiang river and otherwise in a residential area covered by a large number of trees and vegetation. In Shunde, the indoor space is approximately 100 m^3 in an old building, with doors and windows of older construction. This site is located next to a major interstate highway, which has significant traffic both during the day and night (Figure S1). In Xuzhou, the indoor space is approximately 25 m^2 , and the doors and windows are of above average construction. This site is located in the middle of a university campus without traffic and with a large tree cover. Outside of the campus, Xuzhou is a rapidly growing industrial city, which just reached and passed a population of 9 million. In Zhoukou, the indoor space is approximately 45 m^2 and the doors and windows are not leaky compared to other normally constructed apartments. The site is located in the center of a suburban residential area, without tall buildings. In the evening, there are many barbeque and other street food sources located nearby.

Zhuhai is a coastal site located in the subtropical Asian Monsoon region, with high humidity. The main sources of aerosols are from long-range transport, shipping, construction and cooking. The Shunde site has a similar climate to Zhuhai, but instead is located in an industrial region with a significant transportation artery nearby. Xuzhou is located in a temperate environment with 4 typical seasons, a moderate amount of humidity, and wide variation between day and night and one day to the next. The background in this city is consistent with the many rapidly growing urban areas in Asia which are based on heavy industry. Zhoukou has a similar latitude to Xuzhou, but is located 500 km further inland, and therefore is considerably drier (there was no precipitation that occurred throughout the entire measurement campaign in this city). It is also typical of a growing suburban Asian city, which has sources associated with both rapid low-density urbanization and agriculture, including a very large 'fresh from farm to consumption' barbecue culture.

2.2. Low-cost aerosol number concentration detectors

The outdoor and indoor aerosol concentration measurements were taken by the low-cost commercially available aerosol detector manufactured by PA (version PA-II-SD, [Li 2020](#)). The measurements are based on a technique using two side-by-side laser particle counters, where the length of the pulse determines the particle size and the number of pulses determines the number concentration, connected to a USB powered fan to continuously draw in air over a 2-minute period. The number concentration of particles per 0.1 liters of air is computed over five binned size ranges, two of which are used in this paper: 0.3 μm to 0.5 μm and 0.5 μm to 1.0 μm . The sensor has been determined to effectively measure the daily average and statistical distribution of measured PM_{10} conditions at 7 EPA supersites over a 2-year period across the USA, including under extreme events found in both Utah and in California ([Ardon-Dryer 2020](#)). However, a recent study has determined that for particle sizes larger than about 2 μm , the sensor may not work very well, and instead would be better considered as a nephelometer ([Ouimette *et al* 2022](#)). However, given the mixing state and size of the particles, it has been shown that indeed a number concentration can be derived from a nephelometer with a visible wavelength band laser, as this instrument contains ([Dubovik *et al* 2000](#), [Holder *et al* \(2020\)](#), [Holder *et al* \(2020\)](#), [Wang *et al* 2021b](#)). Continuous measurements of particle number from 0.3 μm to 0.5 μm and 0.5 μm to 1.0 μm , actively running 24-hours a day throughout the entire time period measured, are taken both indoor and outdoor, from December 6th to January 7th 2019 in Zhuhai, from December 23rd 2019 to January 19th 2020 in Shunde, from July 19th to August 4th 2020 in Zhoukou, and from July 8th to July 24th 2020 in Xuzhou.

The measurements underlying the results have all been made using the same low-cost sensors, PurpleAir (PA) on a continuous 2-minute basis, with measurements being made 24-hours a day over a minimum of 28 continuous days. The PA sensors were calibrated by comparing the 2-minute continuous measurements against the 2-minute continuous mean made by a co-located GRIMM-180 24-hours a day over a 6-day continuous period. The corrected time series of the PA measurements is shown paired with the time series of the GRIMM-180 in figures 3(a) and (b) [Wang 2022](#). In specific, this work uses the retrieved number concentrations of aerosols by the sensor over 2 bins (ranging from 0.3 to 0.5 microns and 0.5 to 1.0 micron, [Ouimette *et al* 2022](#)).

2.3. Analytics used and statistics generated

At a first glance, the measurements show a clear impact on the indoor environment when the fan equipped with the new filter material is used. However, such a simple analysis does not carefully look into the large amount of variation present in the data, the various event spikes, transitions between the different regimes, outdoor pollution loadings, and porosity of the indoor environment. Similarly, following the USA EPA idea also is clearly insufficient, as the observations clearly show that the efficiency of the removal itself varies greatly, including factors including the aerosol source type and loading, the porosity of the environment, the conditions of the atmosphere, and other factors ([Chen *et al* 2011](#), [Crilly, Di Antonio *et al* 2018](#)). This is tied to the fact that in general, air filter material is based on tests made in a closed chamber environment, under constant atmospheric conditions, at low wind speeds, over long amounts of time and with low concentrations of aerosols. In order to test under real world conditions, this paper adapts a set of quantitative statistics and analytical approaches to further delve into these important details and improve our overall understanding.

2.3.1. Detecting and separating special events

Perturbations of the local air concentration may be due to rapidly changing aerosol emissions sources, changes in the atmosphere including the boundary layer height and wind speed, changes in the indoor environment such as pressure shocks due to opening doors and/or windows, or other changes impacting the chemical and physical removal conditions indoors, such as the introduction of a new air filter material. Usually observed perturbations are indicative of a short-term change, not of the long-term changes in the pseudo-steady-state state. To attempt to better understand the response of the filter to such short term and intense changes, a method is established to specifically quantify how long it takes for such perturbations to return back to pseudo-steady-state conditions,

