Outdoor air pollution in India is not only an urban problem

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Contributed by A. R. Ravishankara, September 22, 2020 (sent for review April 16, 2020; reviewed by Joshua S. Apte and Arlene Fiore)

Urban outdoor air pollution in the developing world, mostly due to particulate matter with diameters smaller than 2.5 µm ($PM_{2.5}$), has been highlighted in recent years. It leads to millions of premature deaths. Outdoor air pollution has also been viewed mostly as an urban problem. We use satellite-derived demarcations to parse India's population into urban and nonurban regions, which agrees with the census data. We also use the satellite-derived surface $PM_{2.5}$ levels to calculate the health impacts in the urban and nonurban regions. We show that outdoor air pollution is just as severe in nonurban regions as in the urban regions of India, with implications to monitoring, regulations, health, and policy.

air pollution | India | $PM_{2.5}$ | health impacts

Air pollution is one of the leading causes of ill health. Indeed, it has been estimated to be the fourth leading cause of premature mortality in the world (1). Air pollution has been mostly associated with urban pollution (2). It originated in big cities such as London and Los Angeles in the previous century (3, 4). Routinely, we see lists of the most polluted cities globally, again emphasizing the connection between air pollution and urban areas, with $PM_{2.5}$ being the dominant pollutant in the last few decades (5). Beijing, Delhi, Mexico City, and Jakarta are associated with high outdoor pollution in the 21st century. The $PM_{2.5}$ pollution levels in these regions are, or were, so overwhelmingly large that it attracted a great deal of attention. The rapid industrialization of Asia has led to a vast number of urban areas with PM pollution that is well beyond the World Health Organization's (WHO) guideline for healthy air (annual mean of 10 $\mu g/m^3$) (6).

Is Air Pollution in the 21st Century Really Only an Urban Problem?

There have been many health impact studies focusing on $PM_{2.5}$ effects in India (7–11). Karambelas et al. (12) have examined the question of urban versus nonurban $PM_{2.5}$ impacts over northern India via modeling calculations for 4 mo. They showed that the impacts of air pollution on nonurban residents were comparable to those on urbanites, thereby making a key point about the role of air pollution on people who are not usually considered to be impacted. They focused on the highly polluted Indo-Gangetic Plain (IGP) using 4-mo annual averages based on the results of a model that uses average emissions over large areas and times. In this article, we examine this question using observed (satellite-derived) values. We show that particulate ($PM_{2.5}$) outdoor air pollution over the entire country of India is not merely urban, but it also affects the nonurban areas just as much as the urban areas, although there are quantitative differences between regions. For each region, the urban and nonurban impacts are roughly the same, and this is true for the entire country.

Results and Discussion

Demarcation between Urban and Nonurban Areas. The demarcation of urban from nonurban regions itself is different over India compared to the western world. In the western world, the large cities and their boundaries are reasonably well defined; this is true even with the urban sprawls that are almost contiguous. The population density in nonurban regions of the developed and new world are very low compared to those in the urban regions. Also, the populations in the urban areas far exceed those in rural areas in the western world. In contrast, nonurban areas in India have large population densities, often with dense clusters of people surrounded by fields.

To parse out populations into urban and nonurban regions, one could look at the census data. Here, we have used the nightlight satellite radiances, which will likely mirror large areas of activities, transportation, and industry. The Suomi National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite (VIIRS) provides average radiance composite images using nighttime light data that were used to define the urban land areas (13–15). The VIIRS nighttime light data were available at 15 arc-seconds (~0.463 km at the equator), and we regridded the data to 2.5 arc-minutes (~4.63 km at the equator). Fig. 1*A* shows the nighttime light data over India. Fig. 1*B* shows the population density at the same 2.5 arc-minute resolution across India from the National Aeronautics and Space Administration Socioeconomic Data and Application Center for 2011 Census data (16). The most densely populated regions are the IGP and the southwest coast of India. The major urban areas are clearly visible in the nightlight data. Associated with these regions (see *SI Appendix*, Fig. S1 for the definition of the regions), the population density is clearly high but not all high population areas have significant night lights. This is particularly so in the eastern IGP (~75–85°E longitudes), where there is a large population density but not large cities. What is starkly evident in comparing Fig. 1 *A* and *B* is that there is a vast population not associated with urban areas. This conclusion is not new, and it is well understood and documented

Significance

The pollution in major cities in India is immense, and they are in the news often. In general, air pollution is viewed as an urban problem. Here, we show that outdoor air pollution due to particulate matter is just as harmful in nonurban (rural) areas as in urban areas in India based on satellite data and calculated health impacts. This finding has a far-reaching impact on how pollution is viewed in India and other developing countries. It is also very timely given that India, and countries like India, are turning attention to addressing air pollution, and they need to be aware of this vast issue.

