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Letter

# Updated World Health Organization Air Quality Guidelines Highlight the Importance of Non-anthropogenic $PM_{2.5}$

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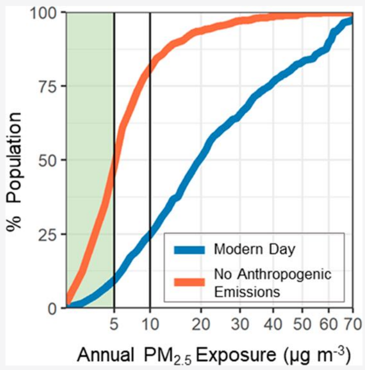
**ABSTRACT:** The World Health Organization recently updated their air quality guideline for annual fine particulate matter ($PM_{2.5}$) exposure from 10 to 5 $\mu g\ m^{-3}$, citing global health considerations. We explore if this guideline is attainable across different regions of the world using a series of model sensitivity simulations for 2019. Our results indicate that >90% of the global population is exposed to $PM_{2.5}$ concentrations that exceed the 5 $\mu g\ m^{-3}$ guideline and that only a few sparsely populated regions (largely in boreal North America and Asia) experience annual average concentrations of <5 $\mu g\ m^{-3}$. We find that even under an extreme abatement scenario, with no anthropogenic emissions, more than half of the world's population would still experience annual $PM_{2.5}$ exposures above the 5 $\mu g\ m^{-3}$ guideline (including >70% and >60% of the African and Asian populations, respectively), largely due to fires and natural dust. Our simulations demonstrate the large heterogeneity in $PM_{2.5}$ composition across different regions and highlight how $PM_{2.5}$ composition is sensitive to reductions in anthropogenic emissions. We thus suggest the use of speciated aerosol exposure guidelines to help facilitate region-specific air quality management decisions and improve health-burden estimates of fine aerosol exposure.




**KEYWORDS:** *$PM_{2.5}$, aerosols, exposure, WHO guideline, composition, health, $PM_{2.5}$ mortality*



## INTRODUCTION

Exposure to fine particulate matter ($PM_{2.5}$) has a harmful impact on human health and is a leading environmental source of premature mortality, responsible for millions of deaths every year.[1,2] Degraded air quality also impacts quality of life and human welfare.[3−7] As a result, many countries have made efforts over the past few decades to set targeted air quality regulations and implement emission abatement technologies.

To provide general guidance for decreasing global air pollution and associated mortality, the World Health Organization (WHO) has released global air quality guidelines (AQGs) since 1987. These AQGs serve as science-based benchmarks to inform country-level policies and regulations. The 1987 AQGs were subsequently updated in 1997 and 2005.[8] However, despite their broad acceptance among the international scientific community, annual $PM_{2.5}$ exposure levels in many regions have remained significantly higher than the annual 2005 WHO guideline of 10 $\mu g\ m^{-3}$.[9]

The WHO recently (September 2021) updated their air quality guidelines, recommending a more stringent limit on annual $PM_{2.5}$ exposure (5 $\mu g\ m^{-3}$) due to additional evidence of the detrimental impact of $PM_{2.5}$ on health, especially at low exposure levels.[10] The broad objective of this new guideline is to promote the regulation and elimination of anthropogenic emissions to improve global air quality. However, much of the global population lives in polluted regions that exceed even the older 2005 AQG for annual $PM_{2.5}$ exposure.[9,11]

Given the global importance of the WHO AQGs, we conduct a series of global model sensitivity simulations to explore the viability of achieving the updated $PM_{2.5}$ guidelines worldwide under different emission abatement scenarios.

