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Large Reductions in Solar Energy Production Due to Dust and Particulate Air Pollution

Mike H. Bergin,*[,†] Chinmay Ghoroi,[‡] Deepa Dixit,[‡] James J. Schauer,[§] and Drew T. Shindell*[,∥]

[†]Civil and Environmental Engineering, Duke University, Durham, North Carolina 27708, United States

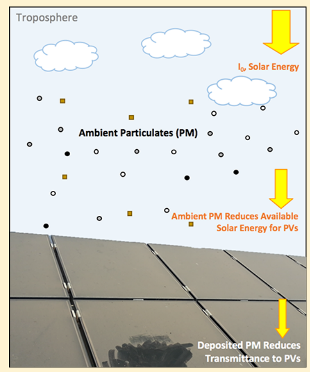
[‡]Chemical Engineering, Indian Institute of Technology Gandhinagar, Gandhinagar, Gujarat, 382355, India

[§]Civil and Environmental Engineering, University of Wisconsin at Madison, Madison, Wisconsin 53706, United States

[∥]Nicholas School of the Environment, Duke University, Durham, North Carolina 27708, United States

Supporting Information

ABSTRACT: Atmospheric particulate matter (PM) has the potential to diminish solar energy production by direct and indirect radiative forcing as well as by being deposited on solar panel surfaces, thereby reducing solar energy transmittance to photovoltaics. Worldwide solar energy production is expected to increase more rapidly than any other energy source into the middle of this century, especially in regions that experience high levels of dust and/or anthropogenic particulate pollutants, including large areas of India, China, and the Arabian Peninsula. Here we combine field measurements and global modeling to estimate the influence of dust and PM related to anthropogenic sources (e.g., fossil and biomass fuel combustion) on solar electricity generation. Results indicate that solar energy production is currently reduced by ∼17−25% across these regions, with roughly equal contributions from ambient PM and PM deposited on photovoltaic surfaces. Reductions due to dust and anthropogenic PM are comparable in northern India, whereas over eastern China, anthropogenic PM dominates. On the basis of current solar generation capacity, PM is responsible for ∼1 and ∼11 GW of solar power reduction in India and China, respectively, underscoring the large role that PM plays in reducing solar power generation output.



INTRODUCTION

Ambient particulate matter is a major health hazard, causing ∼3 million premature deaths annually.[1] It is also widely known that PM affects incoming solar radiation, and hence, it is routinely included in assessments of climate change.[2] It logically follows that PM will also affect solar energy generation, yet there have been only a few local studies of the effect of PM deposited on solar panel surfaces,[3−6] and none that have explored the impact of ambient and deposited PM, including dust and anthropogenic particles. We have therefore combined measurements and modeling to quantify the impacts of both ambient and deposited PM, including dust and anthropogenic particulate pollution, on the solar flux available for energy generation worldwide.

MATERIALS AND METHODS

Particulate Sampling and Analyses of Dust from Solar Panels. Dust samples were collected from multiple solar panels located at IIT Gandhinagar in Ahmedabad, India, and placed in clean dry containers. The mass of the dust was determined using an electronic balance (Shimadzu) with a lower mass detection limit of 100 μg. The deposition area of the collected samples was 100 cm × 164 cm. The two samples were collected on February 29 and March 22, 2016, representing 61 and 84 days of deposition, respectively. After each interval, solar panels were cleaned with water. The water insoluble particle size distribution was also measured on samples using a laser diffraction particle size analyzer (Cilas, model 1190).

The samples were also analyzed for 50 elemental components by inductively coupled mass spectrometry (ICPMS) at the University of Wisconsin at Madison using methods described by Dewana et al.[7] In addition, the samples were analyzed for total carbon, nitrogen, and hydrogen by ASTM method D5373-08 by ALS Envionmental (Tucson, AZ). Aliqouts of the samples were collected on quartz filters and analyzed for organic, carbonate, and elemental carbon before and after acidification using NIOSH method 5040. The dust composition was estimated by converting Si, Al, Ca, Fe, Ti, and K to SiO_2, Al_2O_3, CaO, Fe_2O_3, TiO_2, and K_2O, respectively. In this way, we were able to determine not only the total deposited dust mass but also the fraction of carbon (as carbonate) associated with dust.

