Covid-19 impact on air quality in megacities

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Air pollution is among the highest contributors to mortality worldwide, especially in urban areas. During spring 2020, many countries enacted social distancing measures in order to slow down the ongoing Covid-19 pandemic. A particularly drastic measure, the "lockdown", urged people to stay at home and thereby prevent new Covid-19 infections. In turn, it also reduced traffic and industrial activities. But how much did these lockdown measures improve air quality in large cities, and are there differences in how air quality was affected? Here, we analyse data from two megacities: London as an example for Europe and Delhi as an example for Asia. We consider data during and before the lockdown and compare these to a similar time period from 2019. Overall, we find a reduction in almost all air pollutants with intriguing differences between the two cities. In London, despite smaller average concentrations, we still observe high-pollutant states and an increased tendency towards extreme events (a higher kurtosis during lockdown). For Delhi, we observe a much stronger decrease of pollution concentrations, including high pollution states. These results could help to design rules to improve long-term air quality in megacities.
INTRODUCTION

Cities around the world are facing numerous environmental challenges. Air pollution in cities is among the most pressing topics. Air of persistently low quality that citizens are forced to breathe has a detrimental impact on their health and wellbeing. One third of deaths from stroke, lung cancer and heart disease are due to air pollution [1]. Overall, air pollution is linked to various diseases, like lower respiratory infections, strokes, cancers, asthma attacks, coughs, and chronic obstructive pulmonary diseases [2 4]. As per the State of Global Air 2019 [5], long-term exposure to outdoor and indoor air pollution contributed to nearly 5 million deaths in 2017. Out of these, 3 million deaths are directly attributed to particulate matter of 2.5 microns or smaller (PM2.5). Furthermore, high pollutant concentrations also damage the environment [6 8]. There are many sources contributing to air pollution, including emissions from vehicles, industrial emissions, combustion of biomass, solid waste, and fossil fuels (coal, diesel, and gasoline), construction activities, resuspension of road dust, domestic sectors and small manufacturing industries – all contribute towards the deteriorating air quality in cities [2 9].

The COVID-19 pandemic has lead to increased social distancing and more working hours spent at home. Many countries have initiated a "lockdown", asking or forcing citizens to stay at home, some factories have stopped production as their workers could not keep proper distancing. For example in the UK, on 19 March 2020, the government imposed a lockdown banning all "non-essential" travel and contact with people outside one's home (including family and partners), and shutting down almost all schools, businesses, venues, facilities, amenities and places of worship. Those with symptoms, and their households, were told to self-isolate, while the most vulnerable (the over 70s and those with certain illnesses) were told to shield themselves. Road traffic was significantly reduced, plummeting by 73% to levels not seen since 1955 [10]. Some lockdown restrictions in the UK were gradually eased in May and June. In India, the strongest lockdown measures were imposed from 24 March to 14 April 2020. These were then gradually eased afterwards in various stages. The reduced load of commuters and thereby overall reduction in traffic flow, as well as the reduction of industrial activity during lockdown is expected to improve the air quality, especially in cities. But how much, and in which specific ways, did the lockdown improve air quality and how were different cities affected?

Continued urbanisation leads to an increasing population in cities and the formation and growth of new megacities. Due to their high population density, these centers face particular challenges when it comes to air pollution [11 12]. Here, we focus on an analysis of air quality in two megacities, namely London and Delhi, and use them as representatives for two major classes of megacities. London as an example of an established Western megacity and Delhi as an Asian megacity in an emerging region. The comparison between the two cities will yield important insight on how air quality differs in general between the two locations but also how it can be improved by regulatory means.

Within this paper, we first give an overview of the air quality in both London and Delhi. Next, we compare measurements from the lockdown period in March to April 2020 with measurements from March to April of the previous year 2019. In particular, we analyse individual trajectories, probability distributions but also higher statistical moments. Then, we continue with a discussion of which sources cause which type of air pollution and how adequate guidelines could improve air quality in cities, especially after the current pandemic stops. We conclude that air quality is much easier improved in emerging regions by taking regulatory actions, while Western cities can still profit from reduced traffic and should also investigate residential and background pollution.

