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COVID-19 lockdown closures of emissions sources in India: Lessons for air quality and climate policy

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ABSTRACT

Reduced anthropogenic activities during the COVID-19 pandemic caused significant reductions in ambient fine particulate matter ($PM_{2.5}$), SO_2 and NO_x concentrations across India. However, tropospheric O_3 concentrations spiked over many urban regions. Moreover, reductions in SO_2 and NO_x (atmospheric cooling agents) emissions unmask heating exerted by warming forcers. Basing governmental guidelines, we model daily emissions reductions in CO_2 and short-lived climate forcers (SLCFs) during different lockdown periods using bottom-up regional emission inventory. The transport sector, with maximum level of closure, followed by power plants and industry reduced nearly −50% to −75% emissions of CO_2, primary $PM_{2.5}$, SO_2 and NO_x, while warming SLCFs (black carbon, CH_4, CO and non-methane VOCs) showed insignificant reduction from continuing activity in residential and agricultural sectors. Consequently, the analysis indicates that reduction in the emission ratio of NO_x to NMVOC coincided spatially with observed increases in O_3, consistent with reduced uptake of O_3 from night-time NO_x reactions. Also, similar reductions, occurring for longer timescales (say, a year), can potentially increase the annual warming rate over India from the positive regional temperature response, estimated using climate metric. Further, by linking ongoing policies to sectoral reductions during lockdown, this study shows that the relative pacing of implementation among policies is crucial to avoid counter-productive results. A key policy recommendation is introduction and improving efficacy of programs targeting reduction of NMVOC and warming SLCF emissions (shifts away from biomass cooking technologies, household electrification and curbing open burning of crop residues), must precede the strengthening of policies targeting NO_x and SO_2 dominated sectors.

1. Introduction

The outbreak of the new coronavirus has disrupted human lives worldwide, while influencing the environment indirectly. Coronavirus disease (COVID-19, name given to the disease caused by the virus) was first detected around December 2019 in the Wuhan province of China, which later spread throughout the world and was declared as a pandemic by the World Health Organization (WHO, 2020). Restricting human interaction was considered to be the most effective strategy to prevent the spread. Many governments imposed national lockdowns, shutting down major economic activities and mobility. COVID-19 lockdowns provide a unique opportunity to analyse the system's response of such "unprecedented" controls on emission sources.

The unprecedented closure of many anthropogenic activities led to a pause in emissions of various pollutants – such as fine particulate matter ($PM_{2.5}$), black carbon (BC), organic carbon (OC), oxides of nitrogen (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), methane (CH_4) and non-methane volatile organic compounds (NMVOCs), which affect regional air quality (Venkataraman et al., 2018) and near-term climate (CCAC, 2014; IPCC, 2018). Besides air quality, these pollutants also exert significant temperature response in the near-term by altering the earth's radiative balance (Collins et al., 2013). Owing to their short atmospheric lifetimes (ranging from few days to months or few years) they are referred to as short-lived climate forcers (SLCFs). SLCFs including BC, CH_4, NMVOCs and CO, absorb radiation leading to atmospheric warming, are called warming SLCFs (wSLCFs) while NO_x, SO_2 and OC, scatter radiation causing a cooling effect, are called cooling SLCFs (cSLCFs). Thus, reduction in cSLCFs without complimentary reductions in wSLCFs can unmask the reduction in warming due to GHG mitigation.

The effects of India's COVID-19 related lockdowns on air quality

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levels have been discussed widely (Dhaka et al., 2020; Jain and Sharma, 2020; Kumari and Toshniwal, 2020; Mahato et al., 2020; Navinya et al., 2020; Parida et al., 2020; Sharma et al., 2020; Singh et al., 2020). India declared its first phase national lockdown for 21 days starting from 25th March 2020 onwards (MoHA, 2020a). However, a sequence of lockdowns followed with some activities reopening in a phased manner. Several studies analysed the influence of lockdowns on regional air pollution using data from in-situ air quality monitoring stations across India. Overall, a reduction of ~50% $PM_{2.5}$ was reported, with reductions varying across sites (Jain and Sharma, 2020; Mahato et al., 2020; Navinya et al., 2020; Sharma et al., 2020; Singh et al., 2020). Further, NO_x showed a clear decrease by ~50%, SO_2 experienced a mixed behaviour ranging from negligible to significant decrease at some sites (Navinya et al., 2020; Singh et al., 2020) along with slight increase at some sites (Sharma et al., 2020; Singh et al., 2020). However, levels of ozone, a secondary pollutant formed due to the photochemical reactions of NO_x, VOCs and CO in the troposphere, were found to have significantly increased at major urban sites (Jain and Sharma, 2020; Kumari and Toshniwal, 2020; Mahato et al., 2020; Singh et al., 2020; Urbanemissions.info, 2020). Such non-linear responses of underlying chemistry among the pollutants, where the fate of one pollutant can significantly influence the fate of other(s) (Huang et al., 2020; Singh et al., 2020), pose barriers to prioritizing effective mitigation policies. Simply reducing pollutant emissions may prima facie seem beneficial but could be counterproductive to overall air quality.

Modelling emissions changes under such situations of the unprecedented closure of many anthropogenic activities can aid in assessing non-intuitive impacts on air quality and climate. This can aid the development of future policy actions aimed at securing multiple benefits to air quality and climate. Recent studies have modelled emissions during the lockdown (Beig et al., 2021; Forster et al., 2020; Le Quéré et al., 2020; Liu et al., 2020; Misra et al., 2021; Miyazaki et al., 2021; Sarfraz et al., 2021; Xing et al., 2020; Zhang et al., 2021; Zheng et al., 2020) exploring a variety of aspects such as global temperature response (Forster et al., 2020), impact of emission changes on ambient O_3 and $PM_{2.5}$ concentrations (Miyazaki et al., 2021; Xing et al., 2020; Zhang et al., 2021), sectoral impacts on urban air pollution (Beig et al., 2021; Misra et al., 2021) and possible future emissions recovery pathways post lockdown (Forster et al., 2020; Le Quéré et al., 2020). These studies model single pollutants such as CO_2 (Le Quéré et al., 2020; Liu et al., 2020; Sarfraz et al., 2021; Zheng et al., 2020), CO (Beig et al., 2021) and NOx (Misra et al., 2021; Miyazaki et al., 2021) or O_3 and $PM_{2.5}$ (Zhang et al., 2021) to examine changes in air quality.

