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Key Points:

- Three solid-fuel combustion sources in Africa led to 203,000 annual $PM_{2.5}$-attributable premature mortalities globally and 167,700 in Africa
- Of the five regions and three sources studied, open biomass burning in Central Africa led to the most $PM_{2.5}$-attributed mortalities
- Trash burning contributed the most mortalities in North Africa and residential solid-fuel burning contributed the most mortalities in West Africa

Supporting Information:

Supporting Information may be found in the online version of this article.

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The Effects of Trash, Residential Biofuel, and Open Biomass Burning Emissions on Local and Transported $PM_{2.5}$ and Its Attributed Mortality in Africa

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Abstract Long-term exposure to ambient fine particulate matter ($PM_{2.5}$) is the second leading risk factor of premature death in Sub-Saharan Africa. We use GEOS-Chem to quantify the effects of (a) trash burning, (b) residential solid-fuel burning, and (c) open biomass burning (BB) (i.e., landscape fires) on ambient $PM_{2.5}$ and $PM_{2.5}$-attributable mortality in Africa. Using a series of sensitivity simulations, we excluded each of the three combustion sources in each of five African regions. We estimate that in 2017 emissions from these three combustion sources within Africa increased global ambient $PM_{2.5}$ by 2%, leading to 203,000 (95% confidence interval: 133,000–259,000) premature mortalities yr^{-1} globally and 167,000 premature mortalities yr^{-1} in Africa. BB contributes more ambient $PM_{2.5}$-related premature mortalities per year (63%) than residential solid-fuel burning (29%) and trash burning (8%). Open BB in Central Africa leads to the largest number of $PM_{2.5}$-attributed mortalities inside the region, while trash burning in North Africa and residential solid-fuel burning in West Africa contribute the most regional mortalities for each source. Overall, Africa has a unique ambient air pollution profile because natural sources, such as windblown dust and BB, contribute strongly to ambient $PM_{2.5}$ levels and $PM_{2.5}$-related mortality. Air pollution policies may need to focus on taking preventative measures to avoid exposure to ambient $PM_{2.5}$ from these less-controllable sources.

Plain Language Summary Air pollution substantially impacts human health in Africa and may continue to get worse in the coming years with population and economic growth and urbanization. In this modeling study, we estimate the health benefits from removing three combustion sources (trash burning, residential biofuel used for home cooking and heating, and open biomass burning) and the regional differences across Africa. Our finding suggests that eliminating these sources in Africa can prevent 167,000 premature mortalities each year in the continent alone and 203,000 deaths globally. The information we provide may help policy makers in developing appropriate policies to mitigate the impacts of air pollution in Africa.

1. Introduction

In Africa, fine particulate matter ($PM_{2.5}$) caused 1.1 million premature deaths, when considering ambient and household air pollution (361,000 of the deaths attributed to ambient $PM_{2.5}$) in 2019 (Fisher et al., 2021; Murray et al., 2020) making it the leading environmental risk factor for premature death, ahead of unsafe water, unsafe sanitation, and handwashing. $PM_{2.5}$ leads to health impacts because particles can travel far beyond the head airways and deposit deep in the tracheobronchial or alveolar region of the respiratory system, depending on the diameter of the particle (Hussein et al., 2013; Kodros et al., 2018; Londahl et al., 2009). Long-term exposure to $PM_{2.5}$ has been linked to heart failure, pneumonia, Parkinson's disease, urinary tract infections, dementia, Alzheimer's disease, increased risk for psychiatric disorders, depression, anxiety, increased brain inflammation, reduced fertility and miscarriages, Ischemic heart disease (IHD), lung cancer (LC), stoke, and chronic obstructive pulmonary disease (COPD), etc. (Allen et al., 2016; Braithwaite et al., 2019; Elliott et al., 2013; Grande et al., 2020; Henderson et al., 2011; Holstius et al., 2012; Ilango & Shaffer, 2020; Johnston et al., 2012; Naeher et al., 2007; Peeples, 2020; Stefanidou et al., 2008; Veras et al., 2010). Many people across Africa currently live in regions that exceed the World Health Organization's (WHO) newly revised $PM_{2.5}$ guideline of annual average

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concentration of 5 μg m^{-3} (Ayetor et al., 2021; WHO, 2021a, 2021b). Additionally, Africa is experiencing rapid urbanization, population growth, and a growing economy, and it is projected to grow to 40% of the world's population by 2100 (United Nations, Department of Economic and Social Affairs, & Population Division, 2017). Africa is projected to have the fastest urban growth rate in the world: by 2050, Africa's cities will be home to an additional 950 million people, and the continent's population is anticipated to be primarily urban by 2035 (OECD/SWAC, 2020). Thus, air pollution is likely to increase and impact more people across the continent in the future (Abera et al., 2021; Coker & Kizito, 2018).