## MATERIALS AND METHODS

We model global annual $PM_{2.5}$ exposures under four emission scenarios, using the GEOS-Chem chemical transport model (version 13.2.0) at a horizontal grid resolution of 2° × 2.5° (see the Supporting Information for additional details, including a description of emission inventories). We use 2019 as a representative year that is not influenced by the COVID-19 pandemic, is a reasonably typical fire year, and includes recent updates to anthropogenic emissions inventories.[12]

We conduct a baseline simulation to estimate exposure under "*ModernDay*" (2019) emissions and three further sensitivity simulations: excluding global fossil fuel and biofuel emissions (*noFossil*), excluding all anthropogenic emissions from fossil fuels, biofuels, and agricultural, crop, and livestock

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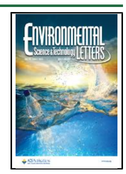

sources and anthropogenic dust from fugitive, industrial, and combustion sources (*noAnthro*; also termed *extreme abatement*), and excluding all anthropogenic and fire emissions (*noAnthro&noFire*). Pyrogenic emissions from wildfires, prescribed burns, and agricultural burning challenge our demarcation of natural and anthropogenic activities, because human activity has modified nearly every component of the fire system.[13−17] Thus, the *noAnthro&noFire* simulation is limited to emissions from biotic sources (e.g., vegetation, soil, and oceans), non-anthropogenic dust, sea salt, lightning, and volcanoes.

Our approach follows previous state-of-the-science approaches for $PM_{2.5}$ source attribution at the global scale.[9,18] For instance, a recent study by McDuffie et al. used the same global model for source apportionment, in combination with high-resolution satellite observations, to estimate local-level $PM_{2.5}$ exposures and anthropogenic source attributions for 2017. Given our goals of (1) contrasting the importance of natural and anthropogenic sources and (2) exploring the role of aerosol composition, in the context of meeting the WHO AQG on national to global scales, we present our results at the native model resolution (2° × 2.5°). McDuffie et al. also show that population-weighted $PM_{2.5}$ exposures generally increase when global models are downscaled using higher-resolution satellite data. As a result, the exposure estimates from this study are at the low end of previous estimates of global $PM_{2.5}$ exposure using the same model,[9,11,19] suggesting that our estimates of $PM_{2.5}$ exposure (and the resulting conclusions) can be viewed as conservative.

To evaluate the simulation, we compare the annual mean simulated surface $PM_{2.5}$ concentrations with surface measurements from regulatory instruments at 578 sites worldwide (Figure S2). We acknowledge the limits of this evaluation, in that existing $PM_{2.5}$ monitoring locations do not adequately capture many regions of the world.[20] Figure S2b shows that the model, as configured, captures much of the observed variability, with a relatively low bias worldwide ($R^2$ of 0.61 and an NMB of −0.095). Figure S2c suggests that the model underestimates $PM_{2.5}$ at the cleanest sites, while reproducing the overall distribution and median $PM_{2.5}$ levels worldwide. While our exposure estimates are based on a global model with inherent uncertainties, this evaluation provides some confidence in the use of GEOS-Chem to estimate annual mean exposures. Our results below are presented as lower limits with limited quantitative precision.

## RESULTS AND DISCUSSION

Annual-average continental $PM_{2.5}$ concentrations for the *ModernDay* simulation range from 1 to 163 $\mu g\ m^{-3}$, with North America and Australia experiencing the cleanest conditions and Africa and Asia subject to the highest $PM_{2.5}$ concentrations (Figure 1a). These $PM_{2.5}$ concentrations and spatial patterns are broadly consistent with the findings of previous work.[9,18,21] The dark green shading in Figure 1a demonstrates that only a few regions (e.g., parts of boreal North America and Asia) currently meet the 5 $\mu g\ m^{-3}$ WHO guideline.

Recent work has attributed millions of $PM_{2.5}$-related deaths to modern day fossil fuel sources[19] and has highlighted the substantial air quality benefits of decarbonization.[22] We find that, under an abatement scenario that completely eliminates all fossil fuel sources (*noFossil*), most of North America, much of Europe, southern Africa, parts of South America, and a smaller fraction of Asia and Australia would experience annual average $PM_{2.5}$ concentrations of <5 $\mu g\ m^{-3}$ (Figure S3).