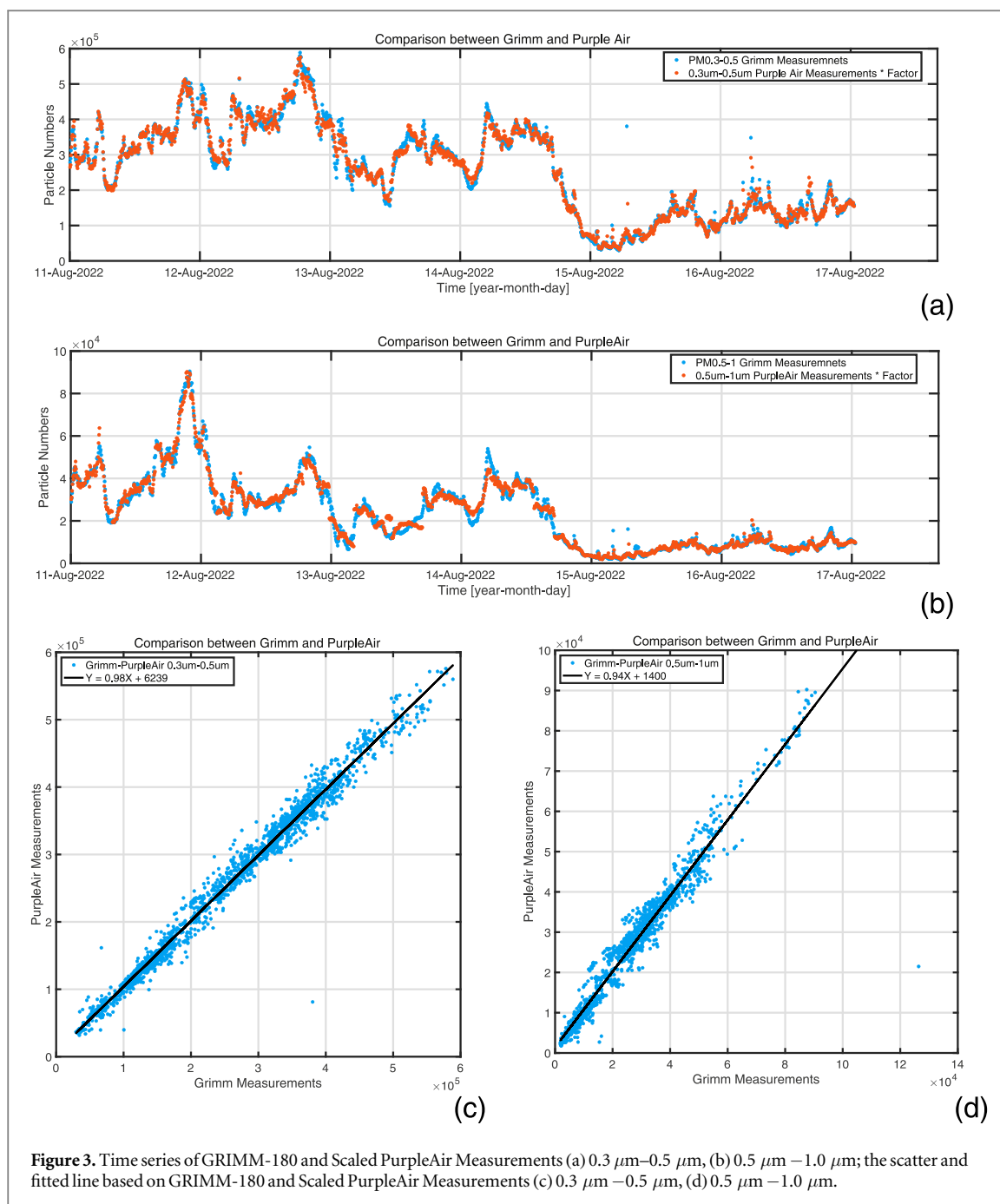


Figure 3. Time series of GRIMM-180 and Scaled PurpleAir Measurements (a) $0.3 \mu\text{m} - 0.5 \mu\text{m}$, (b) $0.5 \mu\text{m} - 1.0 \mu\text{m}$; the scatter and fitted line based on GRIMM-180 and Scaled PurpleAir Measurements (c) $0.3 \mu\text{m} - 0.5 \mu\text{m}$, (d) $0.5 \mu\text{m} - 1.0 \mu\text{m}$.

and the absolute magnitude of such perturbations. This approach allows two different quantitative markers to be used to analyze the effectiveness of the filters and the indoor environment under both pseudo-steady-state and extreme conditions.

Separating the data into these two groups requires two steps. First, the mean and standard deviation of the time series is computed, and second, data corresponding to the extreme events is filtered recursively using these statistics. Any data larger than the mean plus n times the standard deviation is considered an extreme condition. This test is repeated for multiple values of n in steps of 0.05 from $n = 1$ to $n = 2$. In each case, the process iterates until the data removed in the final step is less than 1% of the remaining pseudo-steady-state data. Overall, this procedure takes 5 to 10 cycles to reach a solution for the indoor data, with the outdoor data generally taking more cycles. In all cases, 20% to 25% of the individual measurements are found to be extreme. This technique successfully filters all known actual events as well as many other similarly sized events, from those which may mathematically look like events but in reality, are more likely just associated with measurement uncertainty.

2.3.2. Analytics and measures

The first metric is the removal efficiency (herein called RE), which can be computed both for the fan powered filter material, and the typical indoor living environment (the effect of aerosol removal due only to the walls, items in the indoor living environment, etc). The effective RE values are computed each 2 min throughout the pseudo steady-state time period as given in equation (1),

$$RE = C_{indoor,steady} / C_{outdoor,steady} \quad (1)$$

where $C_{indoor,steady}$ and $C_{outdoor,steady}$ are the respective 2-minute average concentrations indoors and outdoors in [$\mu\text{g}/\text{cm}^3$] for PM and [$\#/ \text{cm}^3$] for number over a given size range. There are four different types of RE which are computed in this work. Specifically there are different values computed when the fan is on and off, and when the windows are open and closed. In each case, the underlying driving forces include deposition to the walls and the fan filter, as well as transport to and from the outside.

The fraction of data not at pseudo-steady-state is calculated differently, to consider both (a) the magnitude of the reduction required to return to pseudo-steady-state and (b) the time for this reduction to occur. Therefore, two new concepts are employed to analyze the measurements: first the drop in concentration between a peak and either pseudo-steady-state or a local minimum, and second the corresponding time for this drop to occur. These two specific concepts (drop and time) are combined into a single metric called the decay gradient (DG), following equation (2),

$$DG = \frac{(Event_{max} - Event_{min})}{(Tau_{Event_{max}} - Tau_{Event_{min}})} \quad (2)$$

where $Event_{max}$ is the local peak of the event in terms of concentration (respectively [$\mu\text{g}/\text{cm}^3$] for PM and [$\#/ \text{cm}^3$] for number concentration), $Event_{min}$ is the concentration (respectively [$\mu\text{g}/\text{cm}^3$] for PM and [$\#/ \text{cm}^3$] for number concentration) when pseudo-steady-state is achieved (or a local minimum in a multi-peak event is found), and tau is the time [minutes] between $Event_{max}$ and $Event_{min}$.

DG is calculated for the indoor environment for every drop from special event (based on its maximum peak plus any obvious secondary local peaks) back to pseudo-steady-state (or local minimums). In all cases a local peak or minimum is considered sufficiently stable for analysis purposes if it is at least 5 min in length. These individual values of DG are then analyzed separately for both conditions under which the fan filter has been used and not used. Further analysis was also made when the windows were both open and closed, since this difference proved to be statistically significant.

These two variables are significant with respect to human health, since the overall exposure to indoor air pollution is a function of both the amount and the length of exposure. These variables emphasize the amount of time and the quantitative reduction to return to pseudo-steady-state in the real indoor air that people are exposed to, not an idealized standard of what a material can achieve. If the rate of removal is similar to or slower than the rate at which new pollutants enter from outside or are emitted on the inside, then the net concentration will not decrease, and the filter is therefore not useful in the real indoor environment.

2.4. Mass conserving 2-box model

We introduce the idea of a mass conserving 2-box model (MC2BM) to quantify and analyze the first order effects of dynamics, air exchange, aerosol deposition, and aerosol filtration between the outdoor and the indoor environment. Our base model is given in equation (3), where the change in mass of the particles with respect to time is due to emissions in the indoor environment (E), transport of polluted air from the outside (based on a rate constant α_1 , transport of polluted air from the inside to the outside plus the natural removal due to the properties of the indoor environment α_2 , and the enhanced removal on the inside due to the use of the filter (also α_2 , but analyzed differently when the filter is turned on).