AIR QUALITY IN MEGA CITIES IN CONTRASTING ENVIRONMENTS

Air pollution is having adverse effects on everyone who lives and works in megacities, such as London or Delhi. Particularly affected are vulnerable groups, like children, elderly people and those with heart and respiratory conditions. People living in deprived areas are also more affected by poor air quality, because often these areas are near busy roads or near industrial areas.

Many different pollutants contribute to low air quality, including sulphur dioxide (SO2), nitrogen dioxide (NO2), nitrogen oxides (NOx), particulate matter (PM10 and PM2.5), lead, benzene, carbon monoxide (CO), benzo(a)pyrene, ozone (O3). Most megacities developed regulations to define thresholds and improve air quality. For example, the UK Air Quality Standards Regulations 2010 sets standards for major pollutants. Similar classifications were developed by the Central Pollution Control Board (CPCB) in India.

The two megacities we study here in detail have very different properties when it comes to climate and pollution. In terms of climate, London has a temperate oceanic climate, whereas Delhi features a dry-winter humid subtropical climate. Like in other megacities, pollution levels in Delhi city are very high and it is identified as being among the world’s most polluted regions [1]. During the winter months, PM concentrations were observed 5 times higher than the annual averages, due to stable meteorological conditions [13]. High PM pollution levels in the city cause six million
asthma cases and 7,350–16,200 premature deaths annually [14]. In contrast, air quality in London has improved in recent years as a result of policies to reduce emissions, primarily from road transport, such as Low and Ultra Low Emission Zones. Further information on air quality in Delhi and London is provided in Supplementary Note 1.

The COVID-19 lockdown has shown a significant reduction in air pollution levels across many countries. For example, air quality in Delhi-NCR and the Indo-Gangetic plain have been reported to be significantly better than before. The current situation is a unique opportunity to understand the baseline emissions both in Delhi and London environment under lockdown conditions in contrasting areas of the cities (suburban, traffic, and urban). In contrast to previous studies on air pollution during Covid-19 lockdown, such as [15–17], we investigate the detailed probability distributions of different pollutants, analysing various locations within the cities. Also, we analyse higher statistical moments and compare two very different megacities in detail.

DATA OVERVIEW

To quantify the impact of the lockdown, we compare the “Covid-19-lockdown” in 2020 with the “business-as-usual” scenario from 2019. Hence, we select dates from mid March to April that will cover the strictest lockdown states in each city. Furthermore, we utilize data from 2019 as a reference. This allows us to better quantify how much pollutant concentrations have changed during the lockdown. The reason to compare the March-April values 2020 with the same period in 2019, instead of January to February 2020 is that there is a clear seasonal dependence in air quality, e.g due to the efficiency of catalysts depending on ambient temperature [18]. In both megacities, we use ten randomly chosen locations to reduce bias in sampling site selection for assessing the air pollutants data.

For London, we utilize open data available from the London air quality network [19]. From the available data, we select a total of ten locations for our analysis: three urban, suburban and road locations each and one industrial location (in the London data set very few industrial locations are available). The approximate locations are marked in Fig. 1. As lockdown period, we chose the dates from March 20 at 0:00 up to May 1 at 0:00. The UK closed off schools [20] on March 20 and went into a wider lockdown on 23 March. We also monitor a moving average of key quantities over the full period March 1 to May 1. We note that all 2020 measurements are marked as “provisional” by LondonAir and still need ratification.

For Delhi, we utilize data provided by the Delhi Pollution Control Committee. From the available data, we again select three urban, suburban and road locations each and one industrial location. The exact locations of monitoring stations are marked in Fig. 2. In Delhi, there were several lockdown stages: Lockdown1.0 started from March 24 to April 14. Lockdown 2.0 was from April 15 to May 3. Lockdown 3.0 started from May 4 to May 17. Here, we analyse the main lockdown period between March 24 and April 21.

To quantify the air quality, we monitor certain pollutant concentrations in both cities. In particular, we monitor nitrogen oxides ($NO$ and $NO_2$ denoted as $NO_x$, where no distinction is made during the recording) as well as small particles, i.e. particulate matter of size less than 2.5 and 10 micrometers ($PM_{2.5}$ and $PM_{10}$). Throughout this article, we will focus on $PM_{10}$ concentrations as well as $NO_x$ concentrations. Not only do $NO_x$ themselves have harmful
impact on health but they are also commonly used to indicate the presence of other pollutants [9]. In Supplementary Notes 2 and 3, we also present plots for PM2.5 and further analysis in which NO and NO2 are analysed individually for the London data set, instead of being aggregated into NOx.