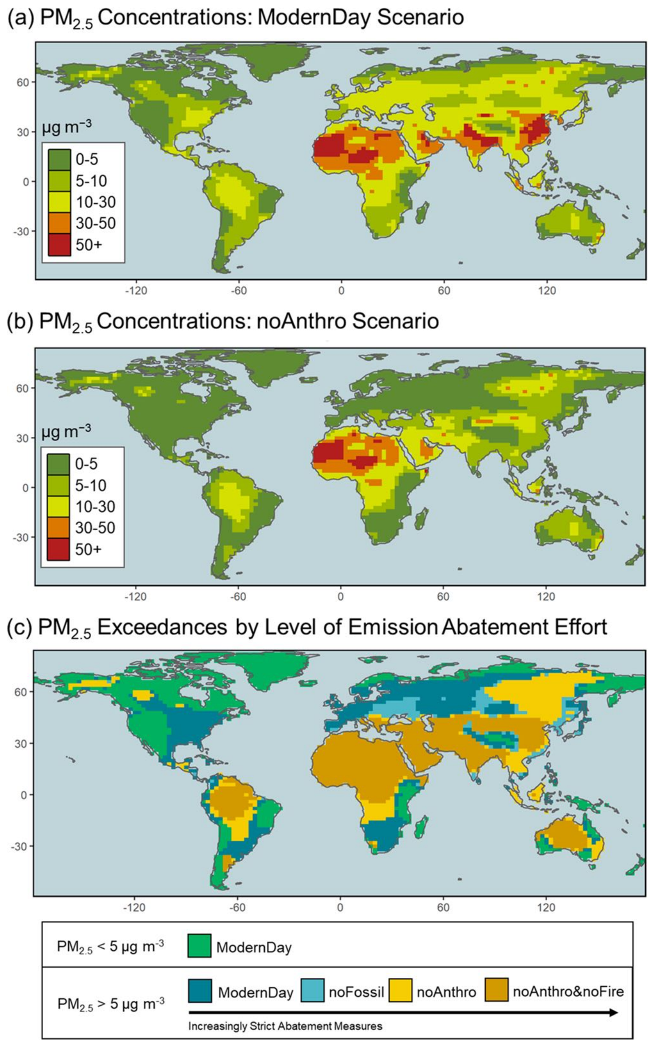


**Figure 1.** Annual $PM_{2.5}$ model-derived concentrations under the (a) *ModernDay* emission scenario and (b) extreme abatement scenario (*noAnthro*). Panel c highlights the relative importance of different sources by plotting WHO $PM_{2.5}$ exceedance areas by scenario type. The *ModernDay*, *noFossil*, *noAnthro*, and *noAnthro&noFire* scenarios are nested subsets in that order, meaning that an exceedance in one scenario denotes an exceedance in all scenarios to its left on the legend. For example, the *noAnthro&noFire* designation means that even without any anthropogenic and fire emissions, the grid boxes in beige still exceed 5 $\mu g\ m^{-3}$ due to the natural background. This also means that these grid boxes exceed the 5 $\mu g\ m^{-3}$ guideline for all other scenarios (*ModernDay*, *noFossil*, and *noAnthro*). Figures S4−S6 provide supporting information and an alternate version using the 2005 WHO guideline of 10 $\mu g\ m^{-3}$.

However, even in the *noFossil* scenario, large parts of South America, northern Africa, the Middle East, and Asia would experience $PM_{2.5}$ levels of >5 $\mu g\ m^{-3}$. While extreme abatement measures that remove all human emissions, including those from agricultural and anthropogenic dust (*noAnthro*), substantially reduce $PM_{2.5}$ concentrations (particularly over Asia), almost all the regions mentioned above would continue to experience annual $PM_{2.5}$ concentrations of >5 $\mu g\ m^{-3}$ (Figure 1b). These results challenge our expectations of realistically achieving clean air (as defined by the current WHO AQG) using purely anthropogenic controls.