GCM Modeling of Ambient PM Radiative Forcing. Global climate modeling (GCM) used the GISS ModelE2 configuration that is nearly identical to that used for Coupled Model Intercomparison Project Phase 5 (CMIP5) and the Atmospheric Chemistry and Climate Model Intercomparison

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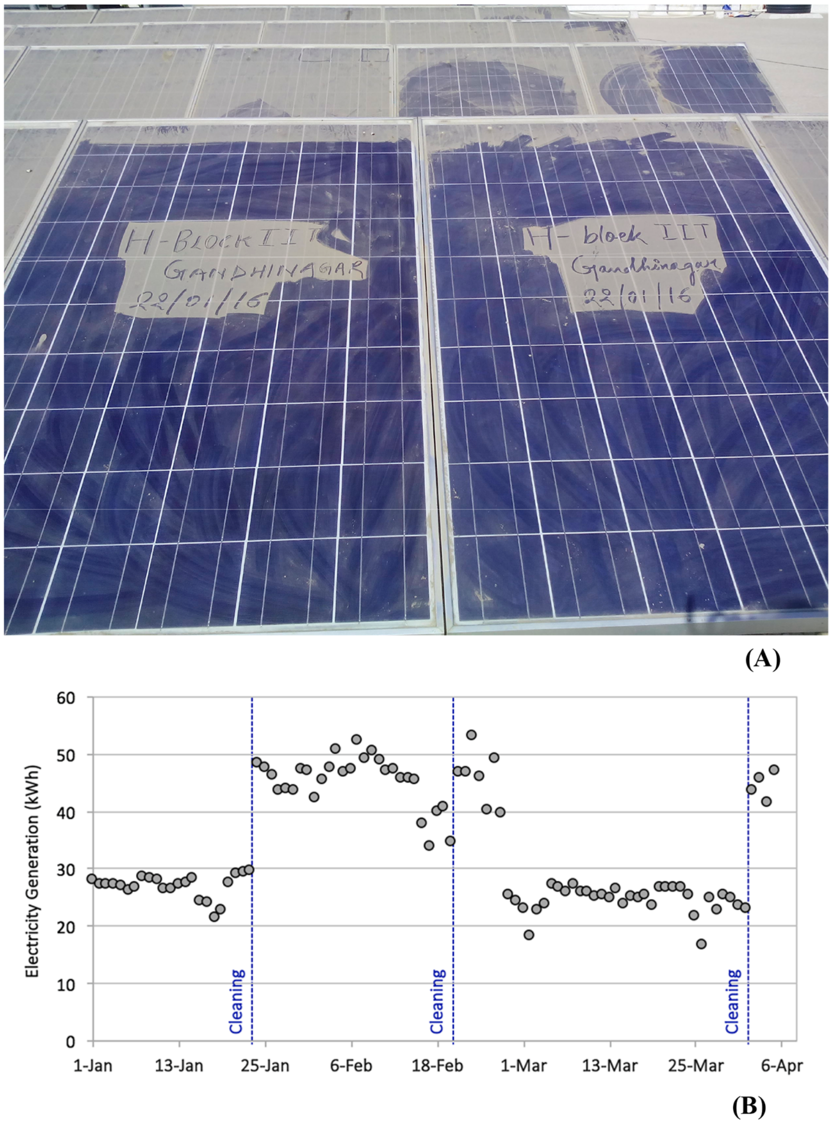

Figure 1. (A) Partially cleaned solar panels representing accumulation of PM for 28 days at IIT Gandhinagar in Ahmedabad, India, and (B) the change in measured solar energy production after several solar panel cleanings.

Project (ACCMIP).[8−10] The model estimates both direct and diffuse irradiance based on clouds and PM and accounts for their effects on the visible flux reaching the surface. Results presented here for the impact of ambient pollutants are based on the calculated change in visible flux (<770 nm, approximately the band gap energy for silicon) reaching the surface that can be attributed to the anthropogenic burden of ionic aerosols, the anthropogenic and biomass burning burdens of organic carbon (OC) and black carbon (BC), the total burden of dust, and the change in ozone relative to preindustrial simulations. For the calculations of the impact of ambient PM on solar irradiance, we include only direct effects given the large uncertainties related to indirect effects. However, we calculate the latter as well and include it in our discussion of overall uncertainties. Although diffuse and direct irradiances were not saved separately in our model runs, on the basis of our prior studies using a similar radiative transfer model, we found that in going from relatively low to high aerosol loadings in polluted regions increases the diffuse irradiance fraction from roughly 15 to 40%.[11] This underscores the need to estimate both diffuse and direct irradiance for solar power estimates. The model also estimates the dry deposition fluxes of the species. These fluxes are used, as described in the next section, to estimate the impact of deposited PM on the transmittance of solar energy to photovoltaics (PVs).