The $PM_{2.5}$ in Africa likely has different physical properties (e.g., size, composition) than $PM_{2.5}$ in many other parts of the world. Compared to other regions of the world, such as North America and Europe, there are relatively few studies on the sources, composition, and health impacts of $PM_{2.5}$ in Africa (Abera et al., 2021; Katoto et al., 2019; Liousse et al., 2014). Important sources of $PM_{2.5}$ in Africa include waste burning, residential solid-fuel burning for cooking and heating, and open biomass burning (BB) (Amegah & Agyei-Mensah, 2017; Bearak et al., 2021; Mead et al., 2008; Naidja et al., 2018; World Health Organization, 2016). We selected these three combustion sources because they are more diffuse and inefficient than sources that have been studied in North America and Europe (e.g., traffic, industry, power generation). While there are other large sources of $PM_{2.5}$ on the African continent, such as natural dust (Kotsyfakis et al., 2019; Urrutia-Pereira et al., 2021), here, we focus on three diffuse combustion sources because they are less controlled across Africa in comparison to other regions of the world, are understudied and unique from fossil-fuel sources that have been studied more historically, and they may have increased emissions in the future with population growth and climate change.

Although some countries have regulations in place that prohibit open trash burning, waste burning is common across Africa due the lack of solid waste collection services, the inability to fund collection programs, and poor waste management (Godfrey et al., 2019; Solomon, 2011). Residents in Africa generate low quantities of waste when compared to other regions of the world, however, only approximately 44% of waste is collected and the future growth rates of waste generation are likely to be large (Godfrey et al., 2019). Sub-Saharan Africa generates less than 0.6 kg per capita per day as opposed to an average of 2.2 kg per capita per day in developed countries (Hoornweg & Bhada-Tata, 2012). When residents burn waste, toxic gaseous and $PM_{2.5}$ are emitted (Christian et al., 2010; Hsu et al., 2016; Wang et al., 2017; Wiedinmyer et al., 2014), leading to degradation of regional air quality.

More than 60% of people who live in Africa still depend on residential combustion of solid fuels such as wood, coal, dung, crop waste, and charcoal for household heating and cooking (Bonjour et al., 2013; Eberhard et al., 2008; Girard, 2002; World Health Organization. Regional Office for South-East Asia, 2006). When combusted, residential solid fuels emit high levels $PM_{2.5}$ with a large fraction composed of black carbon and organic matter. Air pollution from residential solid fuels impacts indoor air quality as well as outdoor air quality in regions of heavy use. Because of the large electricity deficit in Africa (IEA, 2021) residential solid-fuel use is widespread, thus negatively impacting air quality and public health across the region. Population growth in Africa is projected to outpace future electricity access gains (IEA, 2021). According to recent studies, there has been a slow decrease in the use of residential solid fuel for cooking in Africa but few programs have been created to switch to clean fuels for cooking (Stoner et al., 2021).

Across Africa, open BB (i.e., landscape burning) is the largest source of primary fine carbonaceous particles and the second largest source of trace gasses (Aghedo et al., 2007; Andreae & Merlet, 2001; Bond et al., 2004; Giglio et al., 2013). Open BB refers to wildfires, prescribed burning, and agricultural fires, and it encompasses a range of fuel types (e.g., forests, savannas, grasslands). Africa is the largest source of global BB total carbon emissions, contributing ~52% of global BB emissions (Roberts et al., 2009; van der Werf et al., 2003, 2006, 2010). Open BB occurs between November and February in the Northern Hemisphere of Africa (e.g., Ghana, Ivory Coast, Nigeria, Niger, Cameron, Sudan, Uganda) and June until October in the Southern Hemisphere (e.g., Congo, Angola, Zimbabwe, South Africa, Botswana and Zambia, Namibia, Mozambique, Malawi) (Roberts et al., 2009). These emissions have a substantial impact on human health and air quality locally and downwind (Li et al., 2021)

Here, we use the GEOS-Chem global chemical transport model to quantify the effects of three combustion sources in Africa: (a) trash burning, (b) residential solid-fuel burning, and (c) open BB across the five regions of Africa defined by the Global Burden of Disease (GBD): North, Southern, West, Central, and East Africa (Figure S1 in Supporting Information S1). We present an analysis of a range of regional sensitivity simulations to investigate the impacts of local emissions and regional transport on ambient $PM_{2.5}$ levels across Africa. We use the

GBD approach with newly updated concentration-response function from R. Burnett et al. (2018) to estimate the $PM_{2.5}$-attributable mortalities from local and transported air pollution for each of the emissions sources in each of five African regions. To our knowledge, very few health impact assessments have been conducted in this region of the world for the three combustion sources we address here.

