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# "Traffic intervention" policy fails to mitigate air pollution in megacity Delhi

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## ABSTRACT

Megacity Delhi has been ranked amongst the top most polluted cities in the world consistently over the last few years (WHO, 2016). As a desperate and emergency measure, the administration implemented 'traffic intervention' mitigation effort by instigating 'odd-even' policy as a trial for 15 days in January (1–15) 2016. During this period, odd and even numbered private cars were restricted to respective odd and even days. Here we examine the impact of this policy intervention on ambient particulate matter smaller than 2.5 μm ($PM_{2.5}$) through a combination of in-situ, satellite and model data. Traffic restriction reduces $PM_{2.5}$ by 4–6% (maximum up to 10% in three local hotspots) which is within the uncertainty range of satellite-based estimates (and hence not detected). This is not a significant result considering the fact that such step was taken as an emergency measure when $PM_{2.5}$ exposure exceeded 250 μg/m$^3$ during the winter season. The failure is attributed to stable meteorological conditions (winds are not strong enough to disperse $PM_{2.5}$ away) during the period and there was no control over $PM_{2.5}$ outside the periphery of the city. A more comprehensive inter-sectoral and inter-state action plan is required to address this alarming issue in this region.

## 1. Introduction

$PM_{2.5}$ exposure in Delhi is a menace earning the capital of India, the second most populous country in the world, a dubious tag of being one of the top most polluted cities in the world. Ambient $PM_{2.5}$ concentration exceeds the national air quality standard by more than 300% (Central Pollution Control Board, Delhi Central Pollution Control Board, 2016; Dey et al., 2012; Guttikunda and Goel, 2013) in Delhi. $PM_{2.5}$ exposure not only results in morbidity and significant years of life lost(Greenstone et al., 2015) but also translates into estimated burden of ~12000 premature deaths per year in the Indian capital (Chowdhury and Dey, 2016). Air pollution problem in Delhi was recognised long time back and several measures were taken to curb the pollution. The sulphur content of diesel and petrol was reduced by 50 ppm during 1996–2010 and around 1328 industries categorized as 'hazardous' were shut down in this region (Narain and Krupnick, 2007). Following a court order, commercial vehicles older than 15 years were gradually phased out after 1998 and the public transport vehicles were converted to compressed natural gas (CNG)(Narain and Krupnick, 2007). Though the conversion to CNG was initiated around 2002, the intervention was found to have no profound positive impact on reducing pollution over Delhi with exception of CO (Chelani and Devotta, 2005; Kathuria, 2005).

Despite of all these efforts, $PM_{2.5}$ concentration remains alarmingly high in Delhi national capital region (NCR). Annual average $PM_{2.5}$ levels have consistently remained within the range of 110–120 μg/m$^3$ during 2011–2015 (SAFAR, IITM data). In response to various reports showing adverse effects of PM on health, the Government of Delhi initiated a bunch of policies and public measures following the National Green Tribunal Act, 2015 (http://www.greentribunal.gov.in/) which banned the use of diesel vehicles (10 years old) within the city. More recently, the Government introduced 15-days (1st to 15th January 2016) odd-even traffic restriction that allowed odd and even numbered cars (based on the last digit of the license plate) to ply on odd and even days, respectively within the city from 8 am to 8 pm with an exception on Sunday with no restriction. The restriction was only imposed on private vehicles (four wheelers) excluding the two wheelers, public vehicles, school buses and vehicles for public officials and administration. Women were also exempted from the scheme. Though this type of vehicular restriction is new to the residents of Delhi, and was met with

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mixed responses from the public, vehicular rationing or driving restrictions are not uncommon in other parts of the world. Vehicles in Mexico City, Sao Paolo, Bagota, Beijing, Tianjin and Paris have all been under the hammer of the traffic restriction laws, although there have been no clear evidence of its success (Lin et al., 2011). It was found that during and before the 2008 Olympic Games at Beijing, when the traffic restrictions were enforced by the Chinese Government, levels of sulphate and nitrate content of $PM_{2.5}$ increased while ambient concentrations of vehicle related $NO_x$ and volatile organic compounds (VOC) decreased (Wang et al., 2010). Few published reports on the odd-even traffic restriction over Delhi show that there have been slight improvement of average vehicle speed of about 9% between 11 am and 5 pm and also the odd-even policy was able to reduce the number of private cars by only 35% against the expected reduction of ~50% (Goel and Pant, 2016). A study (Li and Guo, 2016) concerning the traffic restriction during 2008 Beijing Olympics found that traffic volume reduced by only 20–40% during the odd even restriction, another study (Wang et al., 2014) found that 47.8% of the regulated car owners did not follow the traffic restriction rules and illegally drove their cars, which may also be a matter of concern for Delhi traffic restriction. Therefore, a comprehensive analysis is required to understand the impact (success or failure) of such desperate policy measure.