Here we examine implications to setting regional policies in regard to both air quality and climate, using a regionally representative spatially resolved emissions inventory over India for a basket of pollutants CO_2, particulate matter (primary $PM_{2.5}$, black carbon, organic carbon) and precursor gases (SO_2, NO_x, CO and VOCs). We seek analogies between the activity closures leading to emission changes and national policies addressing emissions in India, to assess the potential impacts from such policy actions. Our results are based on regionally representative sectoral activity and emission factors (Tibrewal and Venkataraman, 2020; Venkataraman et al., 2018) following standard methods for emissions inventory development (Klimont et al., 2017; McDuffie et al., 2020; Stohl et al., 2015). We calculate emissions changes against a counterfactual - no lockdown scenario - and link them to the observed air quality impacts and estimated potential climate impacts.

2. Data and method

Emissions are modelled under two scenarios – BASE (counterfactual scenario with no lockdown) and COVD (with lockdown). Daily emissions are calculated for 1st January to 31st July 2020, as most activities started to resume from 1st August onwards based on government orders. Emission reductions are combined with observations from air quality monitoring sites and climate metrics to comment on the potential impacts of such unplanned closure of activities, highlighting implications for future air quality and climate policy design.

2.1. Generating baseline emissions

Baseline emissions for this study have been prepared using a regional bottom-up emissions inventory - the Speciated MultipOllutant Generator (SMoG-India). Considering the dynamic nature of emissions sources, SMoG-India reports emissions for 2015 based on activity estimated through sector specific methodologies combined with technology-linked emissions factors (Pandey et al., 2014; Sadavarte and Venkataraman, 2014; Venkataraman et al., 2018). Annual emissions in 2020 for the BASE scenario are thereby obtained from projections from 2015 to 2030 (Tibrewal and Venkataraman, 2020). Activity data for future are extrapolated from 2015 using published sectoral growth rates (Venkataraman et al., 2018). For refineries and power plants actual reported crude throughput for 2019 (MoPNG, 2020) and targeted power generation for 2020 (CEA, 2020) are obtained. The future activities are then apportioned into different technologies based on proposed targets of currently ongoing national policies (Tibrewal and Venkataraman, 2020).

Emissions are resolved into 25 × 25 km grids through sector-specific spatial proxies (Sadavarte and Venkataraman, 2014). Temporally, annual emissions are first distributed by months and then daily emissions are estimated assuming equal emissions in a month. Monthly emissions for residential heating were based on monthly mean-minimum temperatures (Pandey et al., 2014) while the distribution for agricultural residue burning followed the seasonality as present in Global Fire Emissions Database (GFED4) (Giglio et al., 2013). Brick industry emissions were distributed equally across the operational months (November to June). Emissions for power plants and refineries followed the reported monthly generation and crude throughput values.

2.2. Estimating lockdown emissions

Under COVD, emissions changes occurred primarily due to reduction in sectoral activity, there were no shifts in technology. Thus, reductions in emissions are proportional to the reductions in activity with respect to BASE (Fig. 1). Therefore, the percentage reduction in activity under COVD with respect to BASE for each sector and each lockdown period are multiplied by the BASE emissions to estimate the sectoral emissions during lockdown. Modelling activity reductions requires transferring the closure guidelines ((MoHA, 2020b); Table S1) to the inventory source categories (Table 1). Primarily, sectors such as power plants, refineries, light industry and passenger road transport experienced varying intensities of restrictions across the lockdown periods (Fig. 1).

We have attempted to include the inherent temporal and spatial variations in our estimates. For power plants and refineries, actual electricity generation (CEA, 2020) and monthly crude throughput (MoPNG, 2020) for 2020 were obtained. Heavy industry (including cement, iron and steel and non-ferrous metals) and brick kilns are shut off completely during the first lockdown. During the second lockdown, industries only in the rural areas were allowed to start operation. Since most of these manufacturing plants/units are located in or around rural areas, they are allowed to resume from second lockdown onwards. Light industry is assumed to be completely non-operational during the first lockdown, partially resumed in the second lockdown and completely operational from third lockdown onwards. The ratio of urban population to total population is used as a proxy for activity reduction during this phase. Railways remained shut till 10th of May and resumed completely henceforth.

Estimating activity reductions in passenger road transport sector involved a more complex approach. While all passenger vehicles were completely off until the second lockdown, from third lockdown onwards these were partially resumed based on the district classification. All