TIME SERIES

To obtain an initial impression of the data, we plot the temporal evolution of the pollution time series for individual locations and pollutants. The pollutant concentrations display very large fluctuations but with a considerable drop in overall pollutant concentration after the lockdown was initiated around March 20, see Fig. 3. The trend of decreasing pollutants is also observable for other pollutants (see Supplementary Notes 2 and 3). From the time series plots, we can see that 2019 had similar trends and sometimes even higher pollutant concentrations than 2020 before the lockdown.

Specifically, for Delhi, we observe a reduction in all pollutant levels after 25th March 2020. During the lockdown, we can see some instances of an increase in pollutant concentrations in early to mid April. These may be due to the dust storms that occurred in Delhi during those days. This effect can be clearly seen on the PM10 trajectory.

For London, we notice a reduction of pollutants for the baseline NOx concentration (Fig. 3 a). Furthermore, pronounced peaks are visible in concentrations, both for NOx and for PM10. These peaks persist after the lockdown is enacted and we will return to their systematic analysis via kurtosis values later.

Before moving on to probability distributions and moments, we have to point out that Delhi has a much higher concentration of PM10 due to its sub-tropical climate and the high frequency of dust storms [13, 21, 22] but also the decrease due to the lockdown is much more impressive than in the overall less-polluted London.

PROBABILITY DISTRIBUTIONS

Next, we analyse how much the pollutant concentrations vary over the full lockdown period from mid March until end of April in 2020, compared to the reference year of 2019. To visualize how likely certain pollution concentrations are reached, we visualize the empirical probability density functions (PDF) for NOx (Fig. 4) and PM10 (Fig. 5) at an urban, a suburban and a road location.

Overall, the lockdown in 2020 led to lower pollutant concentrations. The PDFs in 2019 tend to be broader than in 2020, i.e. reaching higher pollution states more frequently. Consistently, the 2020 distributions have a much more
Figure 3. 2020 pollution trajectories display a substantial decrease during the lockdown in mid March. We plot the concentrations of NO\textsubscript{x} (left) and PM\textsubscript{10} (right) for Delhi (top row) and London (bottom row). We depict urban locations, namely Stanmore for London and Punjabi Bagh for Delhi.

pronounced peak at low concentration levels. As expected, the pollution levels at the suburban location are generally lower than at the two other sites.

We note that the London distributions are all very similar in their peak near 0 concentration with a following decay. In contrast, the Delhi data displays a maximum probability density at non-zero values, see e.g. the suburban measurement site. This might be explained by the different distributions observed when comparing NO and NO\textsubscript{2} [18]. In Supplementary Note 2, we further disentangle the impact of NO and NO\textsubscript{2} for London.

MOMENTS

We continue to analyse the data more systematically, using the first and (normalized) forth moments of the empirical distributions. In particular, we compute the mean concentration \( \mu = \frac{1}{N} \sum_{i=1}^{N} u_i \) and the kurtosis \( \kappa = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{u_i - \mu}{\sigma} \right)^4 \), where \( u_i \) is the pollutant concentration at step \( i \), \( \sigma \) is the standard deviation and \( N \) is the number of measurements available. The mean \( \mu \) reports the average pollution concentration and thereby provides a quantitative measure of whether pollutant concentrations did indeed drop systematically and by how much. The kurtosis on the other hand quantifies how many extreme events occur in the pollution concentration time series, i.e. how often high-pollution states are assumed. As a reference consider the following: A Gaussian distribution has a kurtosis of 3, while an exponential distribution has a kurtosis of 9. Such exponential distributions were shown to approximate NO concentrations within short time windows [13]. To exclude singular effects specific to one measurement site, we compute the moments for all ten measurement sites in both Delhi and London.