Winters (Dec-Feb) in Delhi typically witness very high levels of $PM_{2.5}$ concentration due to calm condition, inversion, and shallow mixing layer height that favour pollution to accumulate near surface (Kar et al., 2010). The recently published report by the Delhi Pollution Control Committee(Sharma and Dixit, 2016) estimates the average daily concentration of $PM_{2.5}$ in winter remains about 375 $\mu g/m^3$ against the permissible limit of 60 $\mu g/m^3$. The main contributors to total $PM_{2.5}$ in winter are secondary particulate particles (~25–30%), vehicular emissions (~23–28%), biomass burning (~17–26%), municipal solid waste burning (~9%), and suspended soil and road dust(Sharma and Dixit, 2016). An attempt by the Government of Delhi to restrict on-road private vehicles on odd-even basis is expected to cut off about 50% emission from private vehicles. However, a variety of other sources in the surrounding areas of NCR also contribute to total emissions(Sharma and Dixit, 2016).

Here, we examine the spatial heterogeneity in the magnitude of change in $PM_{2.5}$ across Delhi NCR by analyzing Terra-MODIS 3 km Collection 6 (MOD04_3k) aerosol optical depth (AOD) retrievals, converted to $PM_{2.5}$ using daily conversion factor (η) from Goddard Earth Observing System chemical transport model (GEOS-CHEM)(van Donkelaar et al., 2010). $PM_{2.5}$ estimates were bias-corrected(Dey et al., 2012) against coincident in-situ $PM_{2.5}$ data collected by Central Pollution Control Board (CPCB) and validated against System of Air Quality and Weather Forecasting And Research (SAFAR) data. We compute the anomaly of $PM_{2.5}$ during the pre-intervention, intervention and post-intervention periods with respect to corresponding 13-year statistics (2003–15) derived from satellite-based estimates as in-situ data are not available throughout (details are provided in the methods section). ERA-Interim derived meteorological parameters are used to check whether the meteorological conditions acted in unison with the traffic restriction in suppressing the $PM_{2.5}$ concentration over Delhi. We also use a modelling approach to simulate expected reduction in $PM_{2.5}$ concentration due to traffic intervention at similarly high resolution of $4 \times 4$ km$^2$.

## 2. Methods

### 2.1. Satellite-based $PM_{2.5}$ data

MODIS on board EOS-Terra satellite has been remotely sensing aerosol optical depth (AOD) since March 2000. MODIS level 2 data provides AOD at both 10 km and 3 km spatial resolution, with the later (MOD04_3k) was recently introduced as a part of the Collection 6. The 3 km product differs from the older 10 km product in terms of the treatment of surface reflectance in the aerosol retrieval algorithm (Remer et al., 2013). The finer product resolves delicate aerosol features like smoke plumes over land and ocean and could also be retrieved over regions where the 10 km product can barely retrieved. However, the uncertainty in the 3 km product is larger than that of 10 km product(Livingston et al., 2015; Remer et al., 2013).