Author contributions: A.R.R. and L.M.D. designed research; L.M.D. performed research; C.V. contributed emission inventory; A.R.R., L.M.D., and J.R.P. analyzed data; and A.R.R., L.M.D., J.R.P., and C.V. wrote the paper.

Reviewers: J.S.A., University of California, Berkeley; and A.F., Lamont-Doherty Earth Observatory and Columbia University.

The authors declare no competing interest.

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This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2007236117/-/DCSupplemental.

First published November 2, 2020.

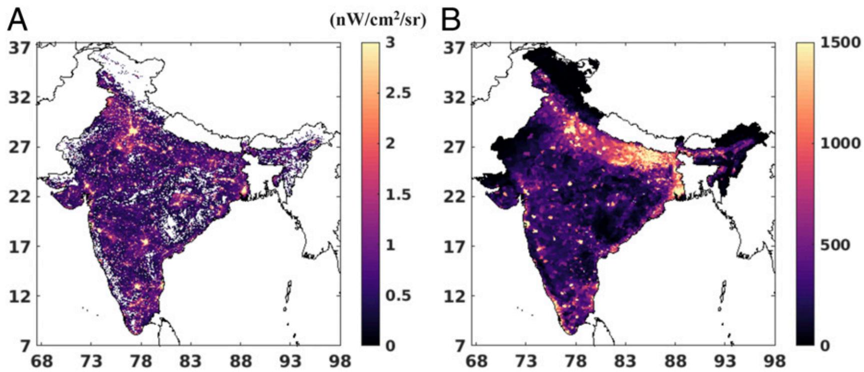

Fig. 1. Annual VIIRS nighttime light data for 2015 (*A*) and population density (based on Census 2011) (*B*).

(Census of India, 2011). Essentially, India is a country with a vast nonurban population.

We define the grids with nighttime light exceeding 1.15 nW/cm^2/sr as urban land. Based on this criterion, we estimate the urban and nonurban population to be 400 million (31%) and 890 million (69%), respectively. These numbers are consistent with the separation between urban (31.16%) and nonurban (68.84%) populations given by the Census of India 2011. *SI Appendix*, Fig. S2 shows good correspondence between the nightlight and the census data for the classification of urban and nonurban regions. It also shows that a large fraction of India's population lives outside of the urban areas.

Surface $PM_{2.5}$ Across Urban and Nonurban Regions. We calculated the annually averaged aerosol optical depth (AOD) from three satellite instruments (*Methods*) that were converted to surface $PM_{2.5}$ abundances using $PM_{2.5}$:AOD ratios from the GEOS-Chem chemical transport model following van Donkelaar et al. (17). (The obtained AOD data separated into urban and nonurban regions is shown in *SI Appendix*, Fig. S3.) We acknowledge that satellite-derived data has an element of modeling since the measured AOD is converted to surface $PM_{2.5}$ abundances using a model. We compared the satellite-derived daily and annual $PM_{2.5}$ with the surface $PM_{2.5}$ measured by Central Pollution Control Board (18) at 20 monitoring sites (mostly in the urban area) (*SI Appendix*, Fig. S4). The slope and correlation coefficient for the annually averaged and daily data comparisons are, respectively, 0.845 and 0.757 and 0.772 and 0.632; the mean bias for both are less than ±30% of the mean. Such comparisons are usually better at higher spatial resolutions. We have used footprints of 4.63 km × 4.63 km for surface $PM_{2.5}$. Hammer et al. (19) have produced data at 0.01° × 0.01° (~1 × 1 km) resolution. The annual mean $PM_{2.5}$ values from this work, GEOS-Chem at 0.25° × 0.3125° resolution, and Hammer et al. (19) are shown in *SI Appendix*, Fig. S5.