With the mean analysis, we quantify a clear trend: The mean of both NO\textsubscript{x} and PM\textsubscript{10} concentrations for all locations is lower in 2020 than it was in 2019. The observed drop in NO concentrations is quite substantial within some locations, such as R3 in London, recording a decrease from more than 70 \( \mu gm^{-3} \) down to merely 20 \( \mu gm^{-3} \). The relative changes in other measurement sites are also impressive: At the U1 site, the mean dropped from approximately 10 \( \mu gm^{-3} \) very close to 0. The same trend of decreasing mean values is also observed for particulate matter (PM\textsubscript{10} in this case). However, the observed concentrations did not drop as much as the NO\textsubscript{x} did. This is likely linked to background sources and non-human factors such as pollen or dust contributing substantially to PM\textsubscript{10} concentrations, see also section on attributing pollutants to sources.
Figure 4. Probability density functions (PDFs) of the NOx concentrations display lower pollution during lockdown. We compare the PDFs from the lockdown period in 2020 with the same time period from 2019. Top: Delhi. Bottom: London. Note the log-scale of the y-axis.

In contrast to the mean, the kurtosis in 2020 often exceeds the values recorded in 2019 substantially. This observation is valid for both NOx and PM10 and might be explained as follows: While on average the pollution levels were reduced, we still observe the similar maximum pollution states. These extreme pollution states contribute to a much higher kurtosis in 2020 than in 2019, where large pollution concentrations were more likely. Hence the probability density as such has changed during the lockdown. Interestingly, the kurtosis and hence the tendency to observe (local) extreme
pollution states increased much more in London than in Delhi. Why this happens remains an open question.

WEATHER EFFECTS AND HIGH POLLUTION STATES

We have seen decreasing pollution concentrations in 2020 during the lockdown period but still very high kurtosis values, in particular for London. Here, we are answering two important questions: How much of the improved air quality could be attributed to weather effects, such as increased ventilation? Secondly, do high-pollution snapshots differ between 2020 and 2019?

Meteorology and ventilation

The ventilation coefficient (VC) indicates the dispersive ability of the atmosphere. It is directly proportional to the assimilative potential or carrying capacity of the atmosphere. High ventilation carries more pollutants away from the region and typically reduces overall pollutant concentrations in megacities. Details of how to compute the VC as a function of the Planetary Boundary Layer (PBL) are explained in the Methods.

We determine the average ventilation coefficient for Delhi during 2019 and 2020 as $VC_{\text{Delhi, 2019}} = 1451m^2/s$ and $VC_{\text{Delhi, 2020}} = 1461m^2/s$, respectively. Whereas for London it is determined as $VC_{\text{London, 2019}} = 1632m^2/s$ and $VC_{\text{London, 2020}} = 1808m^2/s$, see Fig. 8 for detailed trajectories. Even though Delhi lies in a sub-tropical region and has a higher PBL height, its VC is lower than that for London due to relatively lower wind speeds. The National Meteorological Centre, USA and Atmospheric Environment Services, Canada, defined criteria for ventilation coefficients. The criteria for high pollution potential are $VC < 6000m^2/s$ and mean wind speed $< 4m/s$. The dispersion potential is classified as low for $VC < 2000m^2/s$, medium for $2000m^2/s < VC < 6000m^2/s$ and high for $VC > 6000m^2/s$. Thus, both the cities show a low dispersion and hence high potential for pollution. Furthermore, the increased ventilation in London during 2020 has to be considered as small and cannot account for drastic changes.
Figure 7. Kurtosis of pollution levels rose during lockdown, particularly for London. We compare the kurtosis values from the lockdown period in 2020 with the same time period from 2019. Locations are abbreviated as road (R), urban(U), suburban (SU) or industrial(I). Top: Delhi Bottom: London.

Figure 8. Ventilation coefficient trajectories for Delhi (a) and London (b).

in pollution levels. Further analysis of wind statistics is given in Supplementary Note 4.

High-pollution snapshots

In the previous subsection, we used the ventilation coefficient analysis to show that both London and Delhi have the potential to display high-pollution states. Here, we compare typical high-pollution states in 2019 and 2020 to better understand the effect of the lockdown.

We select data with a typical time window of length $T = 7$ days. Details of how such windows are selected based on superstatistical approaches [28, 29] can be found in [18]. We select a snapshot within the 2019 data so that the
Figure 9. High pollution snapshots of NO$_x$ show lower pollution levels during lockdown, particularly for Delhi. We compare the 7 day period with the highest NO$_x$ variance between 2019 and 2020 in Delhi (Top) and London (bottom) at the suburban measurement site. Note again the log-scale of the y-axis.

variance of this snapshot is maximal, i.e. we select a local high-pollution state and then repeat this selection for 2020. Analysing these two high-pollution snapshots in Fig. 9 we note that the data in 2020 can also reach high-pollution levels, almost as high as in 2019 (for London). However, these high pollution levels are less likely in 2020 than they were in 2019. PM2.5 high-pollution snapshots between 2019 and 2020 are almost identical, see Supplementary notes 2 and 3.