In view of these pros and cons of finer resolution data, we tried to capture the spatial gradient of $PM_{2.5}$ within the city of Delhi NCT and the larger National Capital Region (NCR) using 3 km AOD product. Our region of interest constitutes the districts of New Delhi, North Delhi, North East Delhi, North West Delhi, Central Delhi, West Delhi, East Delhi, South Delhi and South West Delhi (NCT of Delhi), Rohtak, Panipat, Sonipat, Jhajjar, Rewari, Gurgaon and Faridabad (Haryana), Gautam Buddha Nagar, Bulandshahar, Faridabad, Meerut, Ghaziabad and Baghpat (Uttar Pradesh) making up the NCR region. Though the odd-even traffic restriction rule was implemented only within the districts of NCT, we extend our analyses up to NCR region to capture intervention effects on surrounding regions as well. We extracted the Dark Target C6 AOD product at 3 km from the MODIS Terra Level 2 at Atmospheric Archive and Distribution System (http://ladsweb .nascom.nasa.gov) for the years 2003–2016 (for a period from 15th Dec to 30th Jan of each year) within the region of our interest. Further, we gridded the geo-located AOD data at 3 km resolution by taking the median AOD for all the geo-located retrievals of AOD that fall within each 3 km grid box. We estimate the daily $PM_{2.5}$ by using the spatially varying daily estimates of conversion factor (η, which is the ratio of $PM_{2.5}$ to columnar AOD) at $0.1^\circ \times 0.1^\circ$ resolution estimated from the GEOS-CHEM chemical transport model. More details about the estimation of η are provided elsewhere(van Donkelaar et al., 2010). The daily η estimates are interpolated at 3 km resolution and are applied to the MODIS Terra AOD to estimate satellite derived $PM_{2.5}$ for a period of 45 days for each winter starting from 2003 to 2016. MODIS-$PM_{2.5}$ is supposed to be biased low over the Indian landmass as has been evidenced in the earlier studies (Dey et al., 2012; van Donkelaar et al., 2010). We compared MODIS-$PM_{2.5}$ with the available coincident measurements of $PM_{2.5}$ over Delhi by the Central Pollution Control Board (CPCB) at eight stations, viz. IHBAS, AnandVihar, Civil Lines, IGI Airport, ITO, Mandir Marg, Punjabi Bagh and R.K. Puram. Due to large spread in data while comparing MODIS-$PM_{2.5}$ and in-situ $PM_{2.5}$, we group MODIS-$PM_{2.5}$ and the corresponding measurements of in-situ $PM_{2.5}$ in every 2nd percentile to minimize the noise in the 3 km MODIS-$PM_{2.5}$ estimates (Mishra et al., 2016; Schutgens et al., 2016). Fig. S1a depicts the comparison between MODIS-$PM_{2.5}$ and in-situ $PM_{2.5}$ and also depicts that the MODIS-$PM_{2.5}$ is biased low. We quantify the bias in the MODIS Terra data as ($\Delta PM_{2.5}$ = In-situ $PM_{2.5}$–MODIS-$PM_{2.5}$) which may be represented by the relation:

$$\Delta PM_{2.5} = -28.71 + 0.55 \times [InsituPM_{2.5}] \quad (R = 0.8, \text{ at } 99\% \text{ CI}) \tag{1}$$

The resulting bias was corrected for MODIS-$PM_{2.5}$ > 28.71 $\mu g/m^3$ to avoid negative $PM_{2.5}$ values. The bias corrected $PM_{2.5}$ for the period from 1st December 2015 to 16th January 2016 was validated against coincident SAFAR $PM_{2.5}$ data (The SAFAR observational network of Air Quality Monitoring Stations (AQMS) and Automatic Weather Stations (AWS) established within city limits represents selected microenvironments of the city including industrial, residential, background/cleaner, urban complex, agricultural zones etc. as per international guidelines which ensures the true representation of city environment, http://safar.tropmet.res.in/MONITORING%20SYSTEM-10-3-Details)) obtained from six measurement stations located respectively at CRRI, Delhi University, IITM, IMD Ayanagar, IMD Lodhi Road and IGI Airport (Fig. S1c). The validation yields satisfactory results with slope 0.88 and R = 0.78. The satellite is able to estimate $PM_{2.5}$ with ~26% uncertainty (estimated with the error in the regression coefficients). Such high uncertainty in satellite retrieved $PM_{2.5}$ estimates can be scaled down by improving the quality of the available in-situ data used for bias-correction. The 3 km MODIS AOD product is also susceptible to be slightly erroneous over regions with high reflectivity and over cities.

Our period of interest commences from 16th December, 2015 and extends up to 31st January 2016. As our interest is to estimate the effect of traffic restriction on the prevailing air quality over Delhi, which was active for 15 days from 1st January, 2016 to 15th January 2016, we subdivide our period of interest to 3 segments, the pre-intervention period (16th December, 2015 to 31st December 2015), the intervention period (1st January, 2016January 2016 to 15th January, 2016) and the post-intervention period (16th January, 2016 to 31st January, 2016). We also estimate the $PM_{2.5}$ for the same three segments for the preceding 13 years to inspect the anomaly of bias-corrected MODIS-$PM_{2.5}$ during the period of traffic restriction.