The satellite-derived annual mean surface $PM_{2.5}$ is shown in Fig. 2*A*. Comparison of Fig. 2*A* with Fig. 1 *A* and *B* clearly shows the surface $PM_{2.5}$ pollution levels are not always significantly different between urban and nonurban areas within the six regions in India. Indeed, Fig. 2*B* shows the population-weighted $PM_{2.5}$ levels separated between urban and nonurban areas for six regions of India, which have different sources, population densities, and meteorologies (20) and shown in *SI Appendix*, Fig. S1. The IGP stands out as the area of highest population-weighted $PM_{2.5}$ (>100 μg/m^3 throughout) and has the largest population density. In this region, the pollution is almost evenly spread across urban and nonurban regions. Most of India outside of the IGP has $PM_{2.5}$ levels between 55 and 90 μg/m^3 (Fig. 2*A*). These pollution levels (on average) are only about a factor of two different from the highest pollution areas that stand out (red-yellow color). Yet, even in the other five regions, there is little difference between population-weighted $PM_{2.5}$ levels between urban and nonurban regions. The annual mean $PM_{2.5}$ levels are much larger than India's national ambient air quality standard (40 μg/m^3, annual mean) in all of the six regions. The mountainous areas in the very northern parts and the lower part of the peninsula have noticeably smaller pollution levels (<40 μg/m^3) than the rest of India. Available in situ $PM_{2.5}$ observations in nonurban areas for the period 2010–2016 are shown in *SI Appendix*, Table T1). As evident in Fig. 2*A* and *SI Appendix*, Table T1, high (>90 μg/m^3) $PM_{2.5}$ concentrations are seen in nonurban areas in the IGP. This is to be compared with southern India, where the

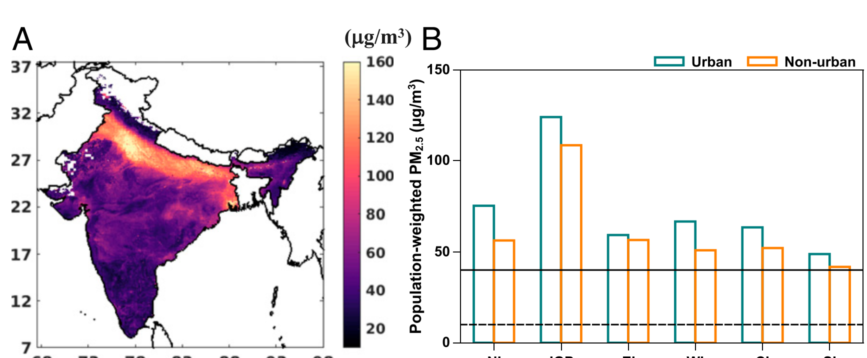

Fig. 2. Satellite-derived annual mean surface $PM_{2.5}$ (*A*) and variation in population-weighted $PM_{2.5}$ over urban and nonurban locations in six regions (*SI Appendix*, Fig. S1) of India for 2015 (*B*). The black dashed and solid horizontal lines correspond to World Health Organization's (10 μg/m^3) and India's (40 μg/m^3) annual mean $PM_{2.5}$ air quality standards, respectively.

mean $PM_{2.5}$ concentrations in nonurban locations are in the range of 30–50 μg/m^3.

Another way to look at this $PM_{2.5}$ distribution is to plot the population exposed to specific levels of $PM_{2.5}$ pollution, as done by Apte et al. (21). Fig. 3*A* shows the distribution of population in urban and nonurban areas over India, and Fig. 3 *B* and *C* shows the normalized population in urban and nonurban areas in the six regions over India with respect to $PM_{2.5}$ concentrations. Some key findings are evident: 1) Most people in India (~84% of the population) are well above the limit of India's standard (40 μg/m^3), and almost the entire country is exposed to levels higher than the WHO standard (10 μg/m^3); 2) there is a long tail of very high concentrations (>160 μg/m^3) in the urban regions in the IGP and parts of nonurban areas in eastern and western India (Fig. 3*B*), and these are the levels that are often publicized; 3) since the health impacts vary logarithmically with the $PM_{2.5}$ pollution levels (for the levels of $PM_{2.5}$ over India), the high concentrations do not proportionally enhance the health burden; 4) there are clean parts of the country where there could be larger relative differences between urban and nonurban regions, but they are relatively small; and 5) the large hump seen in Fig. 3*A* at high $PM_{2.5}$ concentrations is primarily due to the IGP. This was the area analyzed by Karambelas et al. (12) to show that the urban and nonurban areas have similar $PM_{2.5}$ loading and health impacts. Our analyses for the other regions show that the same trend is true although the $PM_{2.5}$ levels are lower than in the IGP.