Estimating the Influence of Deposited PM on Available Solar Energy. On the basis of the deposition of the specific PM components, their influence on the transmittance of visible solar energy to solar panel PV's per unit of deposited mass ($\Delta T/\mathrm{PM_F}$) can be estimated by modifying the approach described by Bergin et al. to estimate the influence of PM deposition on the radiative balance of a surface[12,13] as

$$\frac{\Delta T}{\mathrm{PM_F}} = -\frac{1}{\mathrm{PM_F}} \sum_{i=1}^{n} (E_{\mathrm{abs},i} + \beta_i E_{\mathrm{scat},i})\mathrm{PM}_{\mathrm{F},i} \quad (1)$$

where $n = 4$ and represents the specific PM components (dust, OC, EC/BC, and "other", which represents the sum of the light scattering ions sulfate, nitrate, and ammonium), $\mathrm{PM_F}$ is the total mass loading of PM over a specific time period (grams per square meter), $\mathrm{PM}_{\mathrm{F},i}$ is the mass loading of component i (grams per square meter), E_{abs} and E_{scat} are the particulate matter mass

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absorption and scattering efficiencies (square meters per gram), respectively, and β is the PM upscatter fraction. We also assume that the solar panels are fixed mounted and horizontal. It is important to point out that eq 1 assumes a linear relationship between the change in transmittance and PM mass flux. Observations suggest this to be the case for low to moderate PM loadings,[3,6] leading to transmittance changes of less than ~60%, which are within the range of values we observe and estimate on the basis of eq 1. Analyses of the particle size distributions in the deposited particles indicate a relatively large mode of dust particles having mass median diameters of 15 μm with a smaller mode of particle sizes at 1−2 μm likely related to carbonaceous species and ions as well as smaller dust particles (see the Supporting Information). For dust, the assumed values for E_{abs} and E_{scat} are 0.02 and 1.0 $m^2\ g^{-1}$, consistent with dust measurements made in the Gobi Desert region of China,[14] as well as with measurements of airborne dust made over the Pacific Ocean.[15] We also assume that OC is primarily scattering with negligible influence from light-absorbing organic species (BrC), and that OC and ionic species have similar E_{scat} values of 4 $m^2\ g^{-1}$.[16] The mass absorption efficiency for EC/BC is assumed to be 8 $m^2\ g^{-1}$.[16] The upscatter fraction is taken to be 0.3 for the nondust PM particles assumed to be primarily associated with particles having diameters of ~0.2−2.0 μm, and 0.02 for larger deposited dust particles having diameters of ~5−20 μm.[17] The change in transmittance per PM mass loading ($\Delta T/PM_F$) can be estimated on the basis of the component mass fractions. Below we use eq 1 to estimate $\Delta T/PM_F$ on the basis of measurements of PM_F in northwestern India, as well as from GCM model-estimated fluxes of chemical species worldwide.

■ RESULTS AND DISCUSSION

Observed Influence of PM on Solar PV Energy Production. Figure 1A shows the impact of particulate deposition over an ~1 month period on solar panels in Ahmedabad, India, located in Gujarat province in northwestern India. The partially cleaned solar panels clearly show that PM covers the panel surfaces and suggests that the coating may be influencing solar energy production. Indeed, Figure 1B indicates that for solar panel surface cleanings that occur every 20−30 days, power generation increases by on average ~50% after each cleaning. It is worth pointing out that the deposition appears to be dominated by dust and/or pollution events that occur over periods of several days to roughly 1 week. Past studies have shown that wind-blown dust deposited on solar panels can influence solar panel performance by decreasing the amount of energy reaching PVs.[3−6] Much of the atmospheric PM burden in northern India is influenced not only by wind-blown and fugitive dust but also by anthropogenic sources, including solid biofuel and trash/refuse burning, mobile source emissions, and power generation from fossil fuel combustion that emits PM compounds, including organic (OC) and elemental carbon (EC/BC), as well as ionic species.[18,19] The concentrations of fine particulate matter (PM2.5) in northern India are typically dominated by nondust species with levels that often exceed the health standards set the World Health Organization by more than an order of magnitude.[20]