2. Methods

2.1. GEOS-Chem Model Configuration

We use the global 3-D chemical transport model GEOS-Chem version v12.6.0 (https://doi.org/10.5281/zenodo.3507501) aerosol-only simulation with offline oxidation fields (Bey et al., 2001; Leibensperger et al., 2012; R. J. Park et al., 2004). The model is driven by assimilated meteorological data from the Goddard Earth Observing System Forward Processing product (GEOS-FP) provided by the NASA Global Model and Assimilation Office (GMAO, https://gmao.gsfc.nasa.gov). Each GEOS-Chem simulation was conducted at a horizontal resolution of 2° × 2.5° (~222 by 277.5 km) with 47 vertical layers for the year of 2017 with a one month spin up. The model produced surface level ambient $PM_{2.5}$ concentrations over the continent of Africa including all emission sources using the following equation.

$$\begin{aligned} PM_{2.5} = {} & 1.33\,(NH_4 + NIT + SO_4) + BCPI + BCPO + 1.5\,(OCPO + 1.16 \ast OCPI) \\ & + 1.16 \ast SOA + DST1 + 0.38 \ast DST2 + 1.86 \ast SALA \end{aligned} \tag{1}$$

Equation 1 includes ammonium (NH_4), nitrate (NIT), sulfate (SO_4), hydrophilic black and organic carbon (BCPI and OCPI), hydrophobic black and organic carbon (BCPO and OCPO), secondary organic aerosol (SOA), fine-mode dust aerosol size bins (DST1 and DST2), and fine-mode sea salt (SALA) to calculate surface level ambient $PM_{2.5}$ at an assumed relative humidity of 35%.

Anthropogenic emissions are based on the Community Emissions Data System GBD-Major Air Pollution Sources ($CEDS_{GBD\text{-}MAPS}$) inventory (McDuffie et al., 2020), which is a collection of several inventories and includes trash (Wiedinmyer et al., 2014) and residential solid-fuel burning emissions to ambient air in Africa (Marais & Wiedinmyer, 2016). There are four open BB emissions inventories available over Africa for use with GEOS-Chem: The Global Fire Emission Database (GFED) (Giglio et al., 2013), Fire INventory from NCAR (FINN) (Wiedinmyer et al., 2011), Quick Fire Emissions Data set (QFED) (Koster et al., 2015), and the Global Fire Assimilation System (GFAS) (Kaiser et al., 2012). (See Text S1 in Supporting Information S1) We conducted simulations using each of the four BB emissions inventories to evaluate the impacts of inventory choice on surface level ambient $PM_{2.5}$ estimates over Africa. We used the Mineral Dust Entrainment and Deposition model (Zeng et al., 2019) to account for emissions of mineral dust. Sea salt emissions followed (Jaegle et al., 2011).

The 28 simulations presented in this study are summarized in Table 1. The first four simulations were base-case simulations that varied the open BB emissions inventory. To evaluate the performance of each open BB inventory, we compared the first four simulations to annually averaged $PM_{2.5}$ estimates from Hammer et al. (2020) by conducting a linear least squares regression (Figure 1 and Figure S2 in Supporting Information S1). (See Section 2.3 for additional details.) The All_on_QFED simulation better reproduced annually-averaged surface level ambient $PM_{2.5}$ estimates than the simulations that used the other BB emission inventories: thus, we used the QFED inventory for the remaining 24 simulations.

The remaining simulations were sensitivity simulations that were used to evaluate the impacts of each of the three combustion sources (i.e., trash burning, residential solid-fuel burning, and open BB) by region. By comparing each sensitivity simulation with the base case, we isolated the influence of regional emissions and atmospheric transport on ambient $PM_{2.5}$ levels across the continent. We conducted six sensitivity simulations for each of the three combustion sources, five simulations where the source was turned off in each of the five African regions and one simulation where the source was turned off across the whole African continent. Additionally, we conducted a set of six simulations where we turned off all three of the combustion sources together in each of the five African regions and across the whole African continent.