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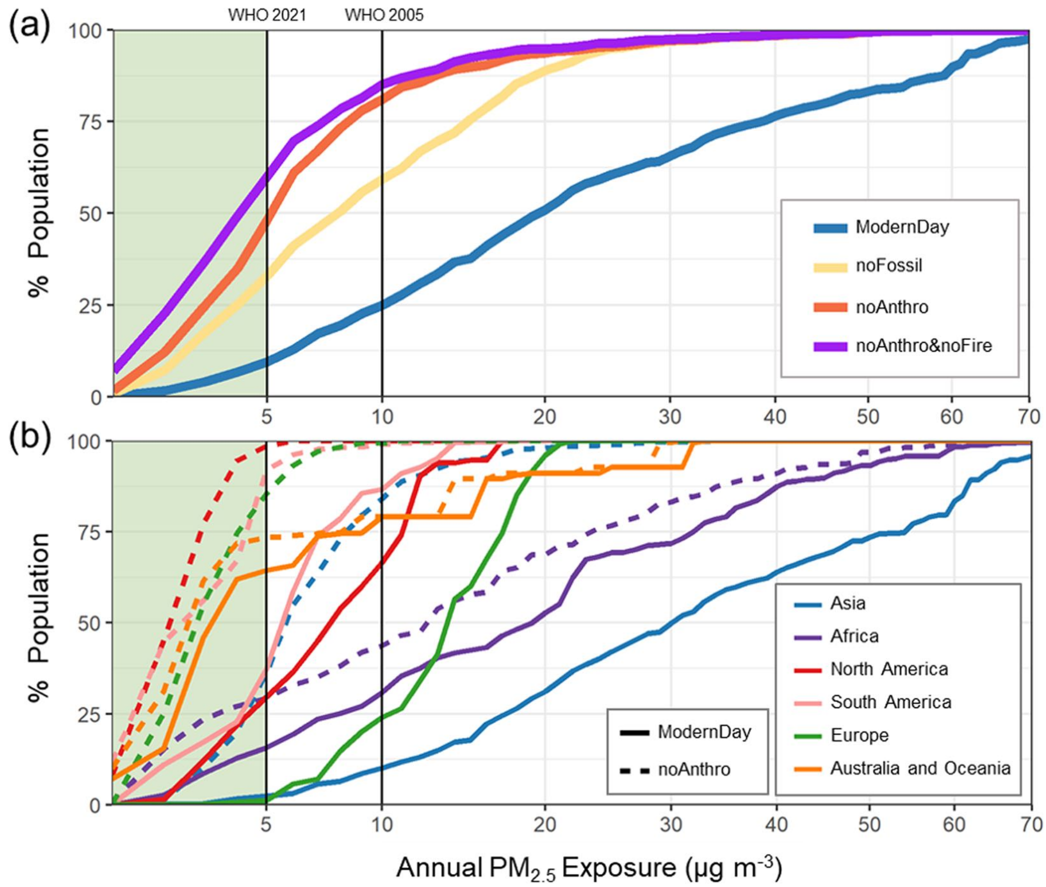


**Figure 2.** Cumulative distribution functions of population exposure to annual $PM_{2.5}$ segmented by (a) emission scenarios and (b) geographic location. Vertical black lines designate the 2005 and 2021 WHO $PM_{2.5}$ guidelines. See Figure S7 for a distribution of average annual $PM_{2.5}$ population exposures segmented by per capita national income and geographic location.

Figure 1c highlights modeled grid box exceedances of the 5 $\mu$g $m^{-3}$ guideline under the different $PM_{2.5}$ sensitivity scenarios. Non-pyrogenic natural sources (*noAnthro&noFire*) alone lead to $PM_{2.5}$ levels of >5 $\mu$g $m^{-3}$ in several areas, including northern and central Africa, the Amazon, parts of central Australia, the Arabian Peninsula, and large portions of Asia. This is largely due to natural dust, along with sea-salt and biogenic organic aerosol, consistent with the work of Zhao et al.[23] Many regions (e.g., boreal Asia, central Africa, and southeast Asia) also exceed the new guidelines due to the influence of biomass burning sources [*noAnthro* (Figure 1c)]. In addition, the *noFossil* and *noAnthro* scenarios in Figure 1c demonstrate that agricultural emissions and anthropogenic dust are important contributors to the $PM_{2.5}$ exceedances in heavily populated regions in eastern Europe and parts of Asia.

