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Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns

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The COVID-19 lockdowns led to major reductions in air pollutant emissions. Here, we quantitatively evaluate changes in ambient NO2, O3, and PM2.5 concentrations arising from these emission changes in 11 cities globally by applying a deweathering machine learning technique. Sudden decreases in deweathered NO2 concentrations and increases in O3 were observed in almost all cities. However, the decline in NO2 concentrations attributable to the lockdowns was not as large as expected, at reductions of 10 to 50%. Accordingly, O3 increased by 2 to 30% (except for London), the total gaseous oxidant (O3 = NO2 + O3) showed limited change, and PM2.5 concentrations decreased in most cities studied but increased in London and Paris. Our results demonstrate the need for a sophisticated analysis to quantify air quality impacts of interventions and indicate that true air quality improvements were notably more limited than some earlier reports or observational data suggested.

INTRODUCTION

Air pollution (both indoor and outdoor) is the single largest environmental risk to human health globally, contributing to 8.8 million deaths in 2015 (1). The World Bank estimated that air pollution costs the global economy $3 trillion in 2015 (2). It has been suggested that poor air quality is correlated with a higher mortality rate from COVID-19 infection (3). Although a causal relationship between the two is difficult to confirm, air pollution contributes to respiratory and cardiovascular diseases and thus has the potential to cause increased COVID-19 death rates (4).

In response to the COVID-19 crisis, governments around the world introduced severe restrictions on behavior or lockdowns, which led to the cessation of a large swathe of economic activity and thus reduced air pollutant emissions (5). The rapid and unprecedented reduction in the economic activity provides a unique opportunity to study the impact of a global-scale natural intervention on air pollution, which offers insights for the prioritization of future clean air actions.

Many recent studies have explored impacts of the COVID-19 lockdowns on air quality. The most common approach is to undertake a simple statistical analysis that compares air quality before and after the lockdowns began or during the lockdowns with the same periods in previous years (6, 7). Some studies also compared the air quality before and after lockdown started for periods with similar meteorological conditions (8). Satellite observations of NO2 have also been used to estimate the reduction in column NO2 due to the lockdowns (3, 9–11).

A major caveat in a number of these studies is that meteorology moderates the link between emissions and pollutant concentrations, and so, weather changes can mask the changes in emissions on air quality (12–14). Such methods cannot explain the observed severe pollution events during the lockdowns in some cities (15–17). Comparisons of pollutant levels in 2020 with previous years may assume that air pollutant emissions have not changed over the past few years, which is often not the case, particularly in those cities where clean air policy actions are in place (14, 18). Furthermore, air pollutant emissions change substantially from winter to spring; thus, a direct comparison of air pollutant concentrations before and during the lockdowns could also give unreliable results. Venter et al. (9) developed statistical models (regression) to estimate the impact of lockdowns on air quality in several countries. However, the performance of the regression was often limited with correlation coefficients as low as 0.2. He et al. (19) applied a “difference-in-difference” approach, which may provide a more accurate estimate of air quality improvement; this method assumes that the control cities are not subject to any impacts.

Air quality modeling can also decouple the effect of emission changes from meteorology (19, 20) and is often applied for scenario analysis. A major challenge in evaluating the impacts of short-term interventions on real-world air quality is to estimate emission changes (16, 20, 21).

Machine learning offers an alternative and reliable method in quantifying changes in air quality due to emissions and meteorological factors (12–14). Myllyvirta and Thieriot (22) used a random forest (RF) method (13), which was developed for assessing long-term air quality changes, to estimate the short-term changes in NO2 and PM10 in Europe due to the COVID-19 lockdowns (see Materials and Methods).

The purpose of this study was to evaluate the impacts and implications of the natural experiment of the COVID-19 lockdowns in spring 2020 on air quality. To do this, we optimized a weather normalization technique based on Grange and Carslaw (13) and Vu et al. (14) to decouple the effects of meteorology from short-term emission changes on surface air quality monitoring data in 11 global cities that were subjected to extensive lockdown measures. The deweathered data allow us to quantitatively evaluate the real-world changes in air quality due to the lockdown measures in these cities (see Materials and Methods). These selected cities cover a range of air pollution climates, from highly to less polluted and from PM2.5- to NO2-dominated...
pollution. Data were divided into roadside, urban background, and rural sites to better understand the impacts of road traffic and urban emissions on air quality changes.

RESULTS

We first estimated the percentage change ($P$) in the observed or deweathered concentrations of air pollutants using the following equation

$$P = \frac{C_i - \bar{C}}{\bar{C}} \times 100\%$$ (1)

where $C$ is the average concentration in the second and third weeks before the lockdown date or equivalent (as a prelockdown baseline), and $C_i$ is the average concentrations in the $i$th day (from the 1st to 28th day) starting in the second week after the lockdown start date for each city and for each year (see Fig. 1). For example

$$P_{2020} = \frac{C_{2020,2020} - C_{2020,2020}}{C_{2020,2020}} \times 100\%$$ (2)

The week immediately before and after the lockdown date was considered a transition period and so was excluded in the calculations. We recognize that the transition may have started earlier in some cities such as London, but for consistency, we applied the same Eq. 1 for calculation. For clarification, we will use $P_{\text{obs}}$ and $P_{\text{dew}}$ to represent changes in observed and deweathered concentrations, respectively.

We then estimated the detrended percentage change ($P^*$) in the concentration of each air pollutant (deweathered only; Fig. 1), calculated by

$$P^* = \frac{P_{2020} - P_{2016-2019}}{P_{2016-2019}} \times 100\%$$ (3)

where $P_{2020}$ and $P_{2016-2019}$ are percentage changes in deweathered concentrations of air pollutants in 2020 and 2016–2019, respectively. $P^*$ was calculated by Monte Carlo simulations ($n = 10,000$) based on the normal distribution of $P_{2020}$ and $P_{2016-2019}$.