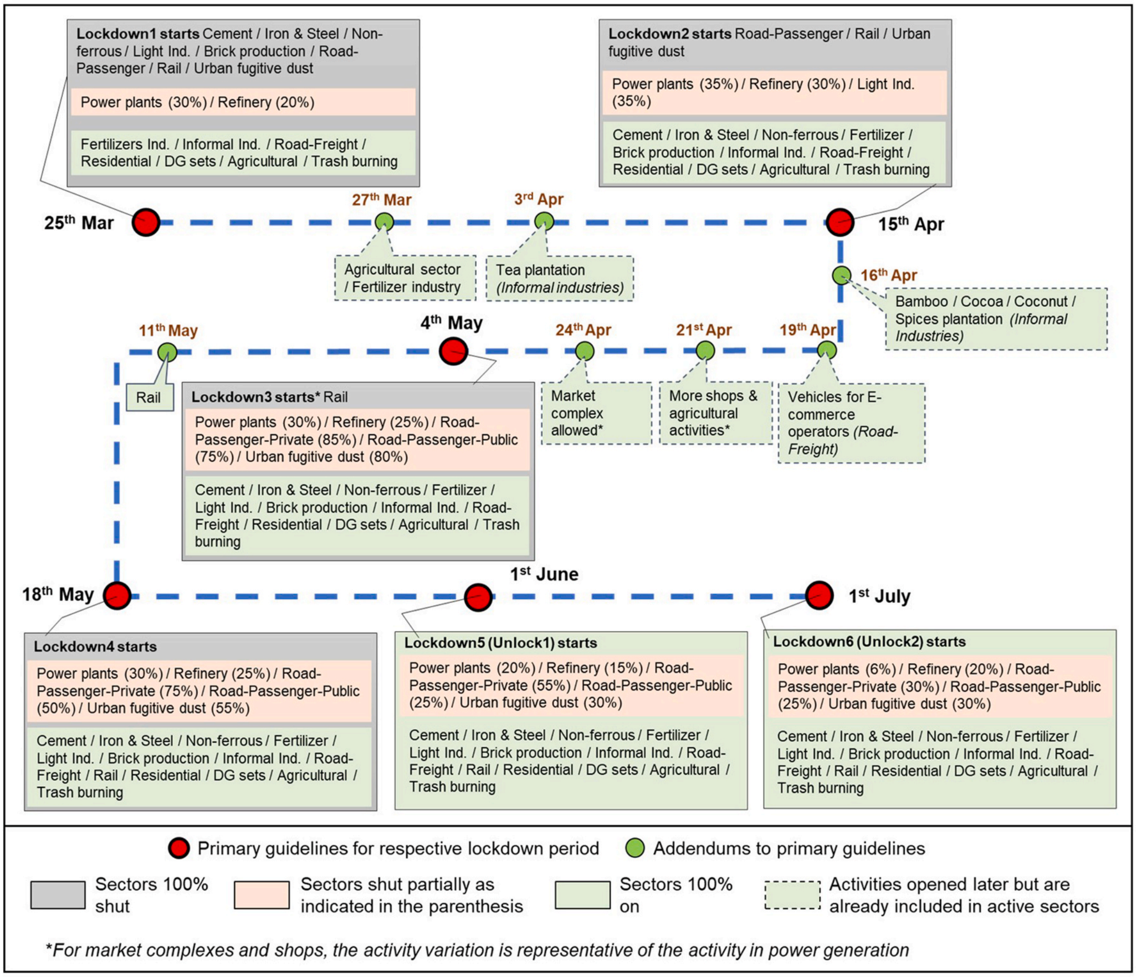

Fig. 1. Sectoral activity evolution across different lockdown periods.

Table 1
Mapping of activities to inventory source categories.

Activities	Inventory source categories
Utilities	Power plants
Industrial	Refineries
Industrial	Cement
Industrial	Iron and Steel
Industrial	Non-Ferrous
Industrial	Fertilizers
Industrial	Light Industry
Manufacturing of essential goods/Agro-based industries	Informal Industry
Industrial	Brick Industry
Passenger transport (mobility)	Public road transport
	Private road transport
	Railways – Passenger
Transport of essential goods	Freight
Residential/Utilities	Residential cooking
	Residential space heating
	Residential water heating
	Residential Lighting
	DG Sets
Agricultural activities	Open burning of crop residue
	Agricultural Tractors
	Agricultural Pumps

districts across the country were divided into three zones by the government – red, orange and green, in descending order of the number of active cases. Zonal distribution of districts at the onset of the third lockdown is used as the base classification (Fig. 2a). For each zone there were different guidelines for public and private vehicles respectively (Fig. 2b). Same restrictions are imposed on districts within each zone based on the guidelines. Now, districts got shuffled across different zones on a daily to weekly basis depending on the number of active cases, for which the required information was difficult to collate. Thus, the restriction levels for each zone are simply relaxed gradually from fourth lockdown onwards based on an educated judgement while maintaining the base zonal classification.

2.3. Linking multi-pollutant emission reductions to air quality and climate impacts

We link estimated emissions changes from scenarios representing the COVID lockdown periods to the observed air quality impacts viz-a viz changes in reported ambient ozone concentrations and estimated potential climate impacts using emissions metric.

Tropospheric ozone is formed by photochemical reactions of NO_x, NMVOCs, CH_4 and CO. Factors influencing ozone formation at any site include availability (in terms of initial concentrations, [M]) of NO_x and NMVOCs, solar radiation and temperature. Based on the availability of NO_x and NMVOCs, ozone forming mechanisms fall into two regimes, 1) NMVOC limited (where $[NO_x] > [NMVOCs]$) and 2) NO_x limited (where $[NMVOCs] > [NO_x]$). Mitigation strategies are highly sensitive to the region's ozone formation regime which dictates the type and relative amounts of precursor(s) that must be controlled. Change in ozone concentrations roughly follows the shifts in "ratio of NMVOCs to NO_x

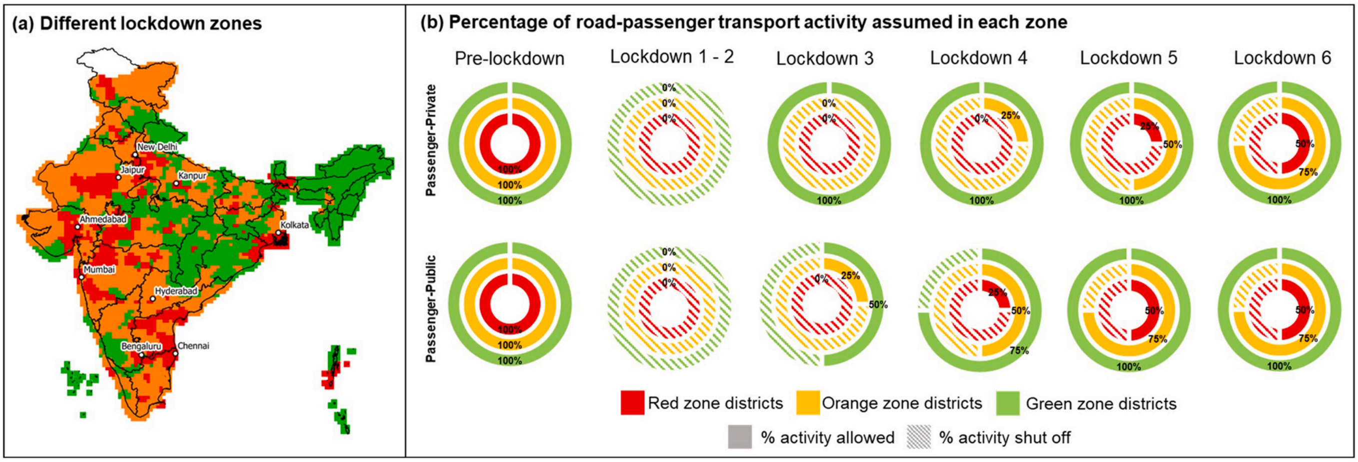

Fig. 2. Zonal variation of public and private road transport activities across different lockdown periods.