### 2.2. Meteorological analyses

Meteorology plays an important role in modulating the $PM_{2.5}$ concentration over a region at all-time scales i.e. seasonally, daily and diurnally (Chelani, 2013; Mishra et al., 2015). Meteorology often modulates the $PM_{2.5}$ concentration by perturbing the ventilation rate (wind speed and mixed layer depth), precipitation induced wet scavenging, dry deposition, controlling the transport of anthropogenic and natural species and the emission of naturally emitted species (Daniel and Winner, 2009). To account for the effect of meteorology on the inflected $PM_{2.5}$ concentration during the pre, post and during the odd-even intervention period, we analyse meteorological variables such as wind speed, wind direction and the stability parameter. The stability parameter is defined as the difference between the temperatures at 1000 hPa and 850 hPa. Relatively higher value of stability parameter represents less stable atmosphere. We used the ERA Interim data at $0.125^{\circ} \times 0.125^{\circ}$ resolution, for analysing the mentioned meteorological variables of our interest from 16th December, 2016 to 31st January, 2016 in three time segments (pre, post and during odd-even intervention). We also analyse long term (2003–2016) climatology of these meteorological parameters to account for the anomaly of the meteorological parameters during the period of intervention.

### 2.3. Analysis using chemical transport models

Impact of the odd-even rule was also estimated using a parallel modelling approach. Multi-sectoral emission inventories were fed into the air quality model along with meteorological inputs to assess air quality in two scenarios – a) with odd-even rule, b) without odd-even rule. The difference in air quality in the two scenarios was ascertained as the impact of the intervention. In this study, we used weather research forecasting (WRF) model (version 3.4.1.) for carrying our meteorological simulations for the study domain covering Delhi and surrounding regions in National Capital Region (NCR). Thereafter, the meteorological fields were fed into the CMAQ model (Ching and Byun, 1999) version 4.7.1 for simulating $PM_{2.5}$ concentrations in the study domain. The CMAQ model takes into account the interactions of different pollutants in the atmosphere and has been used for air quality research across the world and also in India (Chen et al., 2007; Sharma et al., 2016, 2013; Sokhi et al., 2016)

The CMAQ model was fed with a baseline emission inventory for the Delhi–NCR region at a resolution of $4 \times 4\,km^2$. Emission estimates have been originally made for the year 2012 and were projected for the year 2015 based on growth rates prevailing in different sectors. Emission factor approach was used and indigenous emission factors were used wherever possible to derive emission inventory for the region for different contributing sectors like transport, industries, power, DG sets, agricultural burning, refuse burning, residential fuel consumption, etc. Meteorological simulations were carried out using the WRF model for the period December 2015 to January 2016. First 15 days of the simulations were not used in the analysis considering it as the model spinoff period. The model generated 3-dimensional meteorological fields at a resolution of $4 \times 4\,km^2$ were fed into the CMAQ model along with the emission inventory. Boundary conditions for $PM_{2.5}$ concentrations for the study domain were taken from Indian scale runs carried out in (Sharma et al., 2016). This was to account for long range transport of pollutant towards Delhi. 24-hourly $PM_{2.5}$ concentrations were predicted for all the grids in the domain. The model performance was validated by comparing the model predicted values at 10 locations in Delhi where PM2.5 concentrations were measured in the city under the SAFAR monitoring program.

On satisfactory validation of the model, emission inventories were reduced considering the odd-even rule presumably resulting in 50% reduction in cars on-road. We assume 50% reduction in car population as a conservative approach to assess the maximum potential of the odd even traffic restriction, we understand that the actual reduction may be less than 50% (Goel and Pant, 2016) due to various issues as has been observed in similar analyses elsewhere (Wang et al., 2014) and different exemptions given to certain categories during the odd-even rule in Delhi. Both reductions in tail-pipe emissions and road dust re-suspension due to movement of cars were taken into account while estimating the impact of the intervention. The difference in $PM_{2.5}$ concentrations in the baseline and odd-even scenario was ascertained as the impact of the odd-even scheme.