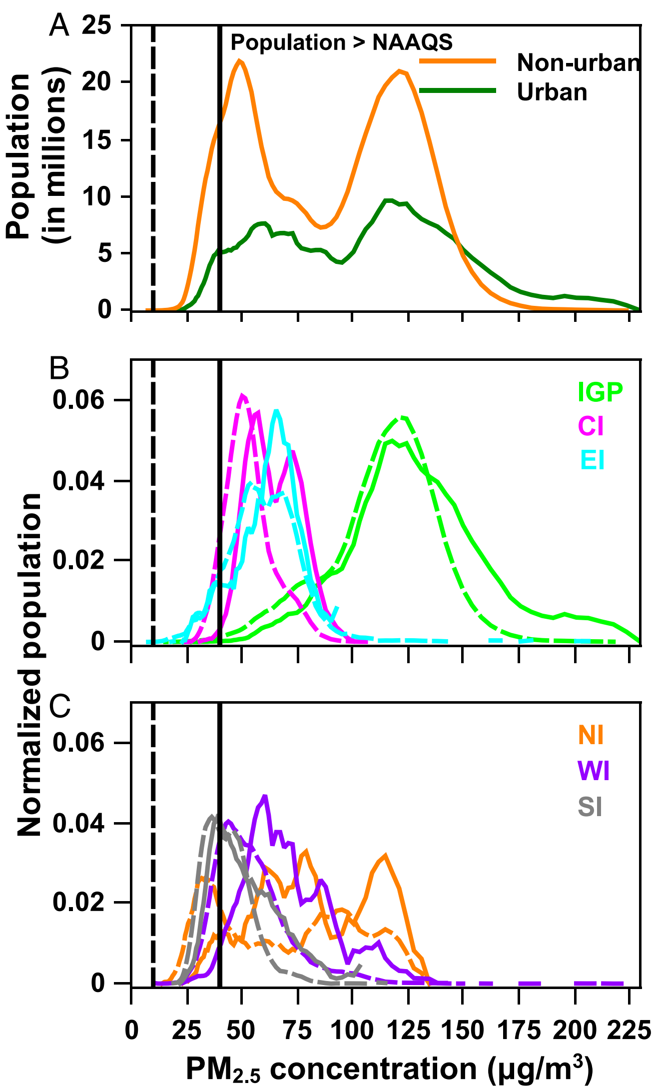

Fig. 3. Distribution of population in urban and nonurban areas (*A*) and normalized population in urban and nonurban areas in the six regions over India with respect to surface $PM_{2.5}$ concentrations (*B* and *C*). The solid and dashed lines, respectively, represent urban and nonurban regions. The black dashed and solid vertical lines correspond to WHO's (10 μg/m^3) and India's (40 μg/m^3) annual mean $PM_{2.5}$ air quality standards, respectively.

Health Impacts of the Observed Surface $PM_{2.5}$ Abundances. We have calculated the premature mortality attributable to $PM_{2.5}$ in the urban and nonurban areas for six causes of death (ischemic heart disease [IHD], stroke, lower respiratory infections [LRI], chronic obstructive pulmonary disease [COPD], lung cancer [LC], and diabetes mellitus type 2). The annual premature mortality attributable to $PM_{2.5}$ for India (urban and nonurban) is 1.05 (5–95 percentiles: 0.687–1.37) million and is comparable to those reported by other studies (1, 10, 22). These premature mortalities attributable to the $PM_{2.5}$ parsed between urban and nonurban areas are shown in Fig. 4*A*. The larger mortality in the nonurban region is due to its larger population. Fig. 4*B* shows the fraction of the premature mortalities that are attributable to $PM_{2.5}$ that occur in urban versus nonurban areas. This distribution is very similar to the population distribution of 31% urban and 69% nonurban. Fig. 4*C* shows premature mortality per million people. Clearly, there is little difference between urban and nonurban regions. The $PM_{2.5}$ levels are comparably high in both urban and nonurban regions. Furthermore, the relative risk changes roughly logarithmically with $PM_{2.5}$ at the levels seen over India. Therefore, the relative risks for the population are almost the same in the two areas. $PM_{2.5}$ air pollution, the major pollution problem in India, is just as much a contributor to the ill health of the nonurban population as the urban population. These mortality numbers will not change significantly if we include the impact of ozone pollution since they are much less than those due to PM pollution (12).

Our calculated premature deaths do have large uncertainties. We include only the uncertainties due to the response functions and not those due to $PM_{2.5}$, baseline mortality rates, model resolution, as these uncertainties dominate in most regions (23). There are significant uncertainties in the $PM_{2.5}$ levels that are not included in the current mortality uncertainties. However, these uncertainties should not affect our conclusion that the nonurban population is at almost the same risk as to the urban population. This is because we are calculating the fraction of $PM_{2.5}$ between urban to nonurban areas using the same satellite and model data. Simply put, the differences in $PM_{2.5}$ levels breathed by urban and nonurban populations are not sufficiently dissimilar to make a significant difference.