First, this equation is fitted under different experimental conditions in which the data is observed to be at pseudo-steady-state, and therefore there is not a known local emissions or significant amount of transport of polluted air from the outside to the inside. This allows us to generate a range of the possible values of α_1 and α_2 which are not influenced by local emissions and/or extreme outdoor pollution events. In this specific case, the value of α_1 is the first order coefficient describing linear air flow to or from the room in exchange with the outside. The value of α_2 is the first order coefficient describing the linear loss of aerosols to the unfiltered indoor environment, and includes dry deposition, turbulent deposition, and any wet deposition which may regularly occur within the indoor environment. Due to the fact that in many places in China, the construction is new, therefore the air exchange is relatively limited to conserve energy.

For this reason, it is essential to further explore the effects of opening and closing windows on the transport rates and the ultimate indoor air quality, at sites in which this work has sufficient data, both α_1 and α_2 are fit under conditions when the filter is off, there are no emissions, and the window is specifically known to be either open or closed.

After establishing the various different magnitudes of the first order effects without the use of the filter, the impacts of the filter are tested under pseudo-steady-state conditions. Again, this set of data is filtered to ensure that there are no aerosol concentration conditions which are influenced by either significant indoor emissions or extreme outdoor pollution events, similar to above, except for the filters being turned on. This allows computation of the term α_2 under pseudo-steady-state conditions.

Under event conditions, either one or both of significant emissions occur inside or outdoor polluted air is transported inside. In these cases, this work makes a simplifying assumption that the emissions source and/or transport event have subsided when the concentration starts its exponential decay back towards pseudo-steady-state. In this specific subset of data that corresponds to these conditions, the terms are analyzed with respect to the reduced equation given in equation (3) (where E is set to zero, and all of the remaining terms are used as previously fit).

$$\frac{dC_{indoor}}{dt} = E + \alpha_1 C_{outdoor} - \alpha_2 C_{indoor} \quad (3)$$

Training is performed under conditions wherein the emissions and indoor loss terms are controlled. These cases, the value of E is zero, and the fan filter is not in use, and therefore the value of α_2 only accounts for loss to the natural indoor environment. In the subset of cases for training where the fan filter is turned on, then α_2 describes the total loss, in this case, the background loss plus the loss due to the air filter. In the case where the windows are open, the values of both α_1 and α_2 may further be different than in the case where the windows are closed.

Special events occur either when there is a significant number of emissions (E) or when a significant amount of mass from the outside comes inside. In the subset of cases where the emissions or transported outdoor pollution is not continuous in time, this work then analyzes the data from the peak (or local peak for a sufficiently significant drop) point and models it as it decays back to the pseudo-steady-state. Further, an assumption is made that there must be at least 3 continuous points of decay (minimum of 6 continuous minutes of decay), or the signal is not considered to be statistically significant and is further filtered. All of the fitting terms are refit in the special event cases, allowing the time it takes for the decay, and the difference in indoor loss and outdoor to indoor transport to be specifically analyzed.

3. Results and discussion

3.1. Indoor and outdoor aerosol characteristics

The mean and (standard deviation) over the dataset in Zhuhai (figure 4(a) and figure 5(a)) are $6.6 \times 10^4 (1.2 \times 10^4) \#/\text{cm}^3$ and $2.0 \times 10^4 (3.6 \times 10^3) \#/\text{cm}^3$ respectively for indoor number concentration of $0.3 \mu\text{m}$ to $0.5 \mu\text{m}$ and $0.5 \mu\text{m}$ to $1.0 \mu\text{m}$. Similarly for outside measurements, the mean and (standard deviation) are $2.2 \times 10^5 (3.9 \times 10^4) \#/\text{cm}^3$ and $7.0 \times 10^4 (1.2 \times 10^4) \#/\text{cm}^3$ respectively. In all cases, the average indoor air concentrations are found to have a concentration that is 24% to 30% of the respective average outdoor air concentration loadings ($\#/\text{cm}^3$ or $\mu\text{g}/\text{cm}^3$), indicating that a simple in-bulk analysis demonstrates that the air filters provide a significant reduction in the particulate loadings indoors. This site has the best result for the fan-filter in terms of bulk removal of aerosols. This is due in part to the fact that the outdoor aerosol loading tends to be relatively low, the indoor environment is the least leaky of all the sites, it is located on the 26th floor and spends a considerable amount of time each day outside of the local boundary layer, and the major sources tend to be bulk shipping and local construction, which are both relatively stable throughout the period studied. While this site also has a large number of vigorous convection events, they only occur over a short amount of time, implying their significant impacts are limited in time, and do not affect the bulk mean properties.

The mean and (standard deviation) over the dataset in Shunde (figure 4(b) and figure 5(b)) are $2.2 \times 10^5 (3.3 \times 10^4) \#/\text{cm}^3$, $6.9 \times 10^4 (1.1 \times 10^4) \#/\text{cm}^3$ and $36(17) \mu\text{g}/\text{cm}^3$ respectively for the indoor number concentration of $0.3 \mu\text{m}$ to $0.5 \mu\text{m}$, $0.5 \mu\text{m}$ to $1.0 \mu\text{m}$ and PM_{10} . Similarly for outside data the mean and (standard deviation) are $2.8 \times 10^5 (5.6 \times 10^4) \#/\text{cm}^3$, $9.2 \times 10^4 (1.8 \times 10^4) \#/\text{cm}^3$ and $49(30.) \mu\text{g}/\text{cm}^3$ respectively, as above. In all cases, the average indoor air concentrations are found to be 76% to 63% that of the respective average outdoor air concentration loadings. This is the site in which the fan filter is least effective in removing aerosols from the indoor air, on a bulk concentration basis. This site is the largest in terms of indoor air volume, the leakiest in terms of porosity, and the closest to a major source of aerosol emissions.

The mean and (standard deviation) over the dataset in Xuzhou (figure 4(c) and figure 5(c)) are $1.3 \times 10^5 (2.3 \times 10^4) \#/\text{cm}^3$, $4.3 \times 10^4 (7.5 \times 10^3) \#/\text{cm}^3$ and $22(12) \mu\text{g}/\text{cm}^3$ respectively for the indoor number concentration of $0.3 \mu\text{m}$ to $0.5 \mu\text{m}$, $0.5 \mu\text{m}$ to $1.0 \mu\text{m}$ and PM_{10} . Similarly for outside data the mean and (standard deviation) are $2.1 \times 10^5 (8.9 \times 10^3) \#/\text{cm}^3$, $6.5 \times 10^4 (2.3 \times 10^2) \#/\text{cm}^3$ and $35(14) \mu\text{g}/\text{cm}^3$ respectively, as above. In all cases, the average indoor air concentrations are found to be 66.3% to 39.2% that of