## 3. Results and discussions

### 3.1. Change in ambient $PM_{2.5}$ during pre-intervention to post-intervention period in delhi NCR

Fig. 1(a) depicts the average concentration of $PM_{2.5}$ overlain on

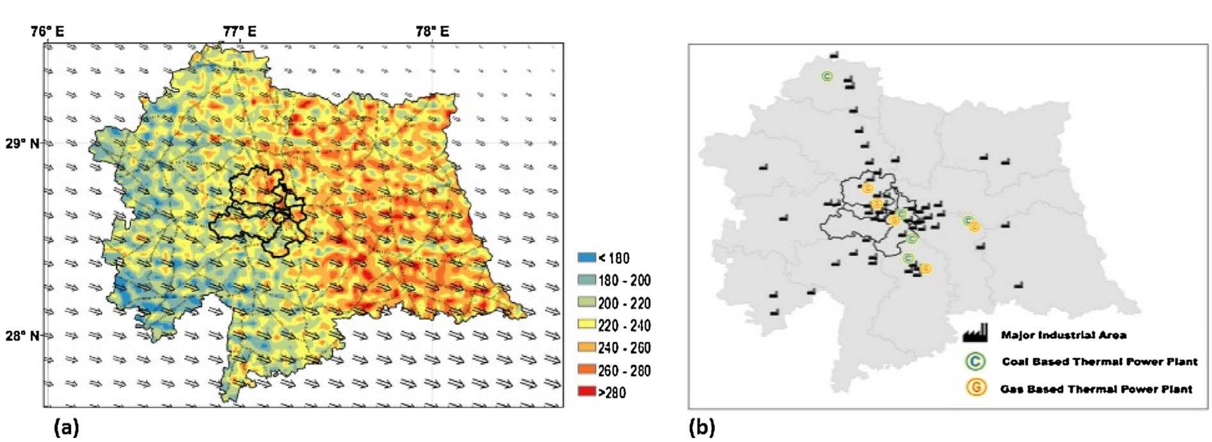


**Fig. 1.** (a) 13 year average winter time $PM_{2.5}$ (in $\mu g/m^3$) over the National Capital Region (NCR) of Delhi, the arrows indicate the wind direction and the size of the arrows indicate the wind speed. The dotted lines indicate major highways. (b) Major point sources of emission (major industrial clusters, coal and gas based power plants) in NCR.

wind vectors over Delhi for 45 days (16th December to 31st January) for the period 2003–2016 during winter. The analysis is restricted within the boundaries of Delhi NCR consisting of 13 districts from Uttar Pradesh and Haryana and 9 districts of the National Capital Territory (NCT, where the odd-even traffic restriction was implemented). It can be seen that MODIS Terra derived $PM_{2.5}$ is higher in the districts on the eastern flank of NCR with respect to the districts which lie on the western NCR. Westerly wind may be held responsible for transport of PM pollution towards the eastern flanks of NCR resulting in the concentration in most of the eastern districts of NCR being almost twice of the districts on the western flanks. Fig. 1(b) depicts the major industrial areas in the NCR as well as the major coal and gas based power plants. There are 3 gas-based power plants and 2 coal-based power plants within the limits of NCT and there are in total 6 gas based and 6 coal based power plants within the boundaries of the NCR. These power plants and large industrial areas mostly emit huge amount of PM, $CO_2$, CO, $SO_2$, $NO_x$ apart from large amount of hazardous chemicals and trace elements like lead, cadmium and mercury(Mittal, 2010). These primary pollution sources along with vehicular emissions and other emissions as discussed above are contributing to the large loading of $PM_{2.5}$ over Delhi.