Deposited PM Composition and Influence on Solar Panel Transmittance. Figure 2 shows the PM mass components of samples collected from solar panel surfaces during February and March 2016 in Ahmedabad. The PM mass

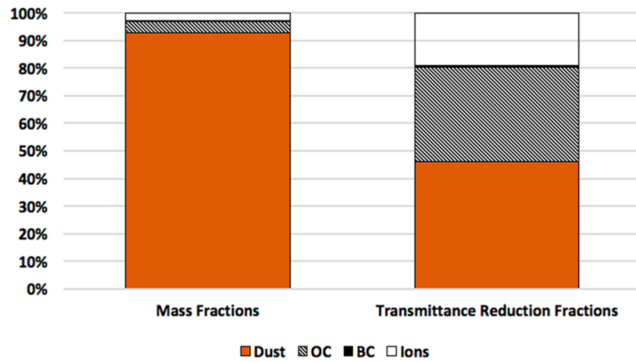

Figure 2. PM components from samples collected from solar panels at IIT Gandhinagar in Ahmedabad, India, and the estimated relative contribution of each component to the decrease in solar panel transmittance.

is dominated by dust (92%), with smaller contributions from organic carbon (4%), ions (4%), and elemental carbon (0.01%). These results reflect the mixture of dust and anthropogenic emissions that occur throughout the region. On the basis of the deposition of the specific PM components, their influence on the transmittance of visible solar energy to solar panel PVs per unit deposited mass ($\Delta T/PM_F$) is estimated using eq 1. The estimated $\Delta T/PM_F$ is −14% $g^{-1}\ m^{-2}$ of PM_F. The $\Delta T/PM_F$ is also directly determined for two samples collected on February 29 and March 22, 2016, that had PM_F values of 3.13 and 4.24 g m^{-2}, respectively. The changes in transmittance, ΔT, determined by averaging the solar energy generation from PVs several days before and several days after the panels were cleaned were 0.55 and 0.51, respectively, which translates into $\Delta T/PM_F$ values of −17 and −12% $g^{-1}\ m^{-2}$, respectively. Hence, the theoretical estimate of −14% $g^{-1}\ m^{-2}$ falls within the range of the measured values. We reiterate that our estimates assume a linear relationship between PM mass loading and ΔT; this may not be true for mass loadings substantially greater than our observed values.

It should be noted that over several 1 week periods in an arid region of northwestern India the change in the transmittance of surrogate glass surfaces due to PM deposition was found to decrease by ~9−17% per week depending on the time of year.[4] These values are within the range of reductions seen in Figure 1 that cover deposition over periods of several weeks. Reported values for $\Delta T/PM_F$ in a relatively clean region of Colorado dominated by dust deposition were found to be on average −4% $g^{-1}\ m^{-2}$, lower than the observed and calculated reductions we present here.[3] It could be that the higher values based on our sampling are due to differences in dust properties as well as the addition of deposited OC/EC and ionic species in the relatively polluted Ahmedabad region. In fact, when only dust is considered in our model, $\Delta T/PM_F$ is reduced to −7% $g^{-1}\ m^{-2}$, in general agreement, although at the higher end of the range of the previous results attributed to mainly dust deposition. An important point to make is that per unit mass, dust has an influence on solar PV transmittance due to its larger particle size and smaller upscatter fraction weaker than that of combustion-related particulate matter. This can be clearly seen in Figure 2, where although deposited nondust PM accounts for only ~8% of the total mass it is estimated to be responsible for nearly 50% of the ΔT.

Estimated Global Influence of PM on Solar Energy Production. The potential global impact of PM deposition, as