$P^*$ removes the “business-as-usual” variability in concentrations from winter to spring (i.e., 2016–2019 as a baseline, $P_{2016-2019}$) and thus represents the change attributable to lockdown measures. This business-as-usual variability can be caused by changes in anthropogenic activities (e.g., domestic heating) and natural processes [e.g., biogenic volatile organic compound (VOC) emissions]. For example, when the domestic heating demand reduces in local spring, there may be less local emissions of air pollutants; as a result, the concentrations of air pollutants are lower if emissions from other major sources do not increase and meteorological conditions are similar.

Changes in NO$_2$, O$_3$, and O$_x$

Observed NO$_2$ levels are highly variable, with daily concentrations changing notably during the study period (Fig. 2 and fig. S1). Pollution events (e.g., spikes in Fig. 2) appeared repeatedly during the lockdowns, such as in Beijing, Wuhan, and Paris. Observed NO$_2$ at roadside sites decreased substantially in all cities after the lockdowns began, with $P_{\text{obs}}$ ranging from $−29.3 ± 33.1\%$ in Berlin to $−53.5 ± 18.9\%$ in London (table S1); observed NO$_2$ at urban background sites also decreased substantially, with the $P_{\text{obs}}$ ranging from $−10.1 ± 36.6\%$ in London to $−60.2 ± 14.8\%$ in Delhi; and observed NO$_2$ at rural sites increased in London ($P_{\text{obs}} = +115.8 ± 90.2\%$) and Paris ($P_{\text{obs}} = +99.2 ± 66.7\%$) but decreased in other cities after lockdown started.

Deweathered NO$_2$ usually shows a similar pattern to the observations, but the magnitudes and sometimes even the signs of changes are different. A sudden drop, distinct from the data in 2018, is clearly observed at urban sites in 2020 after the lockdowns began in all cities except London and Los Angeles, which show a more gradual change (Fig. 2 and fig. S1). This confirms that the sudden changes in 2020 are indeed due to the lockdown measures.

Deweathered NO$_2$ at urban background sites in 2020 decreased in all cities after the lockdowns began, with $P_{\text{dew}}$ ranging from $−18.2 ± 6.0\%$ in London to $−52.9 ± 1.4\%$ in Delhi (Table 1); deweathered NO$_2$ at roadside sites decreased more markedly in most cities (Fig. 2, fig. S1, and table S2). We also noticed that deweathered NO$_2$ ($P_{\text{dew}}$) in 2016–2019 decreased in almost all cities from winter to spring, although the magnitude of change is usually much smaller than in 2020 (Fig. 3). Thus, the absolute values of the detrended NO$_2$ change, $P^*$, is smaller than the corresponding $P_{\text{dew}}$. Table 1 shows that the decline in NO$_2$ due to the lockdown measures at urban background sites is mostly less than 30% in the studied cites.

Deweathered NO and NO$_x$ (=NO + NO$_2$) in 2020 dropped more markedly (table S2) after the lockdown began than was observed for NO$_2$. For example, $P_{\text{dew}}$ values for NO and NO$_x$ at urban background sites in London were approximately $−24.8 ± 6.3\%$ and $−21.0 ± 5.9\%$, respectively, whereas that for NO$_2$ was $−18.2 ± 6.0\%$. At roadside sites in London and Rome, deweathered NO$_2$ decreased by more than 50% during the lockdowns, a much larger change than that for NO$_2$ ($−47.0\%$ in London and $−35.2\%$ in Rome).

In contrast to changes in NO$_2$, observed O$_3$ at roadside sites in 2020 increased in all cases (fig. S1 and table S1) after the lockdown began, with the $P_{\text{obs}}$ values ranging from $+19.5 ± 21.0\%$ in Madrid to $+155.6 ± 83.2\%$ in Milan. Observed O$_3$ at urban/rural sites also increased during the lockdowns (fig. S1). A sudden increase in
Fig. 2. Observed and deweathered daily NO2 and O3 concentrations in selected cities before and after the lockdown start dates or equivalent in 2020 versus 2018. Columns correspond to (A) NO2 at roadside sites, (B) NO2 at urban background sites, and (C) O3 at urban background sites; rows show different cities as indicated. Fine and heavy lines indicate observed and deweathered concentrations, respectively. Data are shown from December to May, shown as day of year (DOY; 1 January = 1), where the vertical dashed lines represent lockdown date. The sudden drop in deweathered NO2 and corresponding increase in deweathered O3 are apparent in Beijing, Wuhan, and Paris, whereas London and Los Angeles show more gradual changes. The saw-like shape in the deweathered data in some cities captures the weekly cycles of NO2 and, to a lesser extent, O3, particularly in western cities. Results from other cities/sites are shown in fig. S1. No data are available for roadside sites in Wuhan.

deweathered O3 after the lockdown began was observed in most of the cities (Fig. 1 and fig. S1). The $P_{dew}$ values (Table 1 and table S2) for deweathered O3 range from +15.0 ± 3.0% in Los Angeles to +128.5 ± 41.9% in Milan at roadside sites, from +14.8 ± 2.2% in Los Angeles to +66.8 ± 29.2% in Milan at urban background sites, and from +1.5 ± 0.9% in London to +57.9 ± 6.3% in Milan at rural sites. However, there is an increasing trend in O3 levels at urban background sites during the same periods in 2016–2019 (Fig. 2 and 3), with $P_{dew}$ values ranging from +12.1 ± 9.1% in New York to +51.2 ± 23.4% in Milan (auxiliary data table S1). As a result, the detrended O3 changes ($P^*$) at urban background sites are much smaller than those of the corresponding $P_{dew}$ values; there is an obvious increase in $P^*$ in Beijing, Wuhan, Milan, and Rome, but a small change or even a decrease in other cities (Table 1).