Fig. S2 (Supplementary material) depicts the thirteen years mean $PM_{2.5}$ concentration and the meteorological parameters during the three time segments. It depicts that the meteorological factors (both wind speed and the stability parameter) are conducive for stagnation of the pollutants during the pre-intervention and intervention periods (Fig. S2 a) resulting in high concentration of $PM_{2.5}$. On the other hand, the meteorology in the post intervention period is climatologically more conducive for dispersion of the pollutants, resulting in relatively low $PM_{2.5}$ concentration during the post intervention period. The stability parameters (temperature difference between 1000 hPa and 850 hPa pressure levels) and wind vectors for the three time segments i.e. pre-intervention (16th to 31st December 2015), intervention (1st to 15th January, 2016) and post-intervention (16th to 31st January, 2016) periods are depicted in the Supplementary Fig. S3 and S4 . The anomalies for these two parameters are depicted in Fig. S5. Fig. 2 shows the anomaly maps of $PM_{2.5}$ for the respective time segments. Relatively increased mean wind speed and decreased mean stability during pre-intervention period make it favourable for dispersion of pollutants. However, the anomaly map of $PM_{2.5}$ during pre-intervention period (Fig. 2a) shows an increased $PM_{2.5}$ concentration (relative to 13 years mean) over most parts of Delhi. Although the concentration over most of the NCT region is observed to decrease with respect to the 13 year climatological mean during the traffic intervention period, higher $PM_{2.5}$ concentration (positive anomaly) over the western flanks of NCR combined with westerly wind may have responsible for increased $PM_{2.5}$ over the western side of NCT (Fig. 2b). This indicates traffic restriction may not be effective in reducing $PM_{2.5}$ if applied only within the limits of NCT given that neighbouring districts (located in NCR) of NCT have equally dirty air. Further, restricting 50% of the private cars which contribute to just about 3% of the total $PM_{2.5}$ emission(Sharma and Dixit, 2016) would not be effective due to prevalence of other factors that contribute to emission of $PM_{2.5}$ in and around the NCT periphery. During the post intervention period (16–31 January, 2016), the absolute $PM_{2.5}$ concentration is much lower than the previous periods. However, some scattered positive anomaly with respect to 13 year climatological mean could be attributed to meteorology that was favourable for pollution to be more stagnant than in the previous years (Fig. S3 & S4). In spite of regulations imposed on the traffic count, the change in $PM_{2.5}$ concentration has remained within the uncertainty range of the satellite-based $PM_{2.5}$ with respect to the pre and the post intervention period perhaps due to transport of pollution from the western districts. Same conclusion can be drawn from the analysis with only SAFAR data.

### *3.2. Simulation to assess the change in $PM_{2.5}$ concentrations in Delhi due to odd-even scheme using WRF-CMAQ models*

The observed $PM_{2.5}$ change discussed previously does not quantify the possible reduction in $PM_{2.5}$ as a result of lower vehicular emission and re-suspended dusts due to traffic restriction. This is addressed by carrying out modelling exercise using the emission inventory presented in Supplementary Table S1. Emission inventory (at a grid resolution of $4 \times 4\ km^2$) is prepared for the NCR including Delhi for various sources e.g. transport, residential, power, industries, open burning etc. The approach used for emission estimation was based on sectoral activity data and emission factors (Eq. (2)).

$$E_k = \sum_l \sum_m \sum_n A_{k,l,m.} ef_{k,l,m.} (1 - \eta_{l,m,n.}).\ X_{k,l,m,n} \tag{2}$$

where *k, l, m, n* are region, sector, fuel or activity type, abatement technology; *E* denotes emissions of pollutants; *A* the activity rate; *ef* the unabated emission factor; $\eta$ the removal efficiency; and *X* the actual application rate of control technology *n* where $\Sigma X = 1$ (Klimont et al., 2002).

Table S1 presents the emission estimates of $PM_{2.5}$ for Delhi and whole NCR. Emission estimates are compared with previous inventories for $PM_{2.5}$ as reported in Sharma and Dixit (2016), and were found to be in close agreement. Sectoral distributions of emissions are shown in Supplementary material Fig. S5. The primary $PM_{2.5}$ emissions along with inventories of other gaseous pollutants (which contribute to secondary particulate formation) were fed into the Community Modeling and Analysis System (CMAQ) model for air quality simulations. The $PM_{2.5}$ concentrations were simulated by the WRF-CMAQ modelling approach(Sharma et al., 2016) for pre-intervention, intervention and post-intervention periods. The modelled average $PM_{2.5}$ concentrations were found to be about 5% higher during the intervention in comparison to the pre-intervention period. This was mainly due to lower PBL and wind speed in January than in December as also reproduced by WRF meteorological simulations. We note that the model simulated $PM_{2.5}$ may be under-estimated slightly (Fig. S7, Supplementary material) due to uncertainties in emission inventories, unaccounted emission sources and error in simulated meteorological simulations. However, the objective here is a relative assessment of maximum possible reduction in $PM_{2.5}$ when the emissions corresponding to lesser vehicles that were taken off the road are reduced in the model. We consider that a decrease of cars by 50% due to the odd-even rule resulted in a reduction of 0.25 T/day of tail-pipe and 8 T/day of road dust $PM_{2.5}$ emissions in Delhi. However, in absence of any information, no additional emissions due to possible increase in two-wheelers/buses or any other modes of transport is assumed in the model. The model was rerun with reduced emission inventory and $PM_{2.5}$ concentration was simulated. The percentage difference in $PM_{2.5}$ in baseline and reduced emissions (due to odd-even rule) scenario is shown in Fig. 3.