emissions ($ER_{NMVOCs/NOx}$)" before and after any intervention (Liu et al., 2013; Wang et al., 2019), Thus, we overlay the spatial distribution of the shift in the $ER_{NMVOCs/NOx}$ during the first lockdown period from the same period under BASE with the sites where ozone formation is found to increase to understand the impact of such controls.

Climate impacts are estimated using Absolute Regional Temperature Change Potentials (ARTP), developed (Aamaas et al., 2017; Collins et al., 2013) using the regional forcing-temperature relationship and change in forcing over a latitude band per unit change in emissions from model simulations (Shindell and Faluvegi, 2009). They represent mean temperature change over a latitude band per unit change in emissions from each band. We used ARTP20 values for the tropics (28°S – 28°N) in response to emissions changes in South Asian region from Collins et al. (2013). The tropics includes the majority of India including the north-west region which is largely associated with heat-waves (Mondal et al., 2020) and India as an emission source region falls within the South Asia domain. We attempt to illustrate the expected change in temperature if each lockdown represented a mitigation scenario. For each lockdown period, the daily mean emissions reductions for each pollutant are scaled for a year, since the small magnitudes of mean regional temperature change per unit emissions reductions may not yield a significant temperature response for short lockdown period (e.g., 20-days) emissions shut off. Also, from a policy evaluation point of view, impacts are assessed from annual reductions in emissions from interventions. For each pollutant, the representative annual emissions reductions are multiplied with the respective ARTP20 value to estimate the temperature change from control of that pollutant. Additionally, activity closures are mapped to different ongoing national policies to understand possible non-intuitive impacts on air quality and climate.

3. Results and discussion

3.1. *Drivers of air quality and climate response*

Transferring activity regulation information (Figure S1) to inventory sectors revealed that activity reductions varied significantly across the sectors (Fig. 1). While residential, informal industry, freight transport and agricultural sectors activities did not alter, the lockdown affected activities for passenger transport, industry, power plants and refineries very significantly. The transport sector was most strongly influenced with a −100% reduction in activity for the first two lockdown periods followed by a phased renewal of the activity. Activity levels for private and public passenger transport reduced ranging from −85% and −75% in third lockdown recovering to −30% and −25% in the sixth lockdown, respectively. Within the industry sector, activity levels for heavy and light industry were reduced by −100% in the first lockdown. Heavy industry includes fertilizers, cement, non-ferrous metal and steel plants, while the balance such as chemical, pulp and paper, machinery, mining, textile and other industries are included in light industry. While heavy industry had no reduction in activity in the second lockdown, light industry saw a partial recovery with an activity level of −35%. Both subsectors resumed their activities completely from third lockdown period onwards. Power plants and refineries had a consistent decrease in activity of around −30%, with the reduction for power plants plummeting to just −6% in the sixth lockdown.

Fig. 3 shows the evolution of different classes of pollutants from January 1st to July 31st of 2020, which drive air quality and climate responses respectively. Air quality drivers include the emissions changes related to primary fine particulate matter (primary PM 2.5; Fig. 3a) and ozone precursors – NO_x (Fig. 3b) and NMVOCs (Fig. 3c). Climate drivers are represented by CO_2 (Fig. 3d) and SLCFs (multiplied by respective GWP20 to obtain CO_2-e). SLCFs are further disaggregated as warming wSLCFs (BC, CH_4, CO and NMVOCs; Fig. 3e) and cooling cSLCFs (SO_2, NO_x and OC; Fig. 3f) based on their absorption versus scattering of solar radiation. Overall, we find that the emissions reductions peaked during the first lockdown period of 21 days. However, the reductions varied across the different pollutants. For primary $PM_{2.5}$, NO_x, CO_2 and cSLCFs, the reductions in daily emissions during the COVID-19 lockdowns with respect to BASE, were estimated to be as high as −75% changing to around −50% within the first lockdown, followed by −25% by the second lockdown and gradually decreased henceforth. However, the reductions for NMVOCs and wSLCFs never diminished below −30%, as these arise primarily from sectors such as residential and agriculture, in which activities continued without change during the COVID-19 lockdowns. While the reductions in NMVOC emissions dropped very gradually during the lockdown periods, for wSLCFs the reductions primarily occurred in the first lockdown (from reductions in activity in industry, brick production and transport sector), with significant recovery (less than −15%) thereafter (from resumption of activity in industry and brick production). Similar ranges in emissions reductions are also reported over major Indian cities from top-down (Misra et al., 2021) and bottom-up (Zhang et al., 2021) estimates for NOx and bottom-up estimates for CO (Beig et al., 2021).