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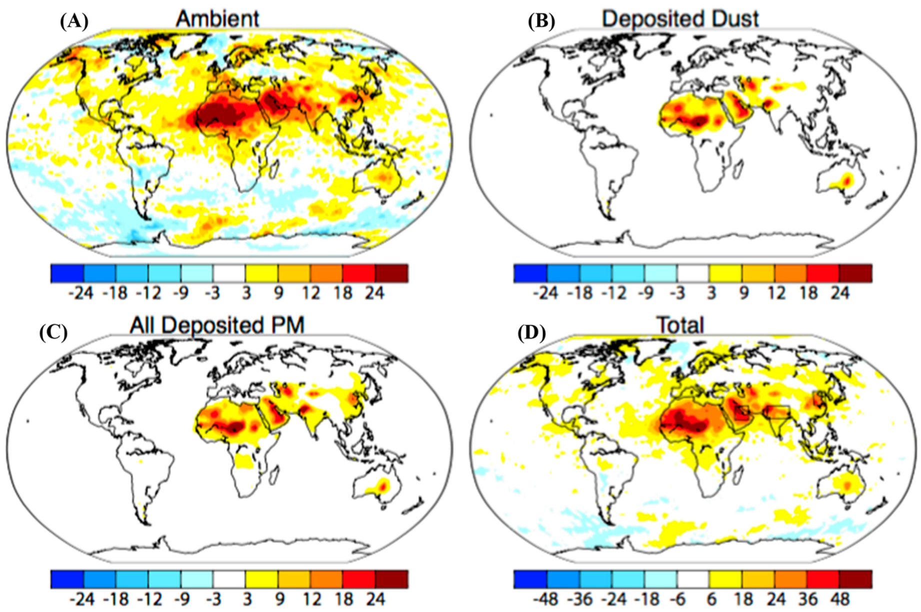

Figure 3. Percent reduction in visible solar energy due to (A) ambient PM (plus a small contribution from ozone), (B) only dust PM deposition, (C) deposition of all PM components, and (D) atmospheric and deposited combined (note the change in scale). Regions outlined in panel D are those analyzed in Figure 4.

well as the influence of ambient PM and ozone on shortwave solar energy reaching the surface, on solar energy production is estimated using surface mass fluxes for each of the PM components calculated in NASA GISS ModelE2,[8] combined with eq 1 to determine the change in transmittance (ΔT_i). The results from the NASA GISS model presented here include only the direct effect for ambient PM, although inclusion of the indirect effect and its influence on solar energy production are discussed. It is worth noting that we assume solar panels are cleaned every month, so that at the beginning of each month $\Delta T = 0$. Figure 3B shows the annual influence of dust deposition on ΔT worldwide, highlighting the influence of dust in arid regions. In northwestern India, there are areas that experience a decrease in the annual amount of available shortwave energy for solar production by as much as ~50%. Values nearly as high are seen for the Arabian Peninsula, another potentially important region for solar energy production. Figure 3C presents the impact of all deposited PM components on ΔT, showing that in regions of poor air quality with relatively high PM concentrations (i.e., China and India) OC/EC and ionic components can reduce available solar energy by 5−20% depending on the specific location. This is particularly true over eastern China and much of northern India. It should be noted that cleaning frequency for solar PVs is a critical factor, and if the time between cleanings is doubled (from every month to every two months), the average ΔT reduction will increase by a factor of 2. This would mean that for a 2 month cleaning cycle much of China and India and all of the Arabian Peninsula would see reductions in solar energy production of at least 25−35%.

PM can also influence the amount of shortwave solar energy available for solar energy production by both direct (scattering and absorption by ambient PM) and indirect (modification of cloud albedo and lifetime) radiative forcing.[21−23] Figure 3A shows the reduction in solar energy due to atmospheric PM when taking into consideration only direct aerosol effects. Dust has a clear influence on available surface shortwave energy over the source regions, including Saharan Africa, the Arabian Peninsula, and northwest India, with annual reductions ranging from ~16% in northern India to 25% over the Sahara. The influence of PM other than dust is also evident throughout the polluted regions in China and India with reductions in available solar energy ranging from on average 5 to 15%. The range is slightly smaller than reductions in solar energy of 15−25% observed during severe agricultural burning events over Singapore.[24] It should also be noted that throughout the eastern United States as well as much of western Europe ambient PM results in shortwave reductions ranging from 3 to 15%, underscoring the potential importance of PM to solar production in regions having moderate levels of ambient PM. Figure 3D shows the combined influence of both deposited PM and ambient PM on the reduction of available solar energy at the surface. Overall, striking impacts are seen over both dusty and polluted regions, with marked reductions in northern India, which experiences both. To highlight this point, we have chosen three regions with expanding solar PV energy production that experience relatively large reductions in available solar energy by PM: northern India (NI, 22−30°N, 70−90°E), eastern central China (ECC, 30−40°N, 107.5−120°E), and the Arabian Peninsula (AP, 20−32°N, 44−56°E) (see Figure 3D). In all regions, both ambient PM and deposited PM contribute significantly to reductions in solar energy production, with the deposited fraction being responsible for 40, 45, and 41% of the total reduction in ECC, NI, and AP, respectively. In the Arabian Peninsula, nearly all (84%) of the estimated ~25% reduction in solar energy production is due to dust, split roughly equally between deposited and ambient dust. For NI, ambient and deposited dust is responsible for roughly half of the 17% reduction in solar energy production, with ambient and deposited nondust PM contributing approximately equally to the other half. By contrast, ECC is a region where nondust PM dominates the 17% reduction in solar energy production, highlighting the importance of anthropogenic PM in polluted regions of China. When the aerosol indirect effect is considered in the model, it is found that the change in the amount of available solar energy at PV surfaces increases by