2.2. Health Impact Assessment

We used our base case and sensitivity simulations to estimate the $PM_{2.5}$-attributable mortalities from local emissions and atmospheric transport across the continent using the GBD approach. To calculate $PM_{2.5}$-attributable

Table 1
Overview of the GEOS-Chem Simulations

Simulation number	Name	Details of simulation
Base case		
1	All_on_GFED	All regions emissions are turned on using GFED
2	All_on_GFAS	All regions emissions are turned on using GFAS
3	All_on_QFED/BASE	All regions emissions are turned on using QFED
4	All_on_FINN	All regions emissions are turned on using FINN
Landscape biomass burning (BB)		
5	Africa_BB_off	All regions of Africa BB $PM_{2.5}$ emissions turned off
6	North_BB_off	North Africa BB $PM_{2.5}$ emissions turned off
7	Southern_BB_off	Southern Africa BB $PM_{2.5}$ emissions turned off
8	Central_BB_off	Central Africa BB $PM_{2.5}$ emissions turned off
9	East_BB_off	East Africa BB $PM_{2.5}$ emissions turned off
10	West_BB_off	West Africa BB $PM_{2.5}$ emissions turned off
Trash (TR)		
11	Africa_trash_off	All regions of Africa TR $PM_{2.5}$ emissions turned off
12	North_trash_off	North Africa TR $PM_{2.5}$ emissions turned off
13	Southern_trash_off	Southern Africa TR $PM_{2.5}$ emissions turned off
14	Central_trash_off	Central Africa TR $PM_{2.5}$ emissions turned off
15	East_trash_off	East Africa TR $PM_{2.5}$ emissions turned off
16	West_trash_off	West Africa TR $PM_{2.5}$ emissions turned off
Residential (RS)		
17	Africa_RS_off	All regions of Africa RS $PM_{2.5}$ emissions turned off
18	North_RS_off	North Africa RS $PM_{2.5}$ emissions turned off
19	Southern_RS_off	Southern Africa RS $PM_{2.5}$ emissions turned off
20	Central_RS_off	Central Africa RS $PM_{2.5}$ emissions turned off
21	East_RS_off	East Africa RS $PM_{2.5}$ emissions turned off
22	West_RS_off	West Africa RS $PM_{2.5}$ emissions turned off
All 3 solid-fuel (SF)		
23	Africa_3C_off	All regions of Africa 3C $PM_{2.5}$ emissions turned off
24	North_3C_off	North Africa 3C $PM_{2.5}$ emissions turned off
25	Southern_3C_off	Southern Africa 3C $PM_{2.5}$ emissions turned off
26	Central_3C_off	Central Africa 3C $PM_{2.5}$ emissions turned off
27	East_3C_off	East Africa 3C $PM_{2.5}$ emissions turned off
28	West_3C_off	West Africa 3C $PM_{2.5}$ emissions turned off

mortalities, we used baseline 2017 mortality data from the Institute of Health Metrics and Evaluation (http://ghdx.healthdata.org/gbd-results-tool) for five causes of premature mortalities: stroke, LC, IHD, COPD, and lower respiratory infections (LRI). Additionally, we used gridded population for 2015 from the NASA Socioeconomic Data and Application Center (SEDAC, N. E., 2022). We regridded our model resolution of $2° \times 2.5°$ to the population data resolution of $0.25° \times 0.25°$.

The Global Exposure Mortality Model (GEMM) concentration response function (CRF) was used to relate ambient $PM_{2.5}$ exposures to the risk of mortality (R. Burnett et al., 2018) for premature mortalities across all age groups. The GEMM was formulated by 41 cohort epidemiological studies in 16 countries (but not including any African countries) for adults that are older than 25 years old and assumes all $PM_{2.5}$ components have equal toxicity. We selected this CRF, because it is based on a larger data set with wider geographical coverage and