The Health Effects Institute report (24) on India's $PM_{2.5}$ air pollution clearly shows the comparable levels of the PM between urban and rural areas. A recent study has shown that the $PM_{2.5}$ levels are very high surrounding the Delhi region (25). Our conclusions, based on the satellite observations, are consistent with these findings. Our study extends the findings of Karambelas et al. (12) that urban and nonurban impacts of $PM_{2.5}$ are the same in the highly polluted IGP. Our study further emphasizes that even in less polluted (relative to the IGP) regions of India, $PM_{2.5}$ affects the urban and nonurban populations similarly. There is 16% of India's population that is not affected by this pollution (below 40 μg/m^3), and that is mostly confined to the very northwestern parts of India, the Western Ghats, and a few regions within India (Fig. 2*A*). The fraction that is below the WHO standards is very small (<0.001%).

The origin of this $PM_{2.5}$ is not addressed here but would be of great interest for mitigation efforts. Based on the current emission inventories in the model (10, 20), the total anthropogenic PM and precursor emissions in the urban and nonurban regions are 25.1 Tg/yr and 53.4 Tg/yr, respectively (*SI Appendix*, Fig. S6).

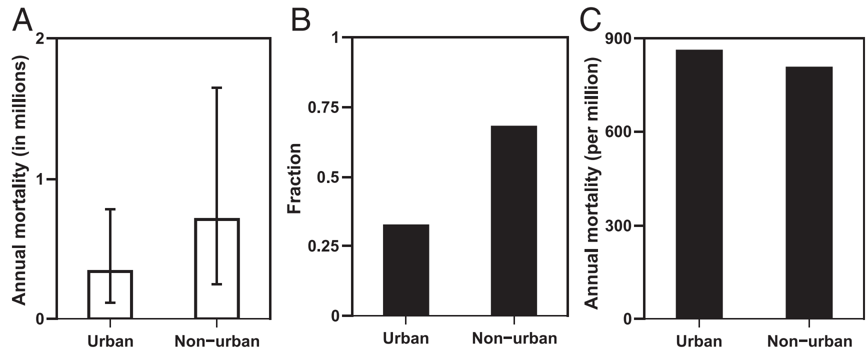

Fig. 4. (*A*) Total annual premature deaths attributed to $PM_{2.5}$ over urban and nonurban regions in India. The lower and upper limit of the error bars correspond to 5th and 95th percentile; fraction of mortality attributed to urban and nonurban regions in India (*B*); and total annual premature deaths attributed to $PM_{2.5}$ per million people over the urban and nonurban regions in India (*C*).

The residential energy use is a significant emissions source, primarily due to household cooking with solid fuels in the nonurban areas. Other sources of air pollution in nonurban areas include stubble burning, brick kilns, coal-fired factories, agricultural processing, power generation, cement factories, and cottage industries. The urban areas are affected by the transport of pollution from the nonurban regions and vice versa. The nonurban emissions in the IGP is a factor of 2–14 higher compared to other regions in India. We have shown previously that eastern India is greatly affected by pollution transport from the IGP (10). It appears that nonurban regions create a significant amount of their own pollution. The contribution of urban vs. nonurban emissions to premature deaths in nonurban areas needs to be investigated in future work.

Our work, along with those of Karambelas et al. (12), highlights the critical need for monitoring $PM_{2.5}$ levels in nonurban areas in India. Enhancing measurements in these regions, which are virtually nonexistent, could help better assess the risks. Further, it highlights the need for significant reductions in $PM_{2.5}$ levels across India. A pan-India approach to reduction would be beneficial. Of course, the outdoor air quality degradation in the nonurban regions is related to the larger indoor $PM_{2.5}$ levels in those regions. Currently, the nonurban population has a lesser ability to reduce their risks because of economic reasons and, thereby, raising equity issues. The nonurban regions have the further confounding influence of indoor air quality due to the use of solid fuels for cooking in inefficient cookstoves. The inclusion of this impact would only tend to enhance the air pollution impacts in nonurban areas relative to urban areas. If one were to add indoor pollution and synergistic effects of nutritional deficiencies in the rural areas (26), not the topics of this paper, there could be even larger impacts on the nonurban populations, especially to women and children. Clearly, the nonurban regions in India are being affected by air pollution as much as the more visible urban regions.