Accordingly, the observed levels of total gaseous oxidant (i.e., O$_x$ = NO$_2$ + O$_3$), a parameter unaffected by the titration reaction between NO and O$_3$ but representing net photochemical production of O$_3$, showed a different pattern to NO$_2$ and O$_3$, with little change before and during the lockdowns, whether at roadside, urban background, or rural sites (Fig. 4). Observed O$_x$ at urban background sites in 2020 range from 35.0 ± 5.4 parts per billion (ppb) in Madrid to 44.8 ± 8.5 ppb in Delhi during the 10-week period with lockdown start date in the middle. Deweathered O$_x$ mixing ratios at urban background sites were remarkably similar across the cities, at approximately 40 ppb (Fig. 4). Only a small change in deweathered O$_x$, before and after lockdown started in 2020, was observed at urban background sites in all the cities, with $P_{dew}$ values ranging from −4.6 ± 3.5% in Delhi to +10.5 ± 0.8% in Berlin (Table 1). Small changes were also seen during the same periods in 2016–2019, with $P_{dew}$ for deweathered O$_3$ ranging from −1.2 ± 7.1% in Beijing to +8.7 ± 1.7% in Berlin (Fig. 2 and auxiliary data table S1). Detrended O$_x$ at urban background sites generally decreased during the study period in most of the cities, but the absolute change is relatively small, i.e., mostly within ±5%; changes at rural sites are more variable with almost half of the cities showing a slight increase (table S3).

**Changes in PM$_2.5$ and PM$_10$**

Figure 5 and fig. S2 show that the average observed PM$_2.5$ levels in 2020 reduced after lockdown started in the two more polluted cities, Wuhan and Delhi. No clear changes were observed in other cities, particularly when comparing levels to those in previous years (Fig. 5 and fig. S2). In Beijing, Paris, and London, pollution events were observed after the lockdowns began (Fig. 5). Unlike NO$_2$, the peak levels observed during the lockdowns were sometimes even higher than those before lockdown began (e.g., London). The $P_{obs}$ values for observed PM$_2.5$ in 2020 range from −40.8 ± 28.4% in Los Angeles to −107.6 ± 148.5% in London at roadside sites, from −38.6 ± 17.2% in Madrid to +152.9 ± 165.0% in London at urban background sites, and from −34.2 ± 26.8% in Delhi to +164.5 ± 148.7% in London at rural sites (table S1).

Deweathered PM$_2.5$ in 2020 showed a clearer pattern than that apparent in the observations (Fig. 5). Unlike deweathered NO$_2$ and O$_3$, a sudden decrease in PM$_2.5$ after lockdowns started was not detected in most of the cities, with the exceptions of Wuhan and Rome (fig. S1). However, sudden decreases were observed in some cities (such as Los Angeles, New York, Beijing, and Wuhan) a few days after or before the lockdowns began. Figure 5 and fig. S2 show that the deweathered PM$_2.5$ before the lockdown began in 2020 was similar to that in 2018 in Beijing, lower in Wuhan, London, Paris, and Berlin, but higher in Rome and Delhi. In Beijing, there was an increase in deweathered PM$_2.5$ after the lockdown began initially, but there was a decrease afterward (Fig. 5). Deweathered PM$_2.5$ in London and Paris also increased after the lockdowns began, but in contrast, there was no obvious decrease even 3 weeks from the lockdown date.

The changes in deweathered PM$_2.5$ are similar at different site types (Fig. 5 and fig. S2). Deweathered PM$_2.5$ at roadside sites in 2020 increased slightly during the lockdowns by +1.0 ± 7.2% in London and +0.2 ± 9.1% (P$_{dew}$) in Paris but decreased with changes ($P_{dew}$) ranging from −2.8 ± 1.3% in New York to −37.8 ± 4.8% in Los Angeles (table S2). A similar trend is also observed in the deweathered PM$_2.5$ at urban background and rural sites (Fig. 5 and fig. S2). An obvious decrease in deweathered PM$_2.5$ at urban background sites during the same study periods was also observed in 2016–2019 in some cities but not in others (Fig. 3 and auxiliary data table S1). The detrended change ($P^*$; Table 1) in PM$_2.5$ at urban background sites shows a decrease in Los Angeles (−40.3 ± 26.9%), Madrid (−24.1 ± 18.4%), Wuhan (−15.7 ± 24.8%), New York (−13.9 ± 6.9%), and Delhi (−5.2 ± 4.8%), but little changes or even increases in the other cities.
The overall patterns of variations in observed and deweathered PM\textsubscript{10} (fig. S4) are similar to those of the PM\textsubscript{2.5} (fig. S3). A slight difference in some cities is that there were more variabilities/contrasting patterns at different types of site. For example, a larger decline in \(P_{\text{dew}}\) for deweathered PM\textsubscript{10} at roadside sites than that at urban background sites is observed in Beijing, Madrid, London, Paris, and Berlin (table S2), potentially reflecting a coarse particle source from road traffic (e.g., non–exhaust emissions) (23). Furthermore, in Los Angeles and Delhi, the decline in deweathered PM\textsubscript{10} is significantly larger than that of PM\textsubscript{2.5} whether at urban background or rural sites (table S2), implying a reduced contribution of coarse particles to PM\textsubscript{10}.