Figure 2a quantifies annual $PM_{2.5}$ exposure across the global population. Under modern day emissions, >75% of the world's population is exposed to >10 $\mu$g $m^{-3}$ (the 2005 AQG) and >90% is exposed to >5 $\mu$g $m^{-3}$ (the 2021 ACG), numbers that are generally consistent with the findings of previous work.[5,9,21] While global fossil fuel abatement (*noFossil*) (tan in Figure 2a) would have limited success in meeting the WHO guidelines (with >65% of the population still in exceedance), it significantly reduces the high tail of the *ModernDay* distribution and decreases annual exposures of >25 $\mu$g $m^{-3}$ from ∼40% to ∼5% of the global population (Figure 2a), likely translating into substantial global health benefits. Removing agricultural and anthropogenic dust emissions (*noAnthro*, orange trace) would further reduce exposure, although >50% the world's population would still be exposed to $PM_{2.5}$ levels of >5 $\mu$g $m^{-3}$. The *noAnthro&noFire* scenario (shown in purple) demonstrates that global $PM_{2.5}$ exposure from non-pyrogenic natural sources alone could result in ∼40% of the global population being exposed to $PM_{2.5}$ levels that are above the revised WHO AQG. To contextualize this result, in our simulations, 14% of the global population experiences natural $PM_{2.5}$ concentrations between 4 and 5 $\mu$g $m^{-3}$ and 8% experiences natural $PM_{2.5}$ concentrations between 5 and 6 $\mu$g $m^{-3}$ (Figure S8); our estimates of whether natural sources exceed the WHO guidelines for these populations may be subject to model bias in the representation of natural aerosol.

Figure 2b illustrates the regional variation in $PM_{2.5}$ response, with populations on many continents still exposed to concentrations substantially above 5 $\mu$g $m^{-3}$, even under extreme anthropogenic emission abatement (*noAnthro*). The figure shows large differences in population exposure between the *ModernDay* (solid lines) and *noAnthro* (dashed lines) scenarios over Asia, Europe, South America, and North America, compared to only moderate reductions in exposures for populations in Africa and Australia, due to the relative importance of non-anthropogenic sources in those regions. Under the *noAnthro* scenario, relatively small percentages of the population in North America (∼2%) and South America (∼8%) experience annual $PM_{2.5}$ exposures of >5 $\mu$g $m^{-3}$, compared to ∼15% and ∼27% in Europe and Australia, respectively. However, even under this extreme scenario, >60%


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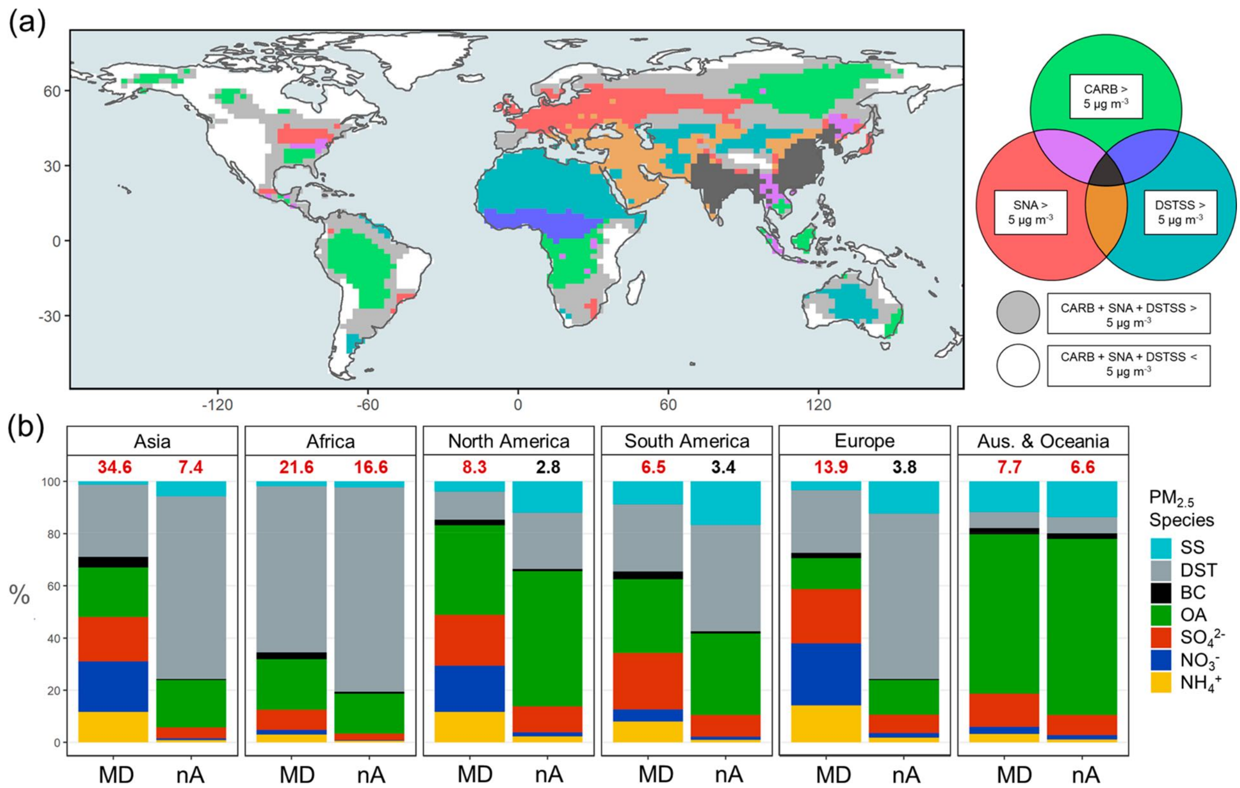