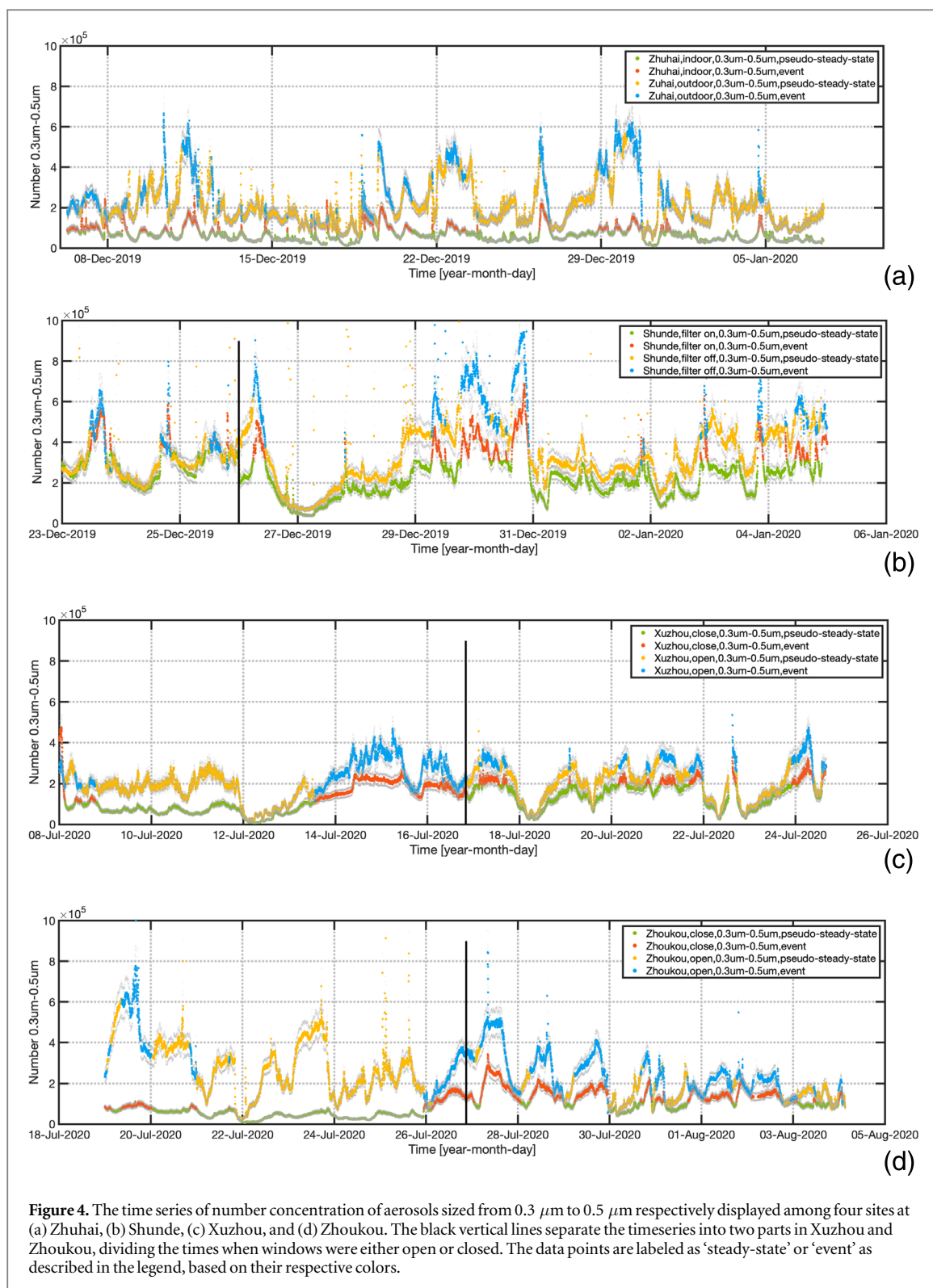
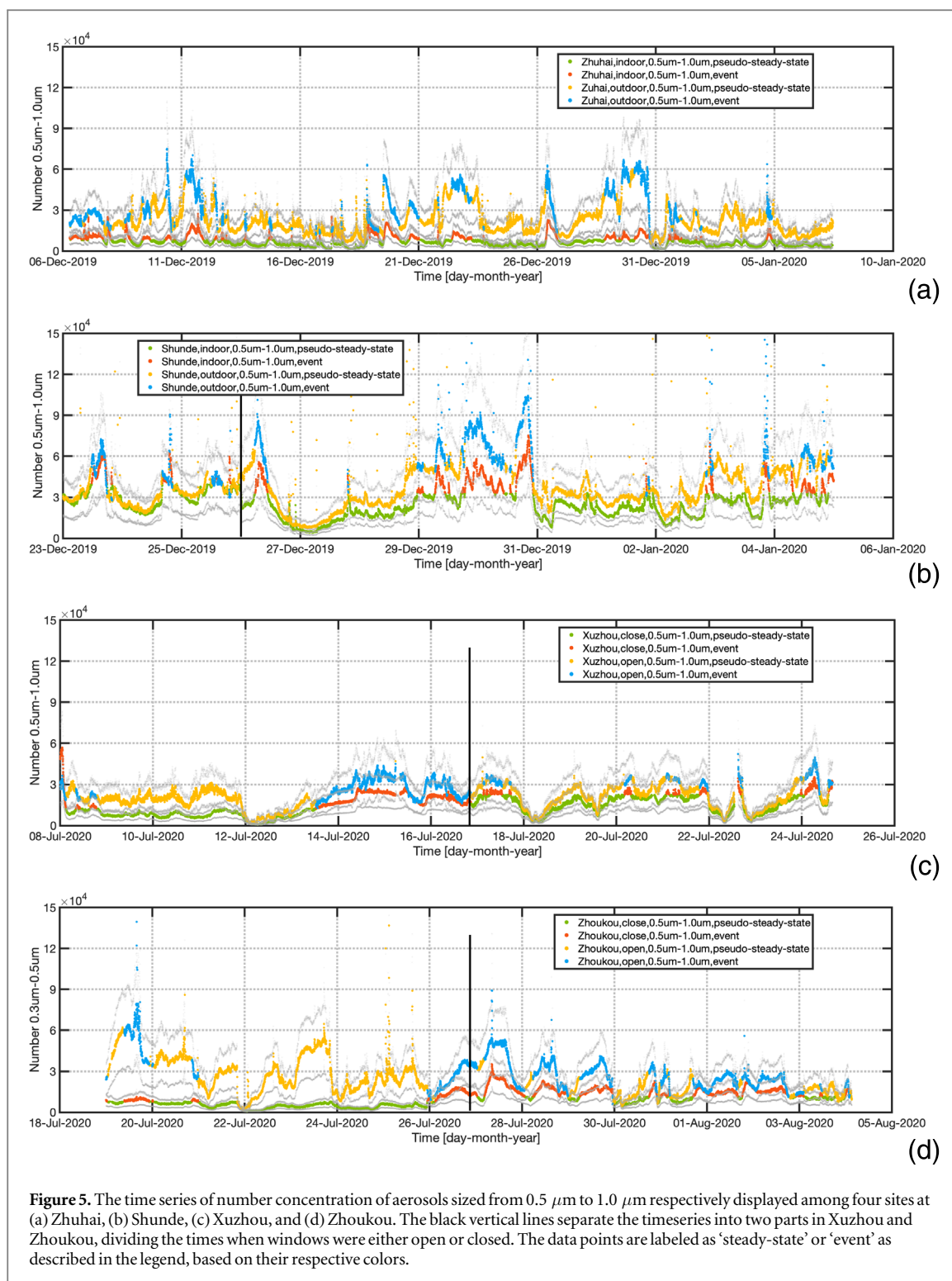


Figure 4. The time series of number concentration of aerosols sized from 0.3 μm to 0.5 μm respectively displayed among four sites at (a) Zuhai, (b) Shunde, (c) Xuzhou, and (d) Zhoukou. The black vertical lines separate the timeseries into two parts in Xuzhou and Zhoukou, dividing the times when windows were either open or closed. The data points are labeled as ‘steady-state’ or ‘event’ as described in the legend, based on their respective colors.

the respective average outdoor air concentration loadings. This site has the largest amount of variability in terms of the effective bulk removal of aerosols from indoor air due to the fan filter. This is in part due to the fact that the local sources on campus are very few, but the medium-distance transported aerosols from the surrounding industry and high-density residential sources are both significant and variable. Furthermore, this site has the most variable meteorology of all of the sites.