**Changes in CO and SO\textsubscript{2}**

Deweathered CO levels were lower after lockdown started than before in 2020. This pattern is different from that in 2018 (fig. S4). A sudden change is observed in Rome and Wuhan only. In Beijing, deweathered CO increased slightly after the lockdown began, before falling for about 2 weeks, after which there was a substantial increase at all three types of sites. Therefore, the deweathered CO decreased substantially, ~40% (\(P_{\text{dew}}\)) lower than that during the same period in 2018. In New York (roadside sites), a decline in deweathered CO is observed a week after the lockdown began. In Delhi, the decreasing trend in deweathered CO at urban background sites is not distinguishable from that in 2018, whereas at rural sites, CO clearly declined from a few days before the lockdown began.

The change in deweathered SO\textsubscript{2} after the lockdowns began is dependent on the site or city (fig. S4). No sudden change is observed in any of the cities immediately after the lockdowns. In Beijing, deweathered roadside and urban SO\textsubscript{2} increased initially and then decreased by ~20%. In all cases, the deweathered SO\textsubscript{2} concentration in 2020 is much lower than that in 2018. In London, deweathered SO\textsubscript{2} declined for a few days before the lockdown began at roadside sites. Deweathered SO\textsubscript{2} in Wuhan and Rome decreased about a month.
before the lockdowns but did not change during the lockdowns. In New York (roadside sites), a decline in deweathered SO$_2$ is observed a week after the lockdown began. Delhi saw a substantial decrease in deweathered CO about 2 weeks after the lockdown started, and the decrease in deweathered CO at urban background sites is not distinguishable from that in 2018, whereas at rural sites, it clearly declined from a few days before the lockdown began.

DISCUSSION

The deweathered and detrended data are used to understand how the air quality responded to the changes in activity associated with the COVID-19 lockdowns of early 2020 and the potential implications of such interventions for developing future air pollution abatement strategies and thus improving human health.

The importance of deweathering and detrending

Large differences between the deweathered and observed concentrations of air pollutants were observed in the studied cities (Fig. 2 and figs. S1 to S3). Observed daily average NO$_2$ concentrations are much higher than the deweathered ones during some periods. Our estimated NO$_2$ decline in Wuhan due to lockdown effects is much lower than that estimated by Le et al. (15), who reported up to 93% reduction in NO$_2$ in Wuhan during the lockdown. If we look at the observations only, we can indeed see >90% decrease from the peak concentration before the lockdown began to the lowest one afterward (Fig. 2), but this is mainly due to changes in meteorological conditions, not emissions. The observed PM$_{2.5}$ also exhibited remarkable meteorologically driven variability regardless of cities or site types and sometimes differed by more than a factor of 3 when compared with deweathered concentrations (Fig. 5 and fig. S2). In general, major differences are apparent between the observed and deweathered results when the meteorological conditions change substantially over the study period. For example, the changes in observed and deweathered PM$_{2.5}$ at urban background sites in Beijing before and after the lockdown began were +19.2 ± 108.6% ($P_{obs}$) and −19.3 ± 9.6% ($P_{dew}$), respectively. In this case, emission reductions and the unfavorable meteorological conditions drove changes of approximately −19.3 and +38.6% in the observed levels, respectively, leading to an overall +19.2% increase in PM$_{2.5}$. Our results demonstrate that meteorological variations, rather than emission changes on the scale of those occurring during the COVID-19 lockdowns, dominate short-term variability in air pollutant concentrations, which is consistent with previous studies (12, 14, 20, 24).

Apart from deweathering, detrending the “business-as-usual” changes is also crucial in estimating real changes attributable to interventions (i.e., lockdowns). In the “business-as-usual” scenario, air pollutant emissions (both anthropogenic and natural) and, thereby, concentrations may change from winter to spring, whether there is a lockdown or not (see 2016–2019 data in Fig. 3). For example, a general increase in deweathered O$_3$ is observed from winter to spring in 2016–2019 in all the studied cities (Figs. 2 and 3 and fig. S1). Such an increase reflects changing photochemical steady-state partitioning from NO$_2$ to O$_3$ (Northern Hemisphere cities moving into spring with increased solar radiation intensity and day length),
would lead to a different conclusion, as by Sicard et al. literature to estimate the lockdown effects by subtracting NO\textsubscript{2} during cle fleet evolution (14 London and Beijing, as a result of clean air policy actions and vehi-
lockdowns are not as large as previous studies have reported (21 7), Shi et al. (2021; 7 : eabd6696)
percentage changes (P).
Taking this “business-as-usual” variability into account, the detrended
enhanced by increased emission and chemical reactivity of VOCs. alongside wider increases in photochemical ozone formation,
emissions. This is consistent with Le Quéré (2019, 16).

Drivers of changes
The deweathered NO\textsubscript{2} showed a sudden decrease after the lock-
down began in most of the cities (Fig. 2 and fig. S1). Detrended NO\textsubscript{2} at urban background sites declined the most in Delhi (−51.0 ± 5.2%), Madrid (−35.2 ± 21.3%), and Wuhan (−33.9 ± 7.3%) (Table 1). A given reduction in NO\textsubscript{2} emission, and hence NO\textsubscript{2} abundance, is expected to lead to a smaller reduction in ambient NO\textsubscript{2} levels, as the fast NO\textsubscript{x}-NO\textsubscript{3} photochemistry shifts the NO\textsubscript{3}/NO\textsubscript{2} ratio in favor of NO\textsubscript{3}. The fact that the NO\textsubscript{2} changes are larger than those of NO\textsubscript{3} supports this argument (tables S1 and S2). A substantially larger decline in NO\textsubscript{2} and NO\textsubscript{3} was observed at roadside than at urban background sites, suggesting that the decline in NO\textsubscript{2} during the lockdowns is largely driven by changes in road traffic as the domi-
nant source of NO\textsubscript{2} in urban atmosphere (16). Mobility data from Google Maps (https://www.google.com/covid19/mobility/) suggest that traffic volumes reduced by 60 to 80% in the cities considered here.