Methods

Definition of Urban and Nonurban Population in India.

Satellite data for calculating urban and nonurban populations. The Earth Observation Group in the National Oceanic and Atmospheric Administration's National Centers for Environmental Information provide the nighttime light data from the VIIRS Day/Night Band (DNB). The VIIRS can detect nighttime lights within the radiation range from 3×10^{-9} W/cm^2/sr to 0.02 W/cm^2/sr, with an extensive spatial coverage from 75°N latitude to 65°S and a swath of 3,000 km (13). We used the annual VIIRS nighttime light data, which contains cloud-free average radiance values (in nW/cm^2/sr) that have removed outliers to filter out fires, other ephemeral lights (e.g., lights on fishing boats and fires), and background (nonlights). The products are produced in 15 arc-seconds that were regridded to 2.5 arc-minutes to match the population grid. The grids with nightlight satellite radiance exceeding 1.15 nW/cm^2/sr were defined as urban land.

Census data. The Indian census of 2011 deemed urban areas as 1) all places with a municipality, corporation, cantonment board (civic administration body in India), or notified town area committee; and 2) all other places which satisfied the following criteria of a minimum population of 5,000 with at least 75% of the male working population engaged in nonagricultural pursuits and a population density of at least 400 persons/km^2.

Comparison of our nighttime light data determined separation between urban and nonurban land compares very well with census data and the established consensus that a large fraction of India's population lives outside of the urban areas (*SI Appendix*, Fig. S2). It should be noted that some of the most densely populated regions in India are the nonurban areas in the eastern IGP (Fig. 1*B*). Many of these nonurban regions have a population density comparable to the US suburbs or many cities.

$PM_{2.5}$ Surface Abundance. India is data-sparse for surface observations. Even the few stations that are available are located in urban regions and provide long-term averaged data. Therefore, we cannot rely on surface data for calculating $PM_{2.5}$ across India, especially in nonurban regions where such data are virtually absent. Consequently, we have used satellite-retrieved AOD and used that information with the $PM_{2.5}$:AOD ratios from a chemical transport model to derive surface $PM_{2.5}$.

Satellite data. We used the AOD from three different satellite instruments: 1) the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard Terra satellite with an equator crossing time at ∼10:30 AM local time (LT); 2) the MODIS instrument aboard the Aqua satellite with an equator crossing time at ∼1:30 PM LT; and 3) the Multiangle Imaging SpectroRadiometer (MISR) instrument aboard the Terra satellite. MODIS measures visible and infrared radiation from 36 spectral bands (0.4–14.5 μm with spatial resolutions of 250 m, 500 m, and 1 km) at nadir. MISR features nine push broom cameras observing the Earth from different angles in four spectral bands (0.443–0.865 m) with resolutions of 275 m to 1.1 km. Both Terra and Aqua MODIS instruments view the entire Earth in 1–2 d, and it takes 9 d for MISR to view the entire globe.

For MODIS, we used the level 2 (collection 6.1) at 3-km spatial resolution "Optical depth land and ocean" product (merged Dark Target and Deep Blue) with the highest quality at 550 nm. For MISR, we used level 2 (version 23) AOD with a spatial resolution of 4.4 km. Although the optical depths derived from these three instruments differ, our calculated differences between urban and nonurban regions are robust and essentially the same (*SI Appendix*, Fig. S3). Both MODIS and MISR show similar seasonal variations except for the monsoon months. The lower AOD during the monsoon season seen by MISR has been attributed to the sampling bias due to cloudy conditions during the monsoon (June–September) months.

GEOS-Chem simulation. We used the GEOS-Chem global three-dimensional model (version 12.0.3) driven by assimilated meteorological data (acmg.seas.harvard.edu/geos). The model has fully coupled tropospheric NO_x-O_x-hydrocarbon-aerosol chemistry. The global GEOS-Chem simulations were made at 2° × 2.5° resolution using Goddard Earth Observing System-Forward Processing (GEOS-FP) meteorology to generate temporally varying boundary conditions for all species for higher-resolution nested simulations at 0.25° × 0.3125° over India. The details of the emissions used are given elsewhere (20). The nested simulations were carried out to determine AOD and surface

$PM_{2.5}$. The simulated AOD was evaluated against observations, as described in David et al. (20). The simulated $PM_{2.5}$ was evaluated against observations from Central Pollution Control Board. The correlation coefficient and bias were 0.793 and 17.8 ± 50.8 $\mu g/m^3$, respectively.