Among the air quality drivers (Fig. 3a–c), primary $PM_{2.5}$ emissions had an aggregate reduction of 285 Gg for the seven months in COVD as compared to BASE, while NO_x and NMVOCs were reduced by 700 and 350 Gg respectively. Primary $PM_{2.5}$ and NO_x are emitted primarily from by industry, transport and followed by power plants. Since the restrictions from industries were lifted from the second lockdown, the reductions were primarily driven by power plants and transport after the first lockdown. Transport had a slightly greater contribution to reduction than power plants. However, for NMVOCs, the reductions were

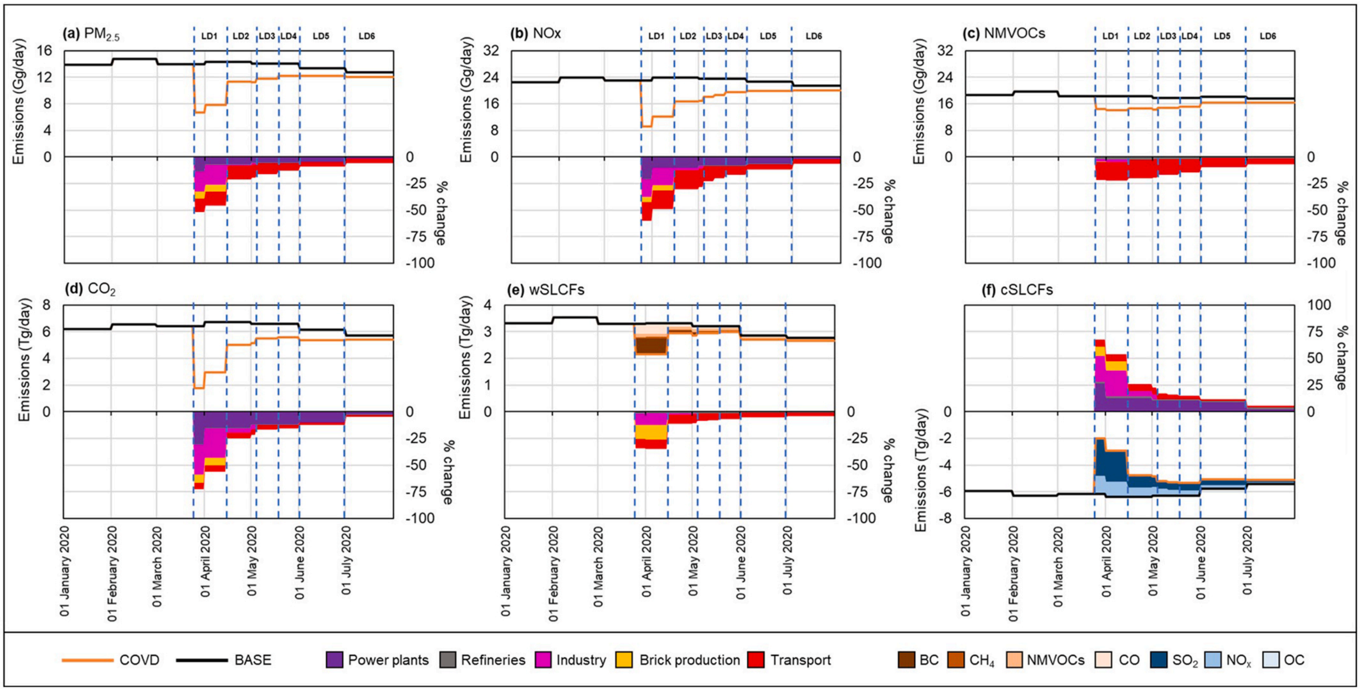

Fig. 3. Sectoral emissions evolution and percentage reduction during COVID-19 lockdown periods in India for (a) Primary PM2.5; Ozone precursors: (b) NOx and (c) NMVOCs; Climate forcers: (d) CO_2, (e) warming SLCFs (wSLCFs) and (f) cooling SLCFs (cSLCFs).

driven only by transport shut down. Among the climate drivers (Fig. 3d–f), CO_2 had an aggregate reduction of 200 Gg and wSLCFs 35 $GgCO_2$-e for the seven months. Reduction in cSLCFs leads to decrease in the cooling effect, thus analogous to increase in CO_2e emissions. Thus, for cSLCFs the aggregated increase in CO_2e emissions is estimated to be 135 $GgCO_2$e during the seven months. CO_2 and cSLCFs shared a similar sectoral contribution dominated industry, power plants and followed by transport. Power plant closures drove the majority of the reductions from second lockdown onwards. As for reductions in wSLCFs, it had nearly equal contributions from industry, brick production and transport in the first lockdown, while it was driven mostly by transport since the second lockdown.

3.2. Linkage to air quality and climate impacts

Emissions changes of such magnitudes (nearly 50–75% reduction), even though lasting for a brief period, can provide interesting insights regarding the atmospheric response to such perturbations, in the contexts of air quality and climate. These can serve as heuristics for strategizing future policy actions. In this context, we establish links between the emissions changes and observed as well as potential impacts (Figs. 4 and 5).

In regard to regional air quality, sensitivity of ozone concentrations towards precursors has been discussed earlier for urban settings (Liu et al., 2013; Wang et al., 2019). As reported in those studies, most urban sites are VOC limited, wherein decreases in NMVOC emissions will contribute to ozone reduction, while decreases in NO_x can lead to an increase in ambient O_3. Reductions in rates of night time NO_x-O_3 reactions from reduced NO_x emissions and related concentrations, leading to reduced O_3 reactive uptake, is implicated in enhancement of O_3 levels (Huang et al., 2020). Such conditions can be identified by shifts to higher values for ratio of NMVOCs emissions to NO_x emissions, $ER_{NMVOCs/NOx}$ following any intervention (Liu et al., 2013; Wang et al., 2019). However, shifts to lower $ER_{NMVOCs/NOx}$ still cannot guarantee ozone mitigation as the ratio of reduction in NMVOCs to that in NO_x is highly crucial (Liu et al., 2013; Wang et al., 2019). For, NO_x limited regimes, the reduction in NMVOCs must exceed that in NO_x for effective O_3 mitigation. Following this reasoning, implications of precursor emission changes on ambient ozone levels for certain urban regions in India, during the lockdown, are evaluated through analysis of $ER_{NMVOCs/NOx}$ under BASE and COVD scenarios in tandem with in-situ observations of changes in ambient ozone levels in those cities.