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~10% over ECC, due to BC-induced warming that decreases cloudiness, and decreases by ~30% over AP and NI due to increased cloudiness (associated primarily with BC and OC). Thus, results indicate that the indirect effect can change the reductions in solar energy production shown in Figure 4 by

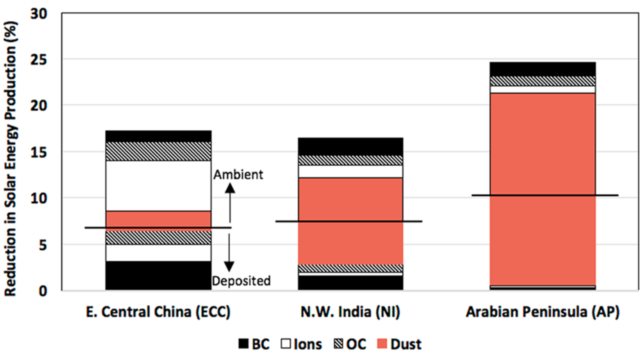

Figure 4. Modeled influence of both ambient PM and deposited PM on the reduction of available energy for solar power production in three key regions.

~1−5%. We stress, however, that indirect effects remain highly uncertain, and results from a single model thus provided limited insight. Future studies will certainly need to account for the influence of changing emissions of PM and related precursors on clouds, which can have an important influence on solar energy production. It is also worth pointing out that the modeled PM mass flux is ~40% of the value measured in Ahmedabad (see the Supporting Information for more detailed results and discussion), suggesting that overall impacts of PM on ΔT are lower limits. The current installed solar energy capacities for both India and China are estimated to be ~6 and ~65 GW, respectively.[25] On the basis of these values, the reductions in power generation due to dust and air pollution are calculated to be ~1 and ~11 GW, respectively. If the time between solar panel cleanings is increased to every 2 months, the reductions in solar energy production for ECC, NI, and AP increase to 24, 23, and 35%, respectively, emphasizing the importance of cleaning solar PVs in regions of high dust and/or anthropogenic PM concentrations. The importance of ambient PM indicates that cleaning the panels is not enough, however, and especially in regions with large contributions from anthropogenic PM, emissions controls would also be needed to maximize solar energy generation. Overall, this work provides a compelling additional reason for policy makers to adopt emissions controls along with the enormous potential benefits to public health and suggests that policy making should include air quality−solar power connections within larger efforts to simultaneously consider public health, energy, and climate change to optimize human welfare in these interlinked sectors.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.estlett.7b00197.

Analyses of deposited PM size distributions, details of estimates of ΔT using NASA GISS model results, details and uncertainties in NASA GISS model estimates, meteorological and surface irradiance data in Ahmedabad over the time period of interest, and details on the solar panels used in this study (PDF)

■ AUTHOR INFORMATION

Corresponding Authors

*E-mail: mike.bergin@duke.edu. Phone: 919-660-5209.
*E-mail: drew.shindell@duke.edu. Phone: 919-681-8467.

ORCID

Mike H. Bergin: 0000-0003-0542-485X

Author Contributions

M.B. designed the project and was involved in the preparation of text and figures. C.G. and D.D. collected solar panel deposit samples, analyzed samples for size distribution determination, and obtained solar generation data. J.S. was responsible for the chemical composition analyses, determined source contributions, and contributed text and data analysis and interpretation. D.S. developed the modeling approach, ran the GCM, analyzed results, and contributed to the text and figures.

Notes

The authors declare no competing financial interest.

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