**ATRIBUTION OF POLLUTANTS EMISSION**

Let us discuss how the observed pollutant concentrations can be attributed to individual emitters, and how they changed during the lockdown.

Air pollution in London is a mixture of emissions created locally and those that come from outside the city. In the city, emissions are contributed from the activities of the 9.908 million population (population density of 5666 per sq.km). Past studies estimated that about 75 per cent of PM pollution and 18% of NO$_2$ in the city originated from outside the city itself, while road transport is considered one of the main contributors of NOx (50%) and PM10 (53%) pollution within the city. Contributing to road transport are the 3.98 million licensed motorized vehicles, which are mainly cars (3.2 million) [30]. Therefore, to achieve clean air in London both local and national policies are required [31] to reduce emission from within and from outside the city.

In Delhi, air pollution arises from a variety of local and regional emission sources. The city has a total population of 16.349 million with a population density of 11312 per sq.km, much higher than for London. The number of licensed vehicles in the city is 10.9 million, this time with a dominant share of two wheelers (7.07 million) [32]. Past studies estimated that about 23% of the PM pollution and 36% of the NO$_x$ emission in the city are contributed from the road transport sector. About 52% of NO$_x$ emissions is attributed to industrial sources [33].

The transport sector is one of the most relevant anthropogenic sources which cause air pollution in Delhi city. The
continuous growing fleet of heterogeneous traffic in the city has resulted in heavy traffic congestion as well as decrease in vehicle speed on roads, leading to an increase in emission from vehicles. While in Delhi the air quality situation has become worse over recent years, in London it has become better. A Low Emission Zone was introduced for London in 2008, and restrictions on polluting traffic have become more stringent since then, with hefty fees discouraging the use of cars in the inner city, in particular old Diesel cars. The impact of the Ultra Low Emission Zone, which was introduced in April 2019, is expected to be significant [34]. It should lead to significant reduction in the number of people living in areas of poor air quality (where levels of NO2 may exceed legal limits) – by 72 per cent in central London and 54 per cent London wide. There have also been average reductions in NO2 levels at roadside sites of more than 12 per cent (with weather effects removed) [34, 35].

Let us interpret these observations and sketch guidelines how air quality could be improved both in Western and Eastern cities alike. For Delhi, the drastic reduction in pollutant concentrations is easily attributed to a substantial reduction in vehicular and industrial activities. Not only did cars and industry emit fewer pollutants but also less dust was raised [36]. Hence, for the future, road traffic regulations and dust distribution should be monitored. For London, traffic and industrial activities in London and its surrounding decreased during the lockdown. Hence, also pollutant concentrations dropped but the new mean distributions in NO\textsubscript{x} for example were higher than the lockdown NO\textsubscript{x} concentrations observed in Delhi. With road and industrial activities contributing less, it leaves the residential areas, the geographical surroundings and background sources [15]. All of these should be monitored more thoroughly and regulations should be considered to improve air quality in the long term.

**SUMMARY AND CONCLUSIONS**

Summarizing, we have compared the impact of Covid-19 induced lockdown measures on the air quality in two major cities: Delhi as an example for an Asian city in an emerging country and London as an example of a Western city, well developed but with a complicated Brexit-induced future. Mean pollution values tend to drop due to lockdown across all pollutants and for almost all investigated measurement sites. This holds for both London and Delhi. However, we also noted certain significant differences: While pollutant concentrations dropped both in London and Delhi, the reduction of NO\textsubscript{x} and PM10 was much stronger in Delhi than in London. A specific observation for London is the change of the probability distributions, manifesting itself as an increase of kurtosis during lockdown. This is explained by the fact that temporary high-pollution states during and before the lockdown are not qualitatively different in London, but persist. Contrary, not only did the mean drop but also the extremely polluted states are much rarer in Delhi during lockdown than before.