A reduction of 1–10% is estimated across different parts of Delhi due to 50% reduction in cars assuming a full compliance of the 'odd-even' policy. Central part of the city with higher vehicular activity shows higher reduction than the outskirts. It is to be noted that main part of the reduction is coming due to reduction in the road dust re-suspension with less number of cars on road, and only a small effect is attributed to reduction in tail-pipe emissions. This reduction is not detected in the analysis of satellite data because of two reasons. In reality, exemptions were given to women and VIP categories and there is no available count of vehicles actually operated during the intervention period. Moreover, there could be a rise in number of two-wheelers due to shift from cars to other modes of road transport.

## 4. Conclusions

In this study we attempt to quantify the effect of traffic restriction during 1st to 15th of January, 2016 on the $PM_{2.5}$ concentration over

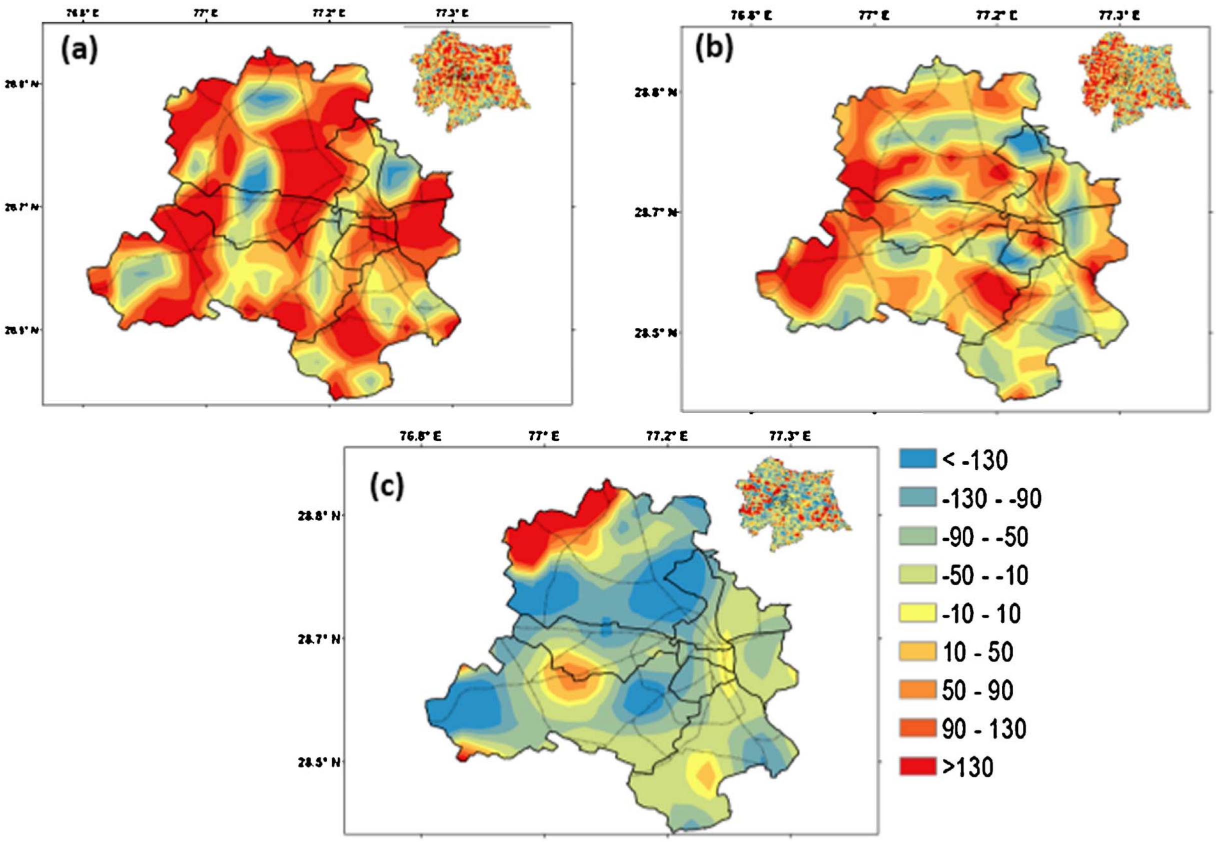


**Fig. 2.** Anomaly of $PM_{2.5}$ (Deviation of $PM_{2.5}$ in the 3 time segments from 13 year average concentration) in the (a) pre-intervention (16th December 2016–31st December 2016), (b) intervention (1st January 2016–15th January 2016) and (c) post-intervention (16th January 2016–31st January 2016) periods with respect to 13 year mean in Delhi NCT. The same for larger NCR is shown as inset.

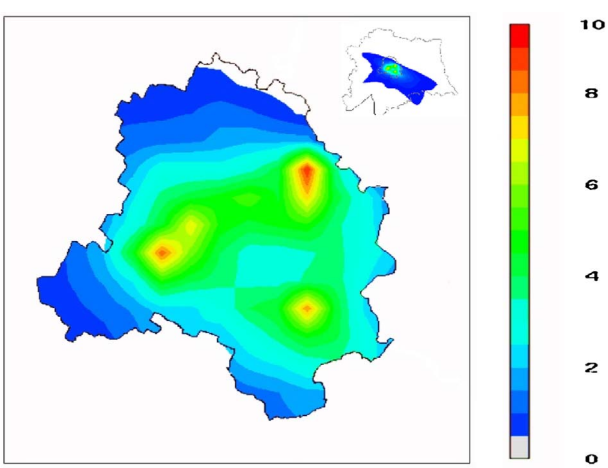


**Fig. 3.** Percentage change in PM2.5 concentration (during 1–15 Jan 2016) due to reduction in emissions due to the odd-even rule.

New Delhi. The change of $PM_{2.5}$ due to traffic restriction remains small and within the uncertainty range of the satellite-based $PM_{2.5}$ estimates. Simulations employing the WRF-CMAQ model reveal a decrease of $PM_{2.5}$ by 8–10% in three pockets of Delhi; while in remaining parts of Delhi NCT, it decreases by only 2–3%. It can be concluded that restricting traffic volume alone cannot control the $PM_{2.5}$ concentration over Delhi, where there are multiple other sources contributing towards making the city's air dirty. What we estimate is the maximum benefit