**Figure 3.** (a) WHO $PM_{2.5}$ exceedance plots segmented across three categories by aerosol composition classes: CARB (black carbon and organic aerosol), SNA (sulfate, nitrate, and ammonium), and DSTSS (fine dust and sea salt). The legend describes the colors corresponding to overlapping regions where multiple categories exceed the 5 $\mu$g m$^{-3}$ guideline. (b) Compositional representation of population-weighted $PM_{2.5}$ exposure for the modern day emission (*ModernDay*, MD) scenario and the extreme abatement (*noAnthro*, nA) scenario organized by continent. The numbers on top of each bar correspond to the population-weighted annual $PM_{2.5}$ exposure for each continent (with levels that exceed the WHO guideline in red). See Figure S9 for a version of panel a with the 2005 WHO guideline of 10 $\mu$g m$^{-3}$.

and >70% of the population in Asia and Africa, respectively, are exposed to >5 $\mu$g m$^{-3}$ of $PM_{2.5}$, largely due to the impact of fires and natural dust. We also note that, per the model underestimate of the limited observations from South American monitoring stations in Figure S2, our estimate of the percentage of the population exposed to concentrations of >5 $\mu$g m$^{-3}$ in South America is likely a lower estimate.

We note that stringent abatement measures on all anthropogenic emissions disproportionately reduces $PM_{2.5}$ exposures in Asia in both an absolute sense and a relative sense. Such measures would decrease the proportion of the population of Asia in exceedance of the revised AQG from >95% to slightly <65%. Proactive fire and dust management techniques could further reduce $PM_{2.5}$ exposures in Asia and Africa. We also note that the impact from sporadic air pollution events (such as fires and dust storms) may be partially mitigated by staying indoors. However, the outsized influence of these sources makes it challenging, if not impossible, to achieve the 5 $\mu$g m$^{-3}$ exposure guideline in these regions. Given that Asia and Africa are host to a number of low- and middle-income countries, our results demonstrate that the regions with the least resources to tackle air pollution are often also in areas with the highest levels of non-anthropogenic $PM_{2.5}$ (Figure 1b,c).

Fine aerosol particles consist of numerous chemical compounds but can be broadly classified into the following categories: black carbon (BC), organic aerosol (OA), sulfate ($SO_4^{2-}$), nitrate ($NO_3^-$), ammonium ($NH_4^+$) aerosol, fine dust (DST), and fine sea salt (SS). While other species have been shown to be important at regional scales (e.g., chloride aerosol over India[24]), the vast majority of global $PM_{2.5}$ is comprised of the species listed above. The diversity in global $PM_{2.5}$ sources and formation mechanisms results in a regionally heterogeneous distribution of these different $PM_{2.5}$ aerosol species across the globe (Figure 3a). Some regions (such as the Amazon and northern Africa) are clearly dominated by certain types of $PM_{2.5}$ (OA and dust, respectively), while many regions exceed the 5 $\mu$g m$^{-3}$ guideline for total $PM_{2.5}$ across multiple individual species, even when taken separately (black regions in Figure 3a).