Contrary to an earlier analysis for the London data [15], we did not observe a statistically significant increase in particulate matter (PM) concentrations during lockdown. In Delhi, there was a very substantial drop in PM concentrations. Note that we compared the spring 2020 season with the spring 2019 season, while [15] compared it to the Winter 2020. Hence, the increase in PM concentrations reported in [15] might be a seasonal effect. Another study comparing the effect of the lockdown on different cities uses data based on daily air quality indices [37]. This is different from our study, where we make use of higher-resolved time series and also study higher moments systematically, such as the kurtosis.

The comparison between Delhi and London during the lockdown provides insightful lessons on air quality control: A very strict lockdown in London did improve the air quality significantly, in particularly in terms of NO\textsubscript{x}, highlighting the effectiveness of e.g. decreasing the traffic of vehicles with combustion engines. Simultaneously, it also shows that a very drastic improvement by regulating traffic or industry alone will not suffice but pollution caused by other causes, such as residential or background, has to be taken into account as well.

The picture for Delhi is quite different: Without a lockdown, the pollutant concentrations are regularly 3 to 5 times as high as in London, indicating a much worse air quality in general. The lockdown in Delhi improved air quality very drastically. This points to the great potential of clean air in Delhi if traffic and industrial emissions were reduced in the future by suitable control or regulation mechanisms.

There still remain many open questions, such as: How did a lockdown affect other cities, e.g. on the American continent or in Africa? Which residential effects in Western cities and which traffic effects in Eastern cities can further be reduced to guarantee a long-term improvement in air quality? The lockdown was at an enormous economic cost, but can a small change in behaviour or a well-designed and balanced control mechanism lead to a sustainable and significant improvement in air quality in the future?
METHODS

Selected locations

In the aggregated moments, we introduced several road (R), urban (U) and suburban (SU) locations, here we give the key to these abbreviations:

For London we abbreviate: R1: Blackwall, R2: Thurrock, R3: Euston Road, U1: Sir John Cass School, U2: Stanmore, U3: Honor Oak Park, SU1: Eltham, SU2: Slade Green, SU3: Keats Way, I1: Beddington Lane.

For Delhi we abbreviate: R1: JLN Stadium, R2: Mandir Marg, R3: Sri Aurbindo Marg, U1: Nehru Nagar, U2: Punjabi Bagh, U3: Rohini Sector 16, SU1: Alipur, SU2: Mundka, SU3: Najafgarh, I1: Anand Vihar.

When plotting individual locations, we use the "1" index, i.e. R1, U1 and SU1 if not specified differently.

Ventilation coefficient

Technically, the VC is given as a function of the height of Planetary Boundary Layer (PBL) and wind speed, namely

\[ VC = \text{PBL height} \times \text{Average Wind speed} \]

where we typically measure height in meters, wind speed in meters per second and hence the VC in \( m^2/s \).

To compare Delhi and London and 2019 with 2020, we obtained the approximate PBL height by using radiosonde data from the University of Wyoming [38] as follows. The PBL is the layer above the ground surface in which the pollutants are mixed and dispersed effectively. Right above the PBL is an inversion layer, which prevents the vertical movement of each air parcel. Here, we identify the PBL height as the lower boundary of this inversion layer, utilizing changes in potential temperature, relative humidity, moisture level, etc. The altitude corresponding to the maximum gradient of the potential temperature, mixing ratio and relative humidity profiles is taken as the PBL height similar to [39].

Data availability

All data that support the results presented in the figures of this study are available from the authors upon reasonable request. Furthermore, the London air pollution concentrations are available on the LondonAir webpage [19]. The Delhi air pollution concentrations were provided by the Delhi Pollution Control Committee (DPCC), New Delhi, but are unfortunately not publicly available.

Code availability

The code to reproduce figures, along with the publicly available LondonAir data is also uploaded here: [https://osf.io/jfw7n/?view_only=9b1d2320cf2c46a1ad890df079a2f6b](https://osf.io/jfw7n/?view_only=9b1d2320cf2c46a1ad890df079a2f6b)

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Author contributions

B.S., S.N., M.K. and C.B. conceived and designed the research. B.S., R.V., A.G. and H.H performed the data analysis and generated the figures. All authors contributed to discussing and interpreting the results and writing the manuscript.
**Competing interests**

The authors declare no competing interests.
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