However, this mobility decrease does not correspond directly to the same reduction in road traffic–related NO\textsubscript{2} emissions. For example, in London, although private car use reduced by about 80%, heavy
vehicles (HGVs) on the road only reduced by 30 to 40%. It is possible that if the change in the number of HGVs, which account for a smaller percentage of total vehicle population but a large pro-
portion of vehicular NO\textsubscript{2} emissions (26, 27), is small, then the changes in total road traffic emissions of NO\textsubscript{2} may be much smaller than expected. Decreases in activity levels from other combustion sources, such as power plants and industry (22), may have contrib-
uted to the decline in NO\textsubscript{2}, at least in some cities, as shown by the small decline in SO\textsubscript{2} in some cities (fig. S4). Such changes are diffi-
cult to quantify, but the much smaller (and absence of any sudden) changes in SO\textsubscript{2} compared with NO\textsubscript{2} (Fig. 2 and fig. S2)—as indicated by the increase in SO\textsubscript{2}/NO\textsubscript{2} ratio in Wuhan, London, Paris, Rome, and Delhi (auxiliary data table S1)—suggest that reductions in NO\textsubscript{3} emissions from stationary sources were less than those from traffic emissions. This is consistent with Le Quéré et al. (5), who estimated

alongside wider increases in photochemical ozone formation, enhanced by increased emission and chemical reactivity of VOCs. Taking this “business-as-usual” variability into account, the detrended percentage changes (P\textsuperscript{*}) in O\textsubscript{3} are much smaller than the correspond-
ing P\textsubscript{dew} (Table 1 and table S3). Not accounting for this seasonality
would lead to a different conclusion, as by Sicard et al. (7), that O\textsubscript{3} concentration increased substantially in response to the lockdowns.

In some cities, there are considerable variabilities in P\textsubscript{dew} in 2016–2019 (Fig. 3). This may be partly due to specific events such as holidays around the lockdown dates, leading to a decrease in air pollutant emissions for a particular year. In this instance, the absolute value of P\textsubscript{dew} in 2016–2019 could be slightly overestimated, and thus that of the P\textsuperscript{*} underestimated. However, because we included 4 years of data (2016–2019) for detrending, the impact of a specific event on the P\textsuperscript{*} values is small.

Our detrended results (Table 1 and table S3) demonstrate that the decreases in NO\textsubscript{2} and increases in O\textsubscript{3} due to the COVID-19 lockdowns are not as large as previous studies have reported (7, 21) or as the raw observational data show (table S1). Note also that an-
thropogenic air pollutant emissions reduce year by year, such as in London and Beijing, as a result of clean air policy actions and vehi-
cle fleet evolution (14, 18). Thus, the approach widely used in the
literature to estimate the lockdown effects by subtracting NO\textsubscript{2} during the equivalent periods in earlier years from that in 2020 (6, 7, 11, 15)
may also overestimate the effects attributed to the lockdowns (Fig. 3 and Table 1).
Considering urban background sites in Wuhan (a widely studied city) as an example, observed NO\textsubscript{2} and O\textsubscript{3} changed by −47.3 ± 17.4% and +166.5 ± 60.5% (P\textsubscript{obs} values, obtained from unadjusted concen-
tration data before/during lockdown; table S1), values similar to those reported by Shi and Brasseur [−54 ± 7% and + 220 ± 20% (25)]; changes of approximately −51.8 and +40.0% are obtained by subtracting NO\textsubscript{2} and O\textsubscript{3} concentrations during the second to fifth weeks after the lockdown dates in 2016–2019 from those in 2020 (i.e., without adjustment for meteorology), values which are similar to those reported by Sicard et al. [−57 and +36% (7)].

Our estimated changes in deweathered NO\textsubscript{2} and O\textsubscript{3} (P\textsubscript{dew}) are −43.9 ± 2.2% and +44.5 ± 3.4%, which are similar to those reported by Zhao et al. [−51.7 and +58% (21)]. However, these estimations (7, 21, 25) are considerably higher (sometimes by a factor of 10) than our detrend-
ed results (P\textsuperscript{*}), which are −33.9 ± 7.3% for NO\textsubscript{2} and +21.8 ± 13.6% for O\textsubscript{3}. This may at least partially explain why the estimated changes in NO\textsubscript{2} and O\textsubscript{3} due to the lockdown effects in the studied cities re-
ported here are lower than those published elsewhere (7, 11, 15, 21, 25), and demonstrate the necessity of disentangling the changes due to meteorological variation and seasonality and from the lockdown-driven changes in emissions to understand the resulting differences in air pollutant concentrations.

Fig. 5. Observed and deweathered daily PM\textsubscript{2.5} concentrations in the selected cities before and after the lockdown start dates or equivalent in 2020 versus 2018. Columns correspond to (A) roadside, (B) urban background, and (C) rural sites; rows show different cities as indicated. Fine and heavy lines indicate ob-
served and deweathered concentrations, respectively. Data are shown from December to May, shown as day of year (1 January = 1), where the vertical dashed lines represent lockdown start date. Results from other cities/sites are shown in fig. S2. No data are available for roadside sites in Wuhan.
that in Europe and the United States, electricity use reduced by 9 and 5%, respectively. Note also that domestic emissions may have increased with an increase in people working or studying from home. We recognize that our methodology is unable to attribute the actual changes in emissions on a sector-by-sector basis. This could be revisited in the future when emission inventories for the spring 2020 lockdown period are developed and evaluated against observations.