Fig. 4a and b depicts the spatial variation in ER during the first lockdown period under BASE and COVD scenarios respectively. The mean ER over India in the BASE scenario is found to be 2.7 while it increased up to 4.0 under the COVD. The factor of shift varied across the country with nearly 80% points shifting within a factor of 2, 10% between 2 and 3 times and 5% more than 3 times (Fig. 4c.). This is because of relatively lesser reductions in NMVOCs than NO_x. In India, nearly 63% of NMVOCs emissions arise from distributed area sources like residential biomass fuel combustion and agricultural residue burning which continued during the lockdown (Fig. 4e and f). We overlaid the spatial distribution of the ratio of $ER_{NMVOCs/NOx}$ during the first lockdown under COVD scenario to that during the same period under the BASE scenario with the sites having an observed increase in ambient ozone concentrations (Fig. 4d.). It is seen those sites of increased O_3 concentrations, mostly urban areas, are coincident with or in close proximity to the areas with an estimated increase in $ER_{NMVOCs/NOx}$ from greater decreases in NO_x than NMVOC emissions. Only 5% of locations with increased O_3 coincide with those of decreases in $ER_{NMVOCs/NOx}$. Such responses are consistent with the findings from earlier studies, suggesting these urban sites may be VOC limited. Therefore, while reductions in NO_x emissions are beneficial for controlling O_3 formation in downwind rural areas with a larger dominance of NMVOC emissions (or NO_x limited regions), avoiding increases in urban ozone concentrations will need further reductions in VOC emissions and concentrations at these locations.

In terms of climate impacts (Forster et al., 2020), evaluated the global temperature response where partial reductions in activity continued for another year since 2020 lockdown and then linearly recovered to baseline by end of 2022. They reported slight cooling due to reduction in CO_2, while insignificant contribution from SLCFs. However, the net impact from SLCFs can be more profound at a regional level (Gettelman et al., 2021; Jones et al., 2021; Yang et al., 2020). We

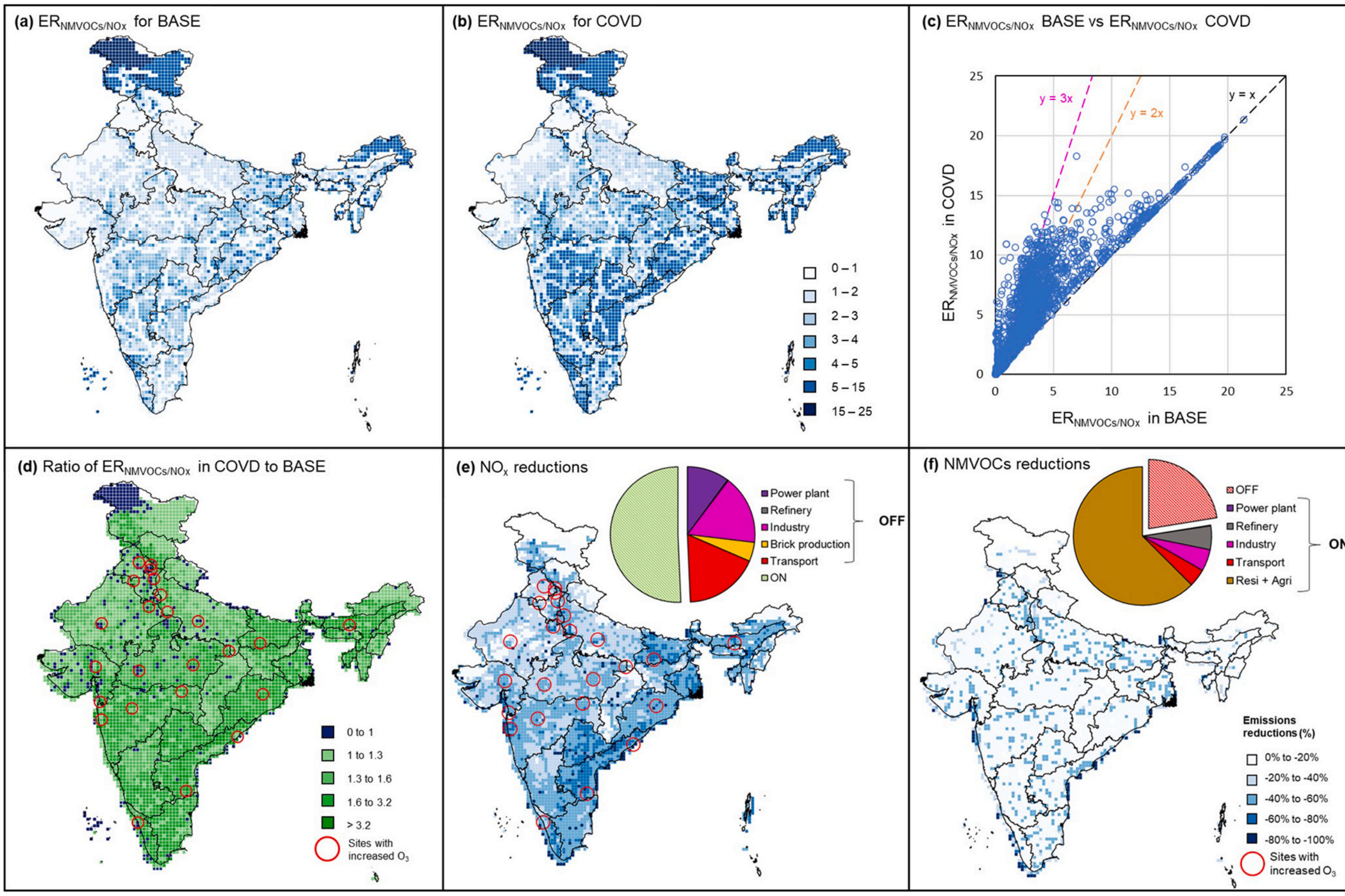

Fig. 4. Establishing links of COVID-19 closure to observed air quality response. Spatial distribution of ratio of mean daily emissions of NMVOCs to NOx ($ER_{NMVOCs/NOx}$) from 25th March 2020 to 15th April 2020 (period of first lockdown) under (a) BASE scenario and (b) COVD scenario. (c) Correlation between $ER_{NMVOCs/NOx}$ in BASE and COVD. (d) Spatial distribution of ratio of $ER_{NMVOCs/NOx}$ in BASE to COVD overlayed with sites where there was recorded increase in ambient O_3 concentrations (red circles). Spatial distribution in reductions and sectoral contribution of (e) NOx and (f) NMVOCs emissions over India. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