The mean and (standard deviation) over the entire dataset in Zhoukou (figure 4(d) and figure 5(d)) are $9.5 \times 10^4 (1.8 \times 10^4) \#/\text{cm}^3$, $2.9 \times 10^4 (5.5 \times 10^3) \#/\text{cm}^3$ and $13(7) \mu\text{g}/\text{cm}^3$ respectively for the indoor number concentration of 0.3 μm to 0.5 μm, 0.5 μm to 1.0 μm and PM₁. Similarly for outside data the mean and (standard deviation) are $2.5 \times 10^5 (4.5 \times 10^4) \#/\text{cm}^3$, $7.6 \times 10^4 (1.3 \times 10^4) \#/\text{cm}^3$ and $41(22) \mu\text{g}/\text{cm}^3$



respectively, as above. In all cases, the average indoor air concentrations are found to be 38.7% to 32.2% that of the respective average outdoor air concentration loadings. This site is found to have the second-best bulk concentration removal of all of the sites studied, but as will be demonstrated later has the best RE (removal only under pseudo-steady-state, i.e., excluding extreme events). This is due to the fact that there are some very strong local sources that occur locally to the site, but are random in nature (such as barbeque and incense burning), coupled with a relatively stable and dry meteorology and very few moderate to long range transported sources.

3.2. Removal efficiency under pseudo-equilibrium conditions

To aid in analysis the computed 2-minute RE is fit at each site, under each set of test conditions (windows open, windows closed, filter on and filter off) a lognormal distribution is fitted to the data, with the best-fit parameters

Table 1. Parameters (actual mean e^μ ; and variance σ) of best-fit lognormal distributions of the PDF of the RE distribution, as a function of site, filter and window status.

Name	States	Item	PM _{0.3–0.5}	PM _{0.5–1.0}
Zhuhai	Filter on	e^μ	0.276	0.270
		σ	0.382	0.377
Shunde	Filter off	e^μ	0.941	0.923
		σ	0.153	0.153
	Filter on	e^μ	0.627	0.615
		σ	0.217	0.215
Xuzhou	Windows close + filter on	e^μ	0.502	0.540
		σ	0.381	0.374
	Windows open + filter on	e^μ	0.701	0.736
		σ	0.136	0.130
Zhoukou	Windows close + filter on	e^μ	0.182	0.183
		σ	0.484	0.472
	Windows open + filter on	e^μ	0.623	0.618
		σ	0.296	0.295

and uncertainty ranges given in table 1. First, there is relative consistency of the 3 different measurements as fitted at each respective location. The median value is computed to be the lowest in Zhoukou with the windows closed and filter on (0.15–0.18 and 0.47–0.60) although the spread in the data is the largest of all of the cases analyzed. The second lowest median is observed in Zhuhai (0.23–0.28 and 0.38–0.45). The next two lowest median values are found in Xuzhou with the windows closed and filter on (0.49–0.54 and 0.38–0.50) and Shunde with the filter on (0.59–0.62 and 0.22–0.23), with the windows closed case having the third largest spread of all cases, while the windows open case has the second lowest spread of all cases analyzed. The next case in terms of an increasing median value is in Zhoukou with the windows open and filter on (0.58–0.62 and 0.30–0.32), which is unique among the sites with windows open in that it is the only one which has a relatively larger spread, most likely due to the large temporal variation of outdoor concentrations. The second least effective case in terms of median value is in Xuzhou with the windows opened and filter on (0.72–0.74 and 0.13–0.15), which does show a significant drop in median as compared to Shunde with filter off, which has the worst median case in this work (0.91–0.95 and 0.15–0.16).

The results show Zhoukou has the highest rate of filter efficiency (both a much lower RE and higher variability of RE) among these four sites. This is consistent given that at low RE, small perturbations associated with small scale turbulence, opening of a window or door, etc could lead to a temporally short but significant change in the RE value at the 5-to-15-minute time scale. At the other end, Shunde in general has the lowest filter efficiency (much higher RE, and much lower variability of RE), consistent with the fact that the building is highly porous and therefore effectively controlled mostly by outside concentrations. The major differences observed first have to do with the flow rate of air from the inside to (from) the outside, with well-sealed buildings (like Zhuhai) and windows closed conditions in Xuzhou and Zhoukou leading to a lower RE. Secondly, the smaller the room size, the lower the RE, as observed between the two smaller indoor sites (Zhoukou and Xuzhou) on one hand, the large Zhuhai and even larger Shunde on the other hand. Thirdly, when the dominant sources of emissions are from the outside, larger spreads are observed with windows closed, while relatively smaller spreads are observed with windows open.

In all cases except for Zhoukou with the windows open and filter on, the particles from 0.5 μm to 1.0 μm are more efficiently removed than those in the range from 0.3 μm to 0.5 μm . This relative reduction rate is true, even though the particles in the band from 0.5 μm to 1.0 μm are smaller than those in the range from 0.3 μm to 0.5 μm , with the relative number concentrations in the even larger particle sizes likely far smaller still. This finding is important in the practical world, since current standards analyze filter removal efficiencies based on PM_{2.5}, PM₁₀, and other mass-based values, which bias towards a small reduction in larger particles, whereas the findings in this work indicate that using a number concentration reduction perspective would instead lead to a more consistent and accurate result following Seinfeld 2003. The findings in this work support the idea that emphasis should shift more to quantifying reductions in terms of the number concentrations of smaller particles, even if the overall change in PM_{2.5} or PM₁₀ is not so obvious.