**Ozone (O₃)** is a secondary pollutant, and its variation is driven by several factors. Dominant among these is the NO₂-O₃ photochemical steady state. The decrease in NO (tables S1 and S2) led to reduced O₃ titration, through which reductions in traffic-related NO emissions translate directly into increases in O₃, relative to the prelockdown period; the time constant for this NOₓ-O₃ interaction in daylight is of the order of minutes. The fact that deweathered NO₃ increased suddenly after the lockdown began and that changes in deweathered NO were more pronounced than those in NOₓ and NO₂, particularly at roadside sites (fig. S1 and table S2), support this well-understood atmospheric chemistry (28). This effect—of a reduced urban decrement in O₃—will be partially offset by reductions in primary NO₂ emissions from traffic and, on a much longer time scale (hours to days, rather than minutes), by net O₃ production. Under an extreme condition, if all traffic-related NO emissions are assumed to be NO, Oₓ would remain unchanged in response to lockdown-driven changes in traffic (but NO₂ would decrease, and O₃ would increase). In reality, primary NO₂ emissions from road traffic decreased during the lockdowns, so O₃ should fall. Detrended O₃ fell slightly at roadside and urban background sites in most of the cities (Table 1 and table S3). Detrended O₃ increased at rural sites in some of the cities (table S3), which indicates an increase in net photochemical production of O₃ at some of the studied sites (28). The different pattern of changes in detrended O₃ represents a nonlinear response of O₃ formation rates to the (relative) changes in NOₓ and VOC emissions, depending on the prevailing O₃ production regime at each location, but usually with a greater impact downwind of conurbation locations (29,30).

Drivers of the response of PM₂.₅ levels to the lockdown measures are more complex since both primary emissions and secondary formation contribute to PM₂.₅ in ambient air. Deweathered PM₂.₅ decreased after the lockdowns began at urban background sites in most of the cities, including Wuhan, Rome, New York, Los Angeles, and Delhi (fig. S2). This could be explained by (i) the expected reductions in primary emissions of PM₂.₅ and its gaseous precursors (e.g., NOₓ, SO₂, and VOCs) during the lockdowns and (ii) limited change in the formation rate of secondary aerosol as shown by the small variation in PM₂.₅/CO ratio (fig. S5).

Deweathered PM₂.₅ increased in London and Paris for an extended period (more than 3 weeks) after the lockdowns began (fig. 5). It also increased in Beijing after the lockdown began, although for a shorter period. One possible explanation for this unexpected result is that enhanced secondary aerosol formation overwhelmed the reduced primary PM₂.₅ emissions. In Chinese megacities, secondary particles typically contribute to >50% of PM₂.₅ mass (31,32). In London, secondary aerosols contribute roughly half of PM₂.₅ at roadside sites, increasing to ~90% of PM₂.₅ at rural sites, with the contribution lying between these values at urban background sites (33). Such contributions are even larger during pollution events (15,16,31). Thus, changes in PM₂.₅ are often driven by variations in secondary aerosols, particularly during pollution events. In Beijing, Sun et al. (34) noted that primary aerosol decreased by 30 to 50%, while secondary inorganic aerosol and secondary organic aerosol (SOA) increased by 60 to 110% and 52 to 175%, respectively, during the early periods of the lockdown in 2020. The fact that substantial increases in PM₂.₅/PM₁₀ (Paris) or PM₂.₅/CO (London; fig. S5) ratios accompanied the increase in deweathered PM₂.₅ (fig. 5 and fig. S2) also supports the greater role of secondary aerosol during the study period in Paris and London. Zhao et al. (35) suggested that SOA formation depends nonlinearly on the ratio of VOCs to NOₓ reduction in NO emissions may lead to increased production of SOA given imbalanced emission abatement of NOₓ and VOCs. Le et al. (15) indicated that multiphase chemistry and enhanced atmospheric oxidative capacity drove haze events in China during the lockdowns. Huang et al. (16) also suggested that increase in oxidative capacity during lockdown in China/Beijing caused the observed air pollution events; however, the changes in deweathered O₃ levels (P_dew) at urban background sites are rather small: Beijing (−1.1 ± 2%), London (+4.2 ± 0.8%), and Paris (+2.1 ± 0.6%) (table S2).

Another possible explanation is associated with changes in long-range transport, which brings air pollutants from nonlocal sources and thus contributes to the increase in deweathered PM₂.₅. In theory, the RF models should have normalized the impacts from long-range transport by including back-trajectory clusters. However, the model may not be able to perfectly reproduce secondary formation processes arising from long-range transport if there were limited cases to learn from, especially as such events tend to be episodic in nature. In this case, the model will treat pollution events arising from long-range transport as if there are higher emissions; this attribution will be retained during deweathering. This will cause uncertainties in the model. More observational data and modeling are needed to fully understand the phenomenon of increases in PM₂.₅ in London, Paris, and Beijing during the lockdowns. However, it is clear that a small reduction in primary PM₂.₅ emissions (e.g., from vehicular emission changes during lockdown) could be readily overwhelmed by enhanced secondary formation and/or PM₂.₅ transported from more polluted regions.

In Wuhan, the deweathered PM₂.₅ decreased to a small degree during the 2 weeks after the lockdown began (fig. 5). However, the deweathered PM₂.₅/CO increased during the lockdowns (fig. S5), which suggests that enhanced secondary pollution (36) offsets the benefits of the reduction in primary emissions during the first 2 weeks of the lockdown. Thereafter, the deweathered PM₂.₅ did decrease more significantly (P_dew = −27.0 ± 18.7%). Similarly, in Beijing, the deweathered PM₂.₅ decreased 2 weeks after the lockdown began, so overall P_dew is negative (−19.3 ± 9.6%). These results suggest that if the reduction in emissions of gaseous precursors is sufficiently large, it should eventually lead to an overall decline in PM₂.₅. Such a hypothesis should be tested with chemical transport models with up-to-date emission inventories when these are available.