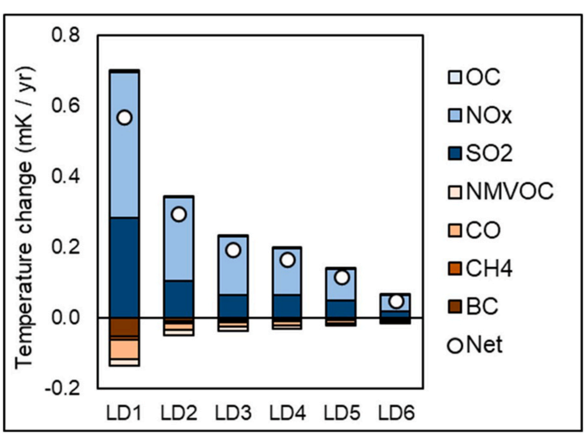

Fig. 5. Establishing links of COVID-19 closure to potential climate response. The stacked bars represent the change in temperature from individual changes in SLCFs emissions using regional temperature potential (RTP-20) assuming the reduction in each lockdown happened over a year. White circles represent the net change in temperature by combining the effects of all SLCFs.

estimated the potential change in regional temperature from reductions in SLCFs over India during the lockdown using ARTP20 as shown in Fig. 5. Combining the change across all SLCFs, it is estimated that any mitigation strategy controlling the sectors in proportions as happened during respective lockdowns will lead to a potential increase in the regional temperature rate, ranging from 0.57 to 0.05 mK/yr across lockdown periods. As we applied ARTP20, this represents the surface temperature response over the tropics band after 20 years, a commonly used time-horizon to evaluate the near-term impacts of policies. Temperature response calculated using this metric (i.e., emissions (Tg/yr) x metric (mK/Tg) = response (mK/yr)) can be interpreted as annual warming rate. Thus, to put things in to perspective, we compared our estimates with the observed mean annual warming trend over India i.e., 15 mK/yr (Sanjay et al., 2020). The warming trend varies seasonally, with pre-monsoon season witnessing the maximum trend of 26 mK/yr. The north-west India associated with frequent heat-waves, has higher rate of increase in maximum temperature, nearly 30–50 mK/yr (Mondal et al., 2020). This implies, sectoral reductions similar to those in lockdown, if scaled for an entire year may lead to additional 2–4% rise in the overall annual trend in warming at the 20th year. The metric varies with time horizons (Aamaas et al., 2017) thereby increasing the response gradually just after emissions perturbation, peaking it at timescales shorter than 20 years and declining henceforth. Thus, increase in annual rate of warming may be even higher than this at shorter-timescales. Moreover, since this represents the mean response over the whole latitude band, an estimate within a finer domain (i.e., Indian land mass) may lead to much higher rate of warming. The reduction in NO_x and SO_2 emissions account for ~80–85% of the estimated temperature response. This reiterates the need to expand policy to include specific sectors targeting wSLCF emissions to counteract unmasking of heating from cSLCF reductions.

We analysed the satellite retrieved changes in columnar burdens of NO_x (Krotkov et al., 2019) and SO_2 (Li et al., 2020), which are found to drive the increase in warming. Mean columnar burden differences between 2020 lockdown periods and corresponding periods from 2019, from daily 0.25° × 0.25° gridded Level 3 data products from the Ozone Monitoring Instrument (OMI) aboard Aura satellite (Figure S2 b and c), showed a majority of the regions experiencing significant reductions, around −50% and above (Figure S2). Overall, we find some consistency in the reduction ranges and spatial coverage over the hotspot regions, between the inventory calculation and satellite detection. A one-to-one comparison of emissions reductions and burdens reductions is not recommended due to nonlinearity in the processes that decide the fate of emissions, such as meteorology and atmospheric chemistry. Additionally, a warming response from reductions in aerosols during COVID-19 lockdown is reported based on climate modelling (Gettelman et al., 2021; Jones et al., 2021; Yang et al., 2020), consistent with the present findings. Again, a direct comparison is not suitable, because model simulations used to derive the metric (Collins et al., 2013) and those in the reported studies include different sets of atmospheric processes and their parameterizations.

3.3. Implications for air quality and climate policies

We made a link to policy by making an analogy between shutdown in activities and selected ongoing national programs. The aim is to understand the non-intuitive impacts of existing policies toward formulating corrective measures. Since transport, industry (including refineries) and power plants were affected we discuss policies related to these sectors. Policies can be categorised based on their primary agenda such as alleviating regional air quality and actions towards climate change mitigation.

Air quality policies primarily promote implementation of emissions control technology to control the degradation of regional air quality. Key policies include stringent emission standards for transport and power plants. For the transport sector, India has already begun the shift to Bharat Stage Emissions Standards VI (BS-VI) from BS-IV (The Hindu, 2020). Bharat Stage Emissions Standards refer to norms that specify the permissible amounts of air pollutants such as $PM_{2.5}$, SO_2, NO_x that can be released from vehicle exhaust. BS-VI are the most stringent emissions standards currently at par with international standards. Shifts to BS-VI can cut the NO_x emissions factors by nearly 25%–85% from BS-IV across vehicle types (ICCT, 2016). For thermal power plants, the government of India recently circulated revised emissions standards with stricter limits for stack emissions of $PM_{2.5}$ and introduced limits for SO_2 and NO_x for the first time (MoEFCC, 2015). In order to comply with these standards, emissions control devices or technology has to be retrofitted for e.g., Lean NO_x Trap (LNT) in diesel vehicles and flue gas desulphurization units (FDGs) in power plants.