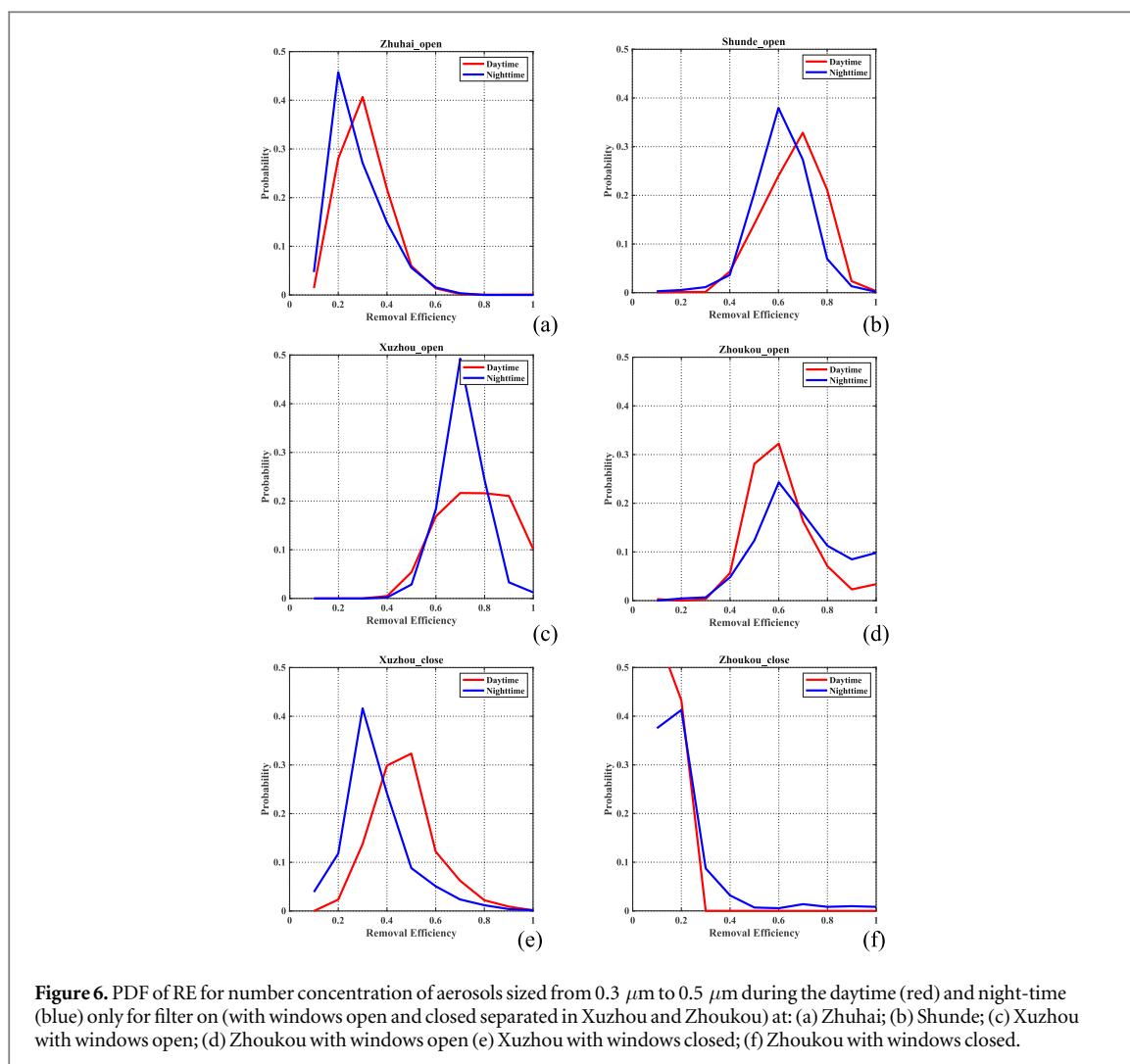


Figure 6. PDF of RE for number concentration of aerosols sized from $0.3 \mu\text{m}$ to $0.5 \mu\text{m}$ during the daytime (red) and night-time (blue) only for filter on (with windows open and closed separated in Xuzhou and Zhoukou) at: (a) Zhuhai; (b) Shunde; (c) Xuzhou with windows open; (d) Zhoukou with windows open (e) Xuzhou with windows closed; (f) Zhoukou with windows closed.

This finding is further demonstrated by the fact that both the mean and the variability of the RE is higher for bigger particles than smaller species. In the case of Zhuhai, this source is likely to be from shipping emissions from the thousands of large ships daily which ply to and from the ports in Hong Kong, Shenzhen, and Guangzhou, and which have their emissions randomly advected towards Zhuhai when the local wind direction blows from east to west.

To better analyze the range of uncertainty and characteristics of the RE distribution at each site under the vastly different boundary layer conditions occurring during daytime and nighttime respectively, all individual RE values are computed and displayed as PDFs in figure 6. In Zhuhai, Shunde, and Xuzhou, the RE is smaller (more efficient removal) at night time than in the day time. In these cases, the local environments tend to all have relatively stable emissions profiles during the night time (shipping, trucks on the expressway, and random medium-range transport from powerplants and factories), all of which run relatively stable throughout the night, while also having more source emissions in the daytime due to construction, personal motor vehicles, and small industry. Furthermore, Shunde and Xuzhou both have a relatively stable night-time atmospheric condition, with more disturbance found during the daytime. In the case of Zhoukou, the opposite is observed, with the daytime RE smaller than the nighttime. This is consistent with the fact that the barbecue and other eating sources dominate at night, coupled with the major non-filter component of removal being dry deposition, which due to the stability of the boundary layer is less at night (since there was no wet deposition present at this site throughout the entire measurement period).

These results are consistent with three facts. First that, within a single environment, there is a similar set of conditions impacting the overall results. Second that this set of conditions is associated with the windows being open or closed (or other issues with porosity). Finally, that larger particles tend to be filtered more effectively than number concentrations from $0.3 \mu\text{m}$ to $0.5 \mu\text{m}$ (or smaller particles), except in Xuzhou and Zhoukou with windows open, in which the larger particles have a similar RE as the smaller particles, likely due to an external source of exclusively larger particles.

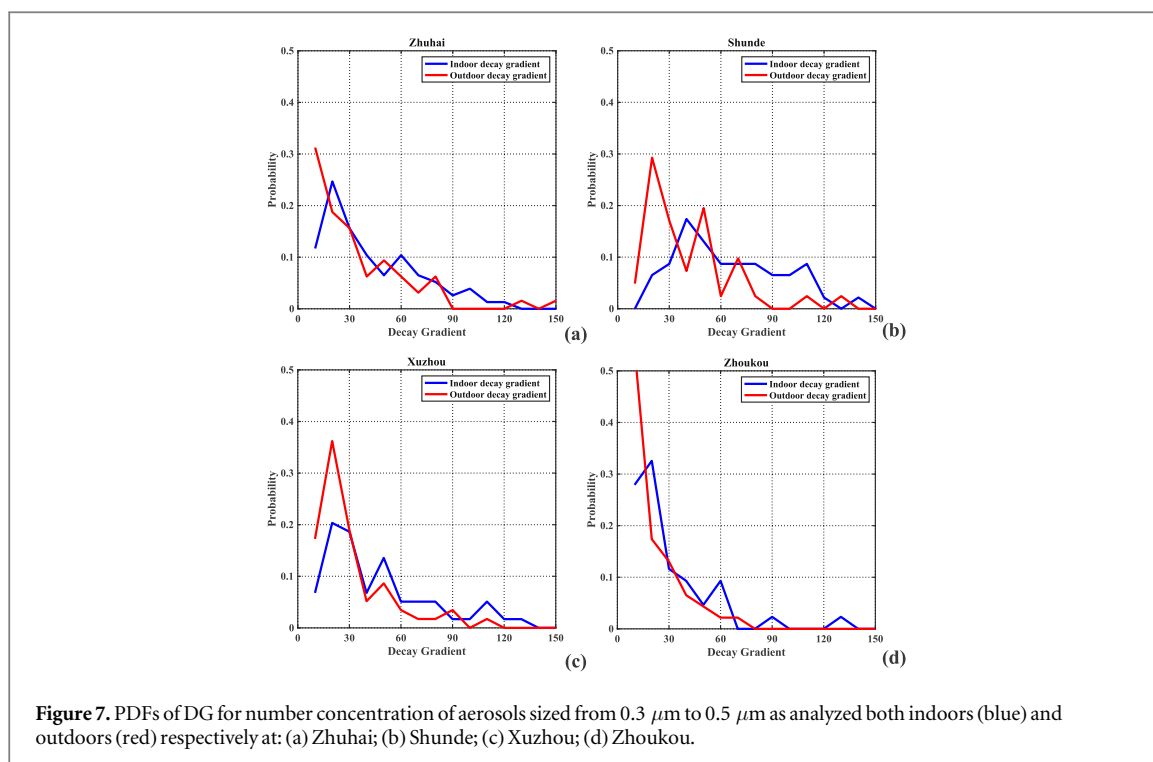


Figure 7. PDFs of DG for number concentration of aerosols sized from $0.3 \mu\text{m}$ to $0.5 \mu\text{m}$ as analyzed both indoors (blue) and outdoors (red) respectively at: (a) Zhuhai; (b) Shunde; (c) Xuzhou; (d) Zhoukou.