**Implications for future air pollution control**

Our results demonstrate that restrictions on economic activities, particularly traffic, brought an immediate decline in deweathered NOₓ in all the studied cities. If similar levels of restriction were to have remained in place, the annual average NOₓ concentration would comply with the air quality guidelines from the World Health Organization (WHO) (i.e., 40 μg m⁻³ for annual NOₓ) for the cities considered under average meteorological conditions, except for a limited number of roadside sites. However, the deweathered percentage decline (i.e., attributed to lockdown effects) in NOₓ is mostly below 30%. This is lower than the expected decline, partly due to the
NOx-O3 photochemical steady state (converting NO to NO2), alongside seasonal effects, and partly due to the still important emissions of NOx from stationary and mobile pollution sources. Detrained O3 increased in most cities. This adds to the complexity of air pollution control, considering the potentially adverse impacts of O3 on human (37, 38) and environmental health, including crop yields (39).

PM2.5 exhibited a more complex response to the lockdown measures. PM2.5 did not show an immediate decline to the lockdown measures except in Wuhan, Rome, and Los Angeles, even at the roadside sites. This is not too unexpected considering the relatively small contribution of road traffic to primary PM2.5 in most of the cities studied here and a large contribution from secondary sources (16, 31). In China, much of the recent decrease in PM2.5 came from the reductions in residential solid fuel use and industrial activity rather than traffic emissions (18, 40). Nevertheless, a decrease in deweathered PM2.5 is observed in most of the cities.

In Delhi, Wuhan, and Beijing, annual average PM2.5 concentrations are so far in exceedance of the WHO guideline (10 µg m⁻³) that the decline is far from sufficient to bring levels into compliance. Even in those cities where the annual average PM2.5 is close to 10 µg m⁻³, such as London and Paris, emission reductions on the scale of the spring 2020 COVID-19 lockdown measures may still be insufficient to bring concentrations into compliance with the current WHO guidelines. In addition, the frequent PM2.5 pollution events during the lockdowns in some cities, such as Beijing, London, and Paris, showed that actions of a magnitude similar to the lockdown measures are far from sufficient to avoid episodic pollution events in these cities. The mechanisms driving such changes have been explored in more detail by recent studies (15–17, 20).

Li et al. (41) suggested that aggressive reductions in NOx and aromatic VOC emissions should be particularly effective for decreasing both PM2.5 and O3 in China. The huge reduction in NOx (fig. S3) and VOCs (16) in response to the COVID-19 lockdowns did reduce PM2.5 pollution in Beijing and Wuhan, but detrained O3 increased substantially (Table 1), at least up until mid-May. A slower pace of VOC emission reduction, relative to that for NOx, could risk a further increase in O3 pollution.

In summary, emission changes associated with the early-2020 COVID-19 lockdown restrictions led to complex and substantial changes in air pollutant levels, but the changes are smaller than expected. The decrease in NO2 will likely have benefits on public health, but the increase in O3 would counteract at least some of this effect (37, 38). The magnitude and even the sign of changes in PM2.5 during the lockdowns differ significantly among the studied cities. Chemical processes of the mixed atmospheric system add complexity to efforts to abate secondary pollution (e.g., O3 and PM2.5) through reduction of precursor emissions (e.g., NOx and VOCs) (42). Future control measures will require a systematic approach toward NOx, O3, and PM2.5 tailored for specific cities, taking into account both primary emissions and secondary processes, to maximize the overall benefits to air quality and human health.

MATERIALS AND METHODS

Selected cities and data

Eleven cities were selected to ensure coverage of contrasting pollution climate: Beijing and Wuhan in China, Milan and Rome in Italy, Madrid in Spain, London in United Kingdom, Paris in France, Berlin in Germany, New York and Los Angeles in the United States, and Delhi in India. Of those, eight are capital cities. Wuhan was added because it was the first city where COVID-19 was reported and lockdown was first imposed. Milan was included because it is in northern Italy, one of the most seriously hit areas after Wuhan. In the United States, New York was the most seriously affected city, whereas Los Angeles was reported to have observed a greater decline in air pollution levels (43). All the study cities have been significantly affected by COVID-19 and implemented stringent lockdown measures to contain the COVID-19 pandemic in early 2020. Such measures were first implemented in Wuhan from 23 January 2020 and then 2 days later in all provinces in China (including Beijing). Tightened restrictive measures were implemented from 23 January 2020 in northern Italy, 13 March 2020 in the United States, 14 March 2020 in Spain, 17 March 2020 in France, 22 March 2020 in Germany, 23 March 2020 in the United Kingdom, and 25 March 2020 in India.

Site-specific hourly concentration of sixcriteria pollutants (PM2.5, PM10, O3, NO2, CO, and SO2) and other auxiliary pollutants (NOx and NO2) from December 2015 to May 2020 were obtained from websites of local or national environmental agency or accredited third parties (table S4). In most cases, data from multiple stations for each site type are available. The NO2 concentrations reported from local governments, typically performed by the widely used molybdenum conversion/chemiluminescence method, may slightly overestimate true NO2 levels due to conversion of other labile N species to NO in the convertor stage. This problem is usually small for polluted urban sites but is larger for rural sites where overestimates of 17 to 30% have been reported (44). This is due to the conversion of NOx from primary sources to secondary nitrogen compounds during its transport toward more rural locations. Hence, concentrations reported as NO2 contain a small proportion of other NOx species, and the “true” NO2 levels would be lower than those officially reported, particularly at rural locations. We note that such uncertainties are effectively “built in” to monitor NOx with respect to regulatory standards. NOx and NO data were obtained in cities where those data were publicly available. Data were usually downloaded from official sources, which are validated by the authorities. For those cities where data were not available from recognized official sources (i.e., Los Angeles and New York) at the time of access, we obtained the air quality data from the “OpenAQ” platform (https://openaq.org/). Data from Los Angeles were downloaded from the U.S. Environmental Protection Agency (USEPA) later (after the data analyses were done here), which were then compared with those from OpenAQ. We found that the site-specific data in Los Angeles from OpenAQ are highly correlated (slope ~ 1, intercept ~ 0) with those from USEPA. Air quality monitoring stations were selected to cover roadside, urban background, and rural sites when possible, and the site types were based on official classifications and maps. The downloaded data were screened and cleaned when necessary, following established methods (24).