On the other hand, climate policies mostly target decarbonization i.e., reduced dependency on fossil fuels through reduction in energy consumption and shifts to alternate cleaner fuel. Key policies include the Perform, Achieve and Trade (PAT) scheme for the industry sector, shifts to electric vehicles in transport and shifts to renewable power generation. Unlike the air quality policies that are based on end-of-pipe control of specific pollutants, these policies influence all the pollutants associated with that technology. Thus, besides mitigating CO_2, they have co-benefits in mitigating other pollutants.

We need to see the reduction in activity during lockdown through the lens of these policies. By analysing the air quality and climate responses during the lockdown (as discussed above), we can have a rudimentary understanding of the counterproductive effects of implementing these policies. Thus, for each lockdown, reduction in activities from industry, transport and power plants can be thought of as an analogy to implementation of PAT scheme, FGDs, BS-VI and shifts to renewable power generation and EV cars. For the discussed ozone response, BS standards mimic the transport closure partially as it only affects NO_x. Since NMVOCs will not be affected at all, thus for a given amount of NO_x reduction the ozone increase may be more enhanced as compared to the increase in lockdown conditions with same NO_x reduction. Shifts to EV vehicles mimics the transport regulations completely as it creates a similar condition with no emissions from vehicles exhaust. Thus, it will potentially create a similar response as observed during the lockdown for a given reduction. In regard to climate response, implementation of BS-VI and FGDs mimic partially as it only reduces the cSLCFs (SO_2 and NO_x) with no concurrent reductions in wSLCFs. Thus, the net temperature increase in Fig. 5 will be enhanced as there will be no compensation from reduction in wSLCFs. Implementation of the PAT scheme, renewable power generation and shifts to EV mimic the lockdown regulation and may result in similar impacts.

Analogies discussed above can help prioritizing the future course of currently ongoing policies. Besides the policies discussed above, there are several ongoing interventions proposed in other sectors as well, such as policies to boost access to clean energy which include shifts to LPG cookstove (Pradhan Mantri Ujjwala Yojana (MoPNG, 2016); and greater influx of electrical devices for lighting, water heating and space heating (Saubhagya scheme (MoP, 2017),). Other air quality policies include curbing open field burning of crop residues (MoA, 2014) and shifts to advance and cleaner firing technologies for fired-clay brick production (Emission standards; (MoEFCC, 2018)). The sectors incorporating these policies did not get regulated during the lockdown, while for the affected sectors the reductions exceed the targets of the policies (Tibrewal and Venkataraman, 2020) within them. Thus, the observed air quality and estimated climate impacts during lockdown closures can be interpreted as a sensitivity scenario where in the interventions in certain sectors are implemented at a much higher potential than those in others. In this case, policies pertaining to sectors such as power plants, industry and transport attain their maximum potential before policies in residential, agricultural and brick industry sectors. This implies, such counter-productive impacts will be felt if, a) policy targets in power plants, industry and transport are strengthened before those in residential, agricultural and brick industry sectors or b) the efficacy in policy implementation in the latter sectors are not monitored. Urgency lies in the fact that both cases (a) and (b) are very likely to happen simultaneously. The former sectors, dominant emitters of CO_2 and air pollutants ($PM_{2.5}$, SO_2 and NO_x), will continue to experience strengthening of decarbonization measures and emissions regulations to keep up with global climate agenda and control the mortality attributable to ambient pollution respectively. Additionally, poor policy formulation and unfeasibility in cleaner alternatives (Tibrewal and Venkataraman, 2020) will prevent the policies in the latter sectors realise their true objectives. This relative pacing among sectoral policies is crucial as interventions in the residential, agricultural and brick industry sectors will control emissions of black carbon (a highly potent global warming agent) while simultaneously providing relief to indoor and ambient air pollution. Setting the pace of policies delivering such co-benefits is highly essential for developing nations like India, where the co-benefits approach seems to be the most viable way to drive climate change mitigation plans (Dubash et al., 2013).

4. Conclusions

The present paper models the evolution of emissions of CO_2 and SLCFs during the COVID-19 lockdown in India. By comparing against a baseline with no lockdown, we report the reduction in emissions for these pollutants in response to closure of major economic activities pertaining to transport, power plants and industry sectors. To the best of our knowledge, this is the first exclusive study to report emissions evolution and changes during COVID-19 lockdown in India. The lockdown imposed an unprecedented scale of activity closure in the transport sector followed by industry, power plants and refineries, while residential and agricultural activities continued to operate. This proved to be a highly unbalanced emissions control scenario where in certain pollutants (CO_2, SO_2, NO_x and CO and primary $PM_{2.5}$) saw reductions as high as −75% while the others (BC, CH_4, NMVOCs and OC) were limited below −30%. Therefore, while prima facie it appears promising, there are counterproductive implications on regional air quality and climate. We link the disproportionate reductions in NO_x and NMVOCs to the observed increases in tropospheric O_3 concentrations at various urban regions across India. Further, we estimate that such disparate controls in cSLCFs and wSLCFs will lead to a net increase in future temperature, adding to the existing rate of warming over the country. While it has been established that policies mitigating an appropriate "basket of pollutants" across multiple sectors would be more effective in delivering simultaneous benefits in air quality and climate, our study goes beyond to provide evidence that the "relative pacing" among these policies in attaining their maximum mitigation potential is also very crucial to prevent counter-productive impacts.

Further, we believe the framework and analyses discussed in this paper hold international relevance. Our study provides a high resolution spatio-temporally varying emissions of all major global warming pollutants (i.e., GHGs, constituents of primary fine particulate matter and precursor gases) during the COVID-19 lockdown over India based on detailed bottom-up modelling, which can be incorporated to improve global assessments. Secondly, a simple metric-based approach (as illustrated here, for India) can provide a good first-level range of potential temperature response until extensive climate model simulations or observations are available. Finally, we illustrated a framework to utilize the lockdown closures as a tool to gauge the counter-productive impacts from differential pacing of sectoral policies.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.114079.

Author contribution

KT and CV conceptualized the study. KT collected all the relevant data, performed calculations and prepared the figures and tables. KT and CV analysed the results and drafted the manuscript.

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