Estimation of Surface $PM_{2.5}$. The satellite-derived surface $PM_{2.5}$ was derived using satellite-observed AOD using the following relationship (27):

$$PM2.5_{surface} = \eta \times AOD_{satellite},$$

where η is the ratio of daily simulated surface $PM_{2.5}$ to AOD. The satellite-observed AOD within a grid (at 0.25° × 0.3125° resolution) was subjected to the same η value. The daily AOD from each instrument was converted to $PM_{2.5}$ separately. After that, the satellite-derived $PM_{2.5}$ values from each instrument that lies within a 2.5 arc-minute grid were averaged to get the daily $PM_{2.5}$. We averaged the daily $PM_{2.5}$ to calculate the annual mean $PM_{2.5}$.

Calculation of Premature Mortality. To estimate the ambient $PM_{2.5}$ exposure in India, the estimated daily surface $PM_{2.5}$ from MODIS (Terra/Aqua) and MISR were averaged and regridded to the population grid (at 2.5 arc-minute resolution). Since the density of MODIS data are larger than that of MISR, the calculated premature mortality is weighted toward the MODIS data. However, the ratio of the urban to nonurban surface $PM_{2.5}$ level does not change with the choice of the MODIS vs. MISR data. The premature mortality due to ambient PM pollution was calculated using the relative risks at different $PM_{2.5}$ concentrations for six causes of death from Global Burden of Disease 2017 (28). The theoretical minimum risk exposure level for ambient PM was defined as a population-weighted annual mean $PM_{2.5}$ between 2.4 and 5.9 $\mu g/m^3$. We have used the state-wise baseline mortality rates (22, 29). The relative risks and baseline mortality rates for LRI, COPD, LC, and diabetes are for all ages, and for IHD and stroke it is age-dependent (above 25 y). The number of mortalities within a grid cell (∼4.63 km) for each cause of death was calculated. After that, the total mortality was calculated for the urban and nonurban regions.

Data Availability. The MODIS aerosol products (Collection 6.1 at 3 km) MOD04_3K from Terra and MYD04_3K from Aqua are available from the Atmosphere Archive and Distribution System Distributed Active Archive Center, https://ladsweb.modaps.eosdis.nasa.gov/. The MISR aerosol product (version 23 at 4.4 km) MIL2ASAE.003 is available from the ftp site ftp://l5ftl01.larc.nasa.gov/MISR/. The satellite-derived $PM_{2.5}$ data used in this study are available at https://mountainscholar.org/handle/10217/210896 (30). The gridded population data for India is available from the NASA Socioeconomic Data and Application Center (https://sedac.ciesin.columbia.edu/), which is based on the 2011 census. The average radiance composite images using nighttime light data from the VIIRS DNB is available from https://payneinstitute.mines.edu/eog-2/viirs/.

ACKNOWLEDGMENTS. This work was funded in part by National Aeronautics and Space Administration Grant 785979618. We are grateful to Joshua Apte and Arlene Fiore for very insightful comments and helpful discussions with Joshua Apte that led to Fig. 3.