The hourly temperature, relative humidity, atmospheric pressure, wind speed, and wind direction data for selected sites were obtained from the nearest meteorological observation site from the NOAA (National Oceanic and Atmospheric Administration) Integrated Surface Database (ISD) using the “worldm5” R package (https://CRAN.R-project.org/package=worldmet). In addition, hourly data for boundary layer height, total cloud cover, surface net solar radiation, and total precipitation at the selected sites were downloaded from the ERA5 reanalysis dataset (ERA5 hourly data on single levels from 1979 to present). For each site, 72-hour back trajectories at an hourly resolution were calculated using the Hybrid Single-Particle
Lagrangian Integrated Trajectory (HYSPLIT) model. The starting height was set as 100 m to ensure that the receptor was aloft but remained within the boundary layer throughout the study period. The back trajectories were then clustered into 12 clusters using the Euclidean distance by “openair” R package (https://cran.r-project.org/web/). Those clusters were used to represent the common air masses that the sites were exposed to.

Observations at the air quality stations are used for official compliance purpose. Although these stations were built to represent the specific environment of the city (i.e., roadside, urban background, and rural), there may be some variabilities in the concentrations of air pollutants at different stations of the same type. This could cause potential uncertainties in our analyses if to represent the whole city. In this study, wherever possible, we used data from multiple stations for each site type (table S4), which reduced this uncertainty. Where only one station is available for a site type, the data may be subject to more influence from local emission sources. Therefore, what we reported here should be treated in the context of the site subject to more influence from local emission sources. Therefore, our analyses focus on the high-resolution temporal variations, and thus, the trend will be broadly representative.

**RF model and weather normalization**

Weather conditions change rapidly, causing variations in the concentration of air pollutants even when emissions do not change. Here, we applied a machine learning–based RF algorithm to decouple the effects of meteorological conditions. To do this, we first build an RF model for each pollutant and for each year (December to May). The RF model–based weather normalization technique was introduced in Grange et al. (12). Briefly, the RF model was built independently for each period (December 2015 to May 2016, December 2016 to May 2017, December 2017 to May 2018, December 2018 to May 2019, and December 2019 to May 2020), each pollutant, and each site type within a city. Seventy percent of the original data were randomly selected to build the model, which was then evaluated with the remainder (30%) of the dataset. Model performance for each pollutant and each time period (i.e., 2016–2020) is illustrated in fig. S6. Similar to Grange et al. (12, 13) and Vu et al. (14), the performance of the models is usually very good, much better than that of regression models (9). The weather normalization was conducted using the “rmweather” R package, available at https://cran.r-project.org/web/packages/rmweather/index.html.

In the Grange et al. (12) approach, a new dataset of input predictor features including time variables (day of the year, day of the week, and hour of the day), but not the Unix time) and meteorological parameters (wind speed, wind direction, temperature, and relative humidity) is first resampled from the original observation dataset. Vu et al. (14) modified the default method to investigate the seasonal variations in trends for comparison with trends in primary emissions, by only resampling the weather variables (not the time variables). Specifically, weather variables at a specific hour of a particular day in the input datasets were generated by randomly selecting from the historical weather data (past 30 years) at the particular hour of different dates within a 4-week period (i.e., 2 weeks before and 2 weeks after that selected date). The two methods are fit for their own purposes but were not used here because (i) Grange et al. (12) normalized the diurnal and seasonal variations of the primary emissions, which is unrealistic in the real world, and (ii) although Vu et al. (14) provided diurnal and seasonal variations of the primary emissions, this is inappropriate in detecting short-term emission interventions because the normalized concentrations for a particular hour of a Julian day were not comparable with those from the different hour of a different Julian day, considering that they were resampled from different weather datasets, which would be affected by different seasonal weather conditions.

To address those limitations and better investigate the impacts of short-term lockdown on air quality, we applied a mixed method. We only normalized the weather data but not time variables, similar to Vu et al. (14), and resampled from the whole study period, similar to Grange et al. (12). The improved method is more suitable for tracking emission changes. The input features for the model included time variables (i.e., Unix time, Julian day, day of the week, and hour of the day), meteorological data from surface observations (i.e., temperature, relative humidity, wind speed, wind direction, and atmospheric pressure), meteorological data from ERA5 reanalysis dataset (i.e., boundary layer height, total cloud cover, surface net solar radiation, and total precipitation), and air mass clusters based on the HYSPLIT back trajectories. The day of week and air mass clusters were categorical variables, while all others were numeric. Following Vu et al. (14), the parameters for the RF models are as follows: a forest of 300 trees, n_tree = 300; the number of variables that may be considered for splitting a node was set as 14; the Euclidian distance by “openair” R package (https://CRAN.R-project.org/). The back trajectories were then clustered into 12 clusters using the k-means method (17), where the 12 clusters were categorical variables, while all others were numeric. The cost of air pollution—strengthening the economic case for action (2016); http://documents.worldbank.org/curated/en/781521473177013155/The-cost-of-air-pollution-strengthening—the-economic-case-for-action.

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/7/3/eabd6696/DC1

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Data and materials availability: Codes and the auxiliary data table S1 are available at https://github.com/songnku/COVID-19-Datasets. Additional data related to this paper may be requested from the corresponding author.

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