Table 2. Statistical analysis of the mean and standard deviation of decay time (min^{-1}) for number concentration of aerosols sized from $0.3 \mu\text{m}$ to $0.5 \mu\text{m}$ measured both indoors and outdoors, as a function of site, filter and window status.

Name	States	Indoor mean	Indoor STD	Outdoor mean	Outdoor STD
Zhuhai	Filter on	0.78	0.58	0.62	0.60
Shunde	Filter off	1.12	0.80	0.87	1.05
	Filter on	1.36	0.69	0.81	0.57
Xuzhou	Windows Close + Filter on	1.05	0.54	0.40	0.26
	Windows Open + Filter on	1.17	1.30	0.72	0.82
Zhoukou	Windows Close + Filter on	0.46	0.36	0.38	0.35
	Windows Open + Filter on	0.78	0.58	0.62	0.60

3.3. Decay gradient under pollution events

The value of DG at each individual site is computed both using the indoor and outdoor measurements. The indoor values are computed only when the fan-filter is running, but combine both window open and window closed conditions, to ensure a sufficient number of extreme events. The outdoor values are computed using the same events, although they may have slightly different peak times based on the transport time from (to) inside to (from) outside, with the results given in figure 7. Larger values of DG are consistent with conditions under which the indoor aerosol has undergone a larger total drop and/or a shorter time to return to pseudo-steady-state (or another obvious local minimum). In both cases, this is consistent with conditions under which the filter is either or both more effectively removing particles and/or doing so more rapidly than under non-filter conditions.

A PDF analysis of the decay rate demonstrates that the indoor DG is generally higher than outdoor DG, consistent with the magnitude of decay being larger indoors than outdoors due to the fan (table 2). In Zhuhai the indoor and outdoor DG have 10%, 50%, and 90% values of 10, 29, 76 and 5, 20, 64 respectively. In Shunde, the indoor and outdoor DG have 10%, 50%, and 90% values of 24, 55, 107 and 13, 29, 69 respectively. In Xuzhou, the indoor and outdoor DG have 10%, 50%, and 90% values of 13, 38, 111 and 9, 18, 65 respectively. In Zhoukou, the indoor and outdoor DG have 10%, 50%, and 90% values of 6, 15, 55 and 3, 8, 38 respectively.

These results are consistent with two facts. First, those locations with a higher level of pollution outside will have a larger DG due to the larger drop in magnitude. This is clearly observed in moderately polluted Xuzhou and Zhoukou both having increases in DG from 1.8 to 2.2 times in their central 30% to 70% of DG results. Second, those locations with a smaller room size will have a larger DG due to the faster time for the drop to occur, with the air mixing rate a function of the room size and porosity, since the same fan and filter have been used in all cases. This is also clearly observed in the larger room size of Zhuhai having a DG of about 1.5 as

Table 3. α_1 and α_2 of four sites under different experimental conditions of MC2BM for number concentration of aerosols sized from 0.3 μm to 0.5 μm and 0.5 μm to 1.0 μm , including the corresponding maximum and minimum respectively.

Name	States	Events	Item	PM _{0.3–0.5}	Min	Max	PM _{0.5–1.0}	Min	Max
Zhuhai	Filter on	Steady state	α_1	0.0040	0.0033	0.0046	0.0043	0.0036	0.0050
			α_2	0.028	0.025	0.031	0.033	0.030	0.037
	Event drop	α_1	0.0031	0.0006	0.0055	0.0043	0.0020	0.0065	
		α_2	0.045	0.036	0.031	0.048	0.040	0.037	
Shunde	Filter on	Steady state	α_1	0.0045	0.0006	0.0084	0.0075	0.0031	0.012
			α_2	0.011	0.0039	0.017	0.014	0.0073	0.022
		Event drop	α_1	0.032	0.015	0.049	0.022	0.0074	0.036
			α_2	0.057	0.028	0.087	0.065	0.037	0.093
	Filter off	Steady state	α_1	0.011	0.0094	0.013	0.012	0.010	0.014
			α_2	0.022	0.019	0.026	0.024	0.020	0.028
		Event drop	α_1	0.014	0.0096	0.019	0.012	0.0077	0.017
			α_2	0.036	0.025	0.047	0.037	0.026	0.048
Xuzhou	Windows Close+ Filter on	Steady state	α_1	0.0038	0.0019	0.0057	0.0048	0.0025	0.0071
			α_2	0.014	0.0087	0.019	0.017	0.011	0.022
		Event drop	α_1	0.014	0.0075	0.020	0.018	0.011	0.025
			α_2	0.032	0.025	0.038	0.039	0.033	0.045
	Windows Open+ Filter on	Steady state	α_1	0.036	0.030	0.043	0.043	0.036	0.049
			α_2	0.057	0.047	0.066	0.063	0.053	0.073
		Event drop	α_1	−0.017	−0.039	0.0041	−0.014	−0.039	0.012
			α_2	0.061	0.017	0.10	0.039	0.0	0.086
Zhoukou	Windows Close+ Filter on	Steady state	α_1	0.0026	0.0018	0.0033	0.0030	0.0021	0.0038
			α_2	0.025	0.019	0.031	0.029	0.022	0.06
		Event drop	α_1	−0.0026	−0.0042	−0.0010	−0.0016	−0.0032	0.0001
			α_2	0.018	0.0073	0.029	0.024	0.013	0.035
	Windows Open+ Filter on	Steady state	α_1	0.0073	0.0045	0.010	0.0081	0.0051	0.011
			α_2	0.043	0.032	0.054	0.049	0.036	0.061
		Event drop	α_1	0.0037	0.0004	0.0070	0.0043	0.0013	0.0073
			α_2	0.018	0.0095	0.026	0.022	0.014	0.030

compared with the smaller room sizes in Xuzhou and Zhoukou. Shunde has both the most heavily polluted outdoor air conditions and also the largest size, coming up with a similar end result to Xuzhou and Zhoukou.