There is a clear relationship between regional aerosol sources (Figure 1c) and the resulting $PM_{2.5}$ composition (Figure 3a), motivating the need to better understand how different $PM_{2.5}$ components respond to individual abatement measures. This is an important prerequisite to developing region-specific air quality management strategies that are capable of targeting the more stringent WHO guideline. For example, increased loadings of SNA (sulfate, nitrate, and ammonium) aerosol from agricultural sources (particularly in Europe and Asia) challenge the notion that fossil fuel reduction alone is sufficient to reduce air pollution in these regions and point to the need for more sustainable agricultural practices (e.g., ref 25).

A compositional analysis of $PM_{2.5}$ exposure across different continents (Figure 3b) further demonstrates the large variability in exposure to different $PM_{2.5}$ constituents. For instance, a major fraction of $PM_{2.5}$ over Africa consists of fine


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dust, compared to North America where dust plays a relatively minor role and OA is much more significant.

Figure 3b also demonstrates that the composition of the $PM_{2.5}$ background (*noAnthro*) differs significantly from the composition of the baseline $PM_{2.5}$ (*ModernDay*) in many regions of the world. Large-scale emission reductions over the coming century can thus be expected to continue changing regional aerosol composition, with increasing fractional contributions from natural sources. Current epidemiological data are inconclusive with respect to the health impacts of this compositional diversity in $PM_{2.5}$ exposure, largely because the specific toxicity of individual $PM_{2.5}$ constituents is still poorly understood.[10] As a result, policy makers and regulators have developed $PM_{2.5}$ exposure guidelines based on epidemiological estimates of disease burdens from unspeciated $PM_{2.5}$. However, recent work has indicated that $PM_{2.5}$ toxicity might vary significantly by aerosol composition and source.[26−31] More research is thus urgently required to estimate the speciated health burdens of $PM_{2.5}$ to accurately inform the next generation of exposure guidelines. The modeled heterogeneity in global $PM_{2.5}$ composition in this study indicates that estimates of human health impacts that do not consider $PM_{2.5}$ composition may be in considerable error, especially in understudied regions (or under future emission regimes). There is thus a clear need for more frequent and widespread measurements of $PM_{2.5}$ composition.

The new WHO guidelines for $PM_{2.5}$ exposure are largely unattainable for many parts of the world, even with extreme abatement efforts, given that the natural background alone often exceeds 5 $\mu$g m$^{-3}$. Both climate change, by modulating natural $PM_{2.5}$ sources, and transboundary transport[32] might further impede efforts to achieve these strict guidelines at the local level. Nonetheless, there exist large and demonstrable opportunities for air quality improvement from a reduced reliance on fossil fuels, particularly over Asia.

The variability in aerosol sources (Figure 1c) and the consequent composition (Figure 3b) support the need for a new generation of AQGs that incorporate compositional information. Advances in measurement techniques over the past decade now make it possible to make speciated $PM_{2.5}$ measurements frequently and at scale. Due to the associated expense and logistical challenges, most monitoring networks continue to rely on bulk mass measurements. However, when viewed against the outsized costs in human health and welfare loss due to increased $PM_{2.5}$ exposures,[7] the cost of deploying more sophisticated measurement networks that also monitor aerosol composition is relatively low. This would allow different $PM_{2.5}$ constituents to be regulated, enabling targeted and region-specific air quality management solutions. It would also create new opportunities for much-needed epidemiological research into differential toxicology, feeding back into the development of improved AQGs. Particle size may provide an alternative and more feasible indicator of composition and source in some regions, because natural aerosol dominates the coarse mode. In particular, $PM_1$ measurements and/or the $PM_{2.5}$:$PM_{10}$ ratio (Figure S10) may serve as a useful indicator of anthropogenic aerosol pollution and help constrain the contribution of natural sources to regional $PM_{2.5}$ burdens. Overall, this work suggests that progress toward cleaner air, as envisioned by the WHO AQG, demands a new perspective on air quality measurement and regulation to realize the intended epidemiological benefits of targeted reductions.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.2c00203.

Additional supporting data (PDF)

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[‖]S.J.P. and T.S.C. are co-first authors.

### Notes

The authors declare no competing financial interest.

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