the odd-even traffic restriction will achieve in short duration. However, we expect that the efficacy of the scheme will further go down in long run as people may opt for alternative vehicles in absence of access to a proper public transport system which will kill the objective of the intervention. Therefore, in the current circumstances, this intervention will continue to fail to deliver the expected benefit. We also feel that the bulk of pollution that lingers outside the NCT limits will not be contained outside the boundaries of the city if the traffic interventions are applied only within the NCT. The study of the Health effects Institute under the Public Health and Air Pollution in Asia project over Delhi (Health Effects Institute Research Report, 2011) revealed that a 10 $\mu g/m^3$ decrease in $PM_{10}$ resulted in a discounted risk of 0.15% in all-cause mortality (non-accidental). It is evident that bulk of $PM_{10}$ in Delhi during the winter is contributed by $PM_{2.5}$(Tiwari et al., 2012). Based on these two studies, we perceive that significant health benefit cannot be expected from this short-term traffic intervention. However, this provides an opportunity to explore the health benefit using retrospective data. A long-term inter-sectoral and inter-state action plan is required to deal with this critical environmental problem. In addition to few studies over Delhi attempting to identify sources of air pollution (Sharma and Dixit, 2016), a comprehensive source profiling study over Delhi should be performed to identify further detailed information about major sources and components of $PM_{2.5}$. Performing such detailed study is also expected to provide us informative knowledge about identifying the sources on which restrictions may be applied to achieve maximum benefit in terms of pollution mitigation and social acceptance.

## Author contributions

S.D., S.N.T., A.K.M. and S.C. designed the research, S.C., A.K.M. and S.S. carried out the analysis, S.C., A.K.M., S.D., S.N.T., S.S. and G.B. prepared the draft.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2017.04.018.

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