3.4. MC2BM applied to indoor and outdoor measurements

In order to evaluate the impacts of indoor and outdoor forcings impacting aerosols including: dynamics, air exchange rate, and dry/wet deposition, filter use, etc, the MC2BM method is applied in this work, and the results are summarized in table 3. The best-fit values of α_1 and α_2 are computed independently for each of the four sites employed in this work under different experimental conditions (Filter on/off and Windows closed/open), and include a statistical measure of their corresponding uncertainty range. All of the indoor and outdoor measurements are divided into ‘steady state’ and ‘event drop’ conditions, whereafter α_1 and α_2 are calculated respectively. The main purpose is threefold: first, to quantify the indoor and outdoor air exchange rate, second, to accurately assess the factors affecting indoor air quality under all of these different scenarios, and third to clearly demonstrate the impact of the ventilation-powered indoor air filter. A larger α_1 value in the steady state implies faster air exchange, which will result in slower removal of aerosols (through deposition, sedimentation, or transport, etc) without the use of filters. Similarly, a large value of α_1 implies that outdoor source of pollution may contribute more significantly to the indoor environment.

The statistical results show that, on one hand whether in steady state or event drop conditions, the loss rate is always much larger than the outdoor to indoor flow rate, and on other hand when the filters are on, the loss rate is always much larger than when the filters are off. In all of the follow cases, the numbers represent a change between steady state conditions (first set) and event drop (second set) conditions. In Zhuhai, where the filter is on and the windows are closed, the values of α_1 and α_2 increase from 0.0040 and 0.028 to 0.0031 and 0.045 respectively. In Shunde, when the filters are on, the values of α_1 and α_2 increase from 0.011 and 0.022 to 0.014 and 0.036 respectively. In both of these cases, the behavior is similar: extreme events have a contribution both from outside as well as inside (hence why the value of α_1 increases), while the filter removal efficiency also increases in total (hence why the value of α_2 increases). In Xuzhou, under windows closed and filters on condition, the value of α_1 decreases from 0.036 to −0.017, while the value of α_2 increases from 0.057 to 0.061. In this case, the behavior of extreme events shows that the extreme source occurred indoors and was sufficiently strong as to overcome the filtration and transport to some extent to the outdoor environment (hence why the

value of α_1 is negative), while at the same time the filter removal efficiency also increases in total (hence why the value of α_2 increases). In Zhoukou, under windows open and filters on condition, the value of α_1 decreases from 0.0073 to 0.0037, while α_2 is decreases from 0.043 to 0.018. In this case, the behavior of extreme events shows that there is a decreased percentage of source from the outside transported to the inside, although there still is some outdoor source (hence why the value of α_1 decreases, but still is positive), while at the same time there is an overall decrease in efficiency of the removal, likely due to a change in the stickiness and/or size of the indoor portion of the extreme source (hence why the value of α_2 decreases, although it still is definitively removing particles).

In general, with filters and windows open, the infiltration of pollution will increase, which is consistent with the filter not only filtering indoor air pollution, but also partially filtering outdoor air pollution. We also noticed that during event drop times with the filter on, that there is increased flow from the outside when windows are open (Zhoukou), which means that some amount of the indoor air pollution high events is clearly contributed from outside sources. In some cases, the indoor filtration efficiency improves under these cases, meaning that the mixture of indoor and outdoor pollution is more effectively removed. In other cases, the indoor filtration efficiency decreases meaning that the mixture of indoor and outdoor pollution are less effectively removed than the indoor pollution or outdoor pollution alone. In other cases, the indoor air pollution events are solely due to indoor sources (Xuzhou and Zhoukou under event drop conditions), although in the case of Xuzhou this results in the highest observed rate of filter efficiency, while in Zhoukou this results in the lowest observed rate of filtration. This implies that the difference between the composition of the indoor air pollution and outdoor air pollution properties is extremely important variable to consider. Compared with Zhuhai and Shunde, Xuzhou and Zhoukou have worse outdoor air quality in general (i.e., during steady-state conditions), which is often affected by outdoor traffic (Both Xuzhou and Zhoukou), smoking occurring just outside of buildings (Xuzhou), and barbecues (Zhoukou) etc The results show that when the filter is in use, it is able to mitigate both indoor and outdoor air pollution that has intruded indoors effectively, through a combination of reducing the residence time of peak events including both externally transported and indoor sources. It also reduces the indoor air pollution levels by continuing to suppress the indoor air pollution during the steady-state times, which prevents the formation of new peak events from occurring under low-emissions event conditions.

4. Conclusions

The combination of measurements of aerosol number concentration over two size ranges, the newly computed metrics of RE and DG, and the 2-box mass conserving modeling are capable of quantifying the effects of new-materials on household ventilation fans to reduce indoor air pollution in common household environments. The median lognormally fit removal efficiency from 0.3 μm to 0.5 μm is 28%, 63%, 50%, and 18% respectively for Zhuhai, Shunde, Xuzhou, and Zhoukou. The rates of reduction quantified using the box model demonstrate that the removal rates can effectively completely suppress extreme events indoors as well as some amount of pollution outdoors nearby. It is also demonstrated that under polluted indoor conditions, the filter reduces the amount of time it takes to return to steady-state as well as to suppress extreme events.

The model results are dependent on both the indoor and outdoor aerosol concentration, the state of indoor/outdoor mixing, the removal of the room, the removal from the fan filter, and the duration of extreme events themselves. Additional factors are observed to also be important, including: geographic area, background conditions, local climate, the leakiness of the indoor environment, and short term variations of high concentration events. These results demonstrate a that physically relevant measures of indoor air pollution reduction require analysis over magnitude and time, specifically requiring that the rate of removal be larger than the accumulation in order to be effective. A very high removal efficiency which is slow may not work as well as a lower removal efficiency which responds quickly.

The DG introduced in this work was found to be 0.61, 1.15, 0.81, and 0.32 inside and slower but still positive outside respectively in Zhuhai, Shunde, Xuzhou, and Zhoukou, which is consistent with the idea that more heavily polluted cities and smaller sized rooms will have a higher DG. It also demonstrated that with the fan filter in use, extreme events are reduced faster and/or more significantly in the indoor environment, but also to some extent also observed in the outdoor environment. This is a clear indication that the fan filter works better than merely opening windows and increasing ventilation.

Finally, the results support multiple practical applications and findings. First, the highest aerosol removal rates and greatest indoor air quality gains in terms of both removal efficiency under pseudo-steady-state and decay gradient under pollution event conditions happens when there are one or both of higher indoor air flow rates and a reduction in the air exchange between the inside and outside air. This is only not the case when there is a strong spike in indoor emissions at the same time that the outside has relatively clean conditions such as during precipitation events. Second, deeper analysis of the flow of pollutants from outdoors to indoors (or visa-

versa) should be considered more deeply by future studies. Increased indoor/outdoor air exchange leads to less efficient removal by the filter material due to changes in the indoor turbulence as well as gradient flow. Third, the fan filters used herein are able to reduce peak events more rapidly as compared to not using the fan filter, indicating that even when it is on average clean, that the overall exposure time to infrequent but large events can still be effectively mitigated.

Based on these results, future studies are urged to more carefully consider a few things. First, adapting, using, and improving upon the analytic approaches introduced herein will provide new insights for indoor air quality improvement in real-world conditions. Second, including an increased focus on aerosol conditions under high temporal resolution, including both background conditions as well as air pollution events will allow for deeper understanding of the effectiveness of mitigation efforts. This can be expanded by looking at aerosols over different size ranges in more detail. In specific, quantifying ways to account for short duration but intense aerosol events and the length of time that these extreme events occur before they return to steady-state both are practical and important areas to consider for further studies.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://doi.org/10.6084/m9.figshare.17111021.v2>.

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