1. A. J. Cohen *et al*., Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: An analysis of data from the global burden of diseases study 2015. *Lancet* **389**, 1907–1918 (2017).
2. H. Ritchie, M. Roser, Outdoor Air Pollution. Our World in Data. https://ourworldindata.org/outdoor-air-pollution. Accessed 10 December 2019.
3. F. E. Littman, P. L. Magill, Some unique aspects of air pollution in Los Angeles. *Air Repair* **3**, 29–34 (1953).
4. E. T. Wilkins, Air pollution aspects of the London fog of December 1952. *Q. J. R. Meteorol. Soc.* **80**, 267–271 (1954).
5. World Health Organization, *Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease* (World Health Organization, 2016).
6. Z. An *et al*., Severe haze in northern China: A synergy of anthropogenic emissions and atmospheric processes. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 8657–8666 (2019).
7. S. Chowdhury, S. Dey, Cause-specific premature death from ambient PM2.5 exposure in India: Estimate adjusted for baseline mortality. *Environ. Int.* **91**, 283–290 (2016).
8. S. Ghude *et al*., Premature mortality in India due to PM2.5 and ozone exposure. *Geophys. Res. Lett.* **43**, 4650–4658 (2016).
9. J. Lelieveld, C. Barlas, D. Giannadaki, A. Pozzer, Model calculated global, regional and megacity premature mortality due to air pollution. *Atmos. Chem. Phys.* **13**, 7023–7037 (2013).
10. L. M. David *et al*., Premature mortality due to $PM_{2.5}$ over India: Effect of atmospheric transport and anthropogenic emissions. *Geohealth* **3**, 2–10 (2019).
11. L. Conibear, E. W. Butt, C. Knote, S. R. Arnold, D. V. Spracklen, Residential energy use emissions dominate health impacts from exposure to ambient particulate matter in India. *Nat. Commun.* **9**, 617 (2018).
12. A. Karambelas *et al*., Urban versus rural health impacts attributable to PM2.5 and O3 in northern India. *Environ. Res. Lett.* **13**, 064010 (2018).
13. K. Baugh, F.-C. Hsu, C. D. Elvidge, M. Zhizhin, Nighttime lights compositing using the VIIRS day-night band: Preliminary results. *Proc. Asia-Pacific Adv. Netw.* **35**, 70–86 (2013).
14. Y. Dou, Z. Liu, C. He, H. Yue, Urban land extraction using VIIRS nighttime light data: An evaluation of three popular methods. *Remote Sens.* **9**, 175 (2017).
15. K. Shi *et al*., Evaluation of NPP-VIIRS night-time light composite data for extracting built-up urban areas. *Remote Sens. Lett.* **5**, 358–366 (2014).
16. Center for International Earth Science Information Network–CIESIN–Columbia University, Gridded Population of the World, (GPWv4): Population density, revision 11 (Version 4, NASA socioeconomic data and applications center [SEDAC], Palisades, NY, 2018).
17. A. van Donkelaar, R. V. Martin, R. J. Park, Estimating ground-level PM2.5 using aerosol optical depth determined from satellite remote sensing. *J. Geophys. Res. Atmos.* **111**, 1–10 (2006).
18. Ministry of Environment and Forests, Continuous ambient air quality monitoring (CAAQM) (2018). https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing/data. Accessed 1 April 2020.
19. M. S. Hammer *et al*., Global estimates and long-term trends of fine particulate matter concentrations (1998-2018). *Environ. Sci. Technol.* **54**, 7879–7890 (2020).
20. L. M. David *et al*., Aerosol optical depth over India. *J. Geophys. Res. Atmos.* **123**, 3688–3703 (2018).
21. J. S. Apte, P. Pant, Toward cleaner air for a billion Indians. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 10614–10616 (2019).
22. K. Balakrishnan *et al*.; India State-Level Disease Burden Initiative Air Pollution Collaborators, The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: The global burden of disease study 2017. *Lancet Planet. Health* **3**, e26–e39 (2019).
23. J. K. Kodros *et al*., Quantifying the contribution to uncertainty in mortality attributed to household, ambient, and joint exposure to $PM_{2.5}$ from residential solid fuel use. *Geohealth* **2**, 25–39 (2018).
24. Health Effects Institute, "Burden of disease attributable to major air pollution sources in India" (HEI Special Report, Boston, MA, 2018). https://www.healtheffects.org/publication/gbd-air-pollution-india. Accessed 20 October 2020.
25. S. Chowdhury *et al*., Tracking ambient PM2.5 build-up in Delhi national capital region during the dry season over 15 years using a high-resolution (1 km) satellite aerosol dataset. *Atmos. Environ.* **204**, 142–150 (2019).
26. International Institute for Population Science (IIPS) and ICF, "National Family Health Survey (NFHS-4), 2015-16: India" (IIPS, Mumbai, 2017). Available at http://dhsprogram.com/pubs/pdf/FR339/FR339.pdf. Accessed 20 October 2020.
27. Y. Liu *et al*., Mapping annual mean ground-level PM2.5 concentrations using Multiangle Imaging Spectroradiometer aerosol optical thickness over the contiguous United States. *J. Geophys. Res. Atmos.* **109**, 1–10 (2004).
28. GBD 2017 Risk Factors Collaborators, Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990-2017: A systematic analysis for the global burden of disease Stu. *Lancet* **392**, 1923–1994 (2018).
29. L. Dandona *et al*.; India State-Level Disease Burden Initiative Collaborators, Nations within a nation: Variations in epidemiological transition across the states of India, 1990-2016 in the global burden of disease study. *Lancet* **390**, 2437–2460 (2017).
30. L. M. David, Dataset associated with "Outdoor air pollution in India is not only an urban problem." Colorado State University. Libraries. http://dx.doi.org/10.25675/10217/210896. Deposited 24 July 2020.