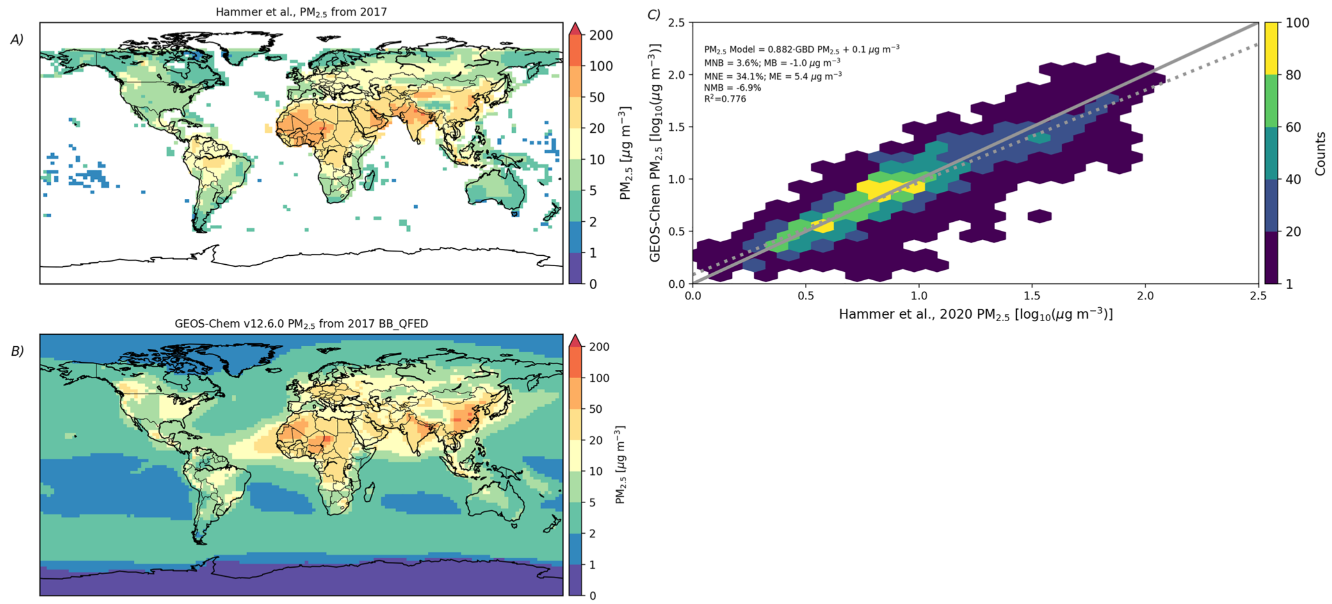

Figure 1. (a) $PM_{2.5}$ estimates from Hammer et al. (2020) from the year 2017 regridded to GEOS-Chem resolution (i.e., 2° × 2.5°). (b) GEOS-Chem base case surface ambient $PM_{2.5}$ estimates using Quick Fire Emissions Dataset open biomass burning inventory (All_on_QFED/BASE). (c) Linear least squares regression for global 2017 $PM_{2.5}$ estimates from Hammer et al. (2020) versus the GEOS-Chem base case estimates, with the mean bias, mean error, mean normalized bias, mean normalized error, and normalized mean bias provided as statistical metrics.

included a wider range of ambient air pollution exposure levels compared to previous CRF meta analyses. Using the GEMM coefficients we report mean premature mortalities including their uncertainty range of ±2 × standard error. Further, we acknowledge that our choice of GEMM CRF, which does not include health studies in Africa (R. Burnett et al., 2018), assumes equal toxicity for all $PM_{2.5}$ components (M. Park et al., 2018), and is applied to all age groups, will contribute to uncertainty in our mortality estimates. We applied the CRF using the attribution method. The equation used to calculate $PM_{2.5}$-attributable mortality from residential solid-fuel use from emissions in North Africa is provided below.

$$M_{RS\_North=}\left(\frac{PM_{2.5,BASE} - PM_{2.5,RS\_NORTH}}{PM_{2.5,BASE}}\right) \times M_{BASE} \quad (2)$$

where M_{RS_North} is defined as the number of premature mortalities attributable to residential solid-fuel combustion emissions in North Africa, $PM_{2.5,BASE}$ is the estimated ambient $PM_{2.5}$ concentrations the base case simulation, and $PM_{2.5,RS\_North}$ is the estimated ambient $PM_{2.5}$ concentrations from each of the simulation where residential solid-fuel use emissions were turned off in the North, and M_{BASE} is total $PM_{2.5}$-related mortalities in the base case simulation. For each of the five GBD regions of Africa, we used an equivalent version of Equation 2 to calculate the annual premature mortalities attributed to emissions from each combustion source in each region.

Measurement data that is available across Africa suggests that ambient $PM_{2.5}$ concentrations vary substantially throughout Africa (Arku, 2015; Arku et al., 2008). Our model resolution does not capture the spatial variability of $PM_{2.5}$ at the city-scale, which may lead to exposure misclassification. Kodros et al. (2016) suggested that lower horizontal model grid resolutions may underestimate the fraction of the population that is exposed to higher $PM_{2.5}$ concentrations at least for anthropogenic sources that spatially correlate with where people live, meaning that our $PM_{2.5}$-related mortality values may be biased low.

2.3. Model Evaluation

Insufficient $PM_{2.5}$ monitoring data exists across Africa (Martin et al., 2019). Therefore, we used annually averaged $PM_{2.5}$ estimates from Hammer et al. (2020) to evaluate our simulations. These estimates combine data from satellites, ground measurements, and chemical-transport models. We evaluated the model using statistical metrics: the slope, coefficient of determination (R^2), mean normalized bias, mean bias (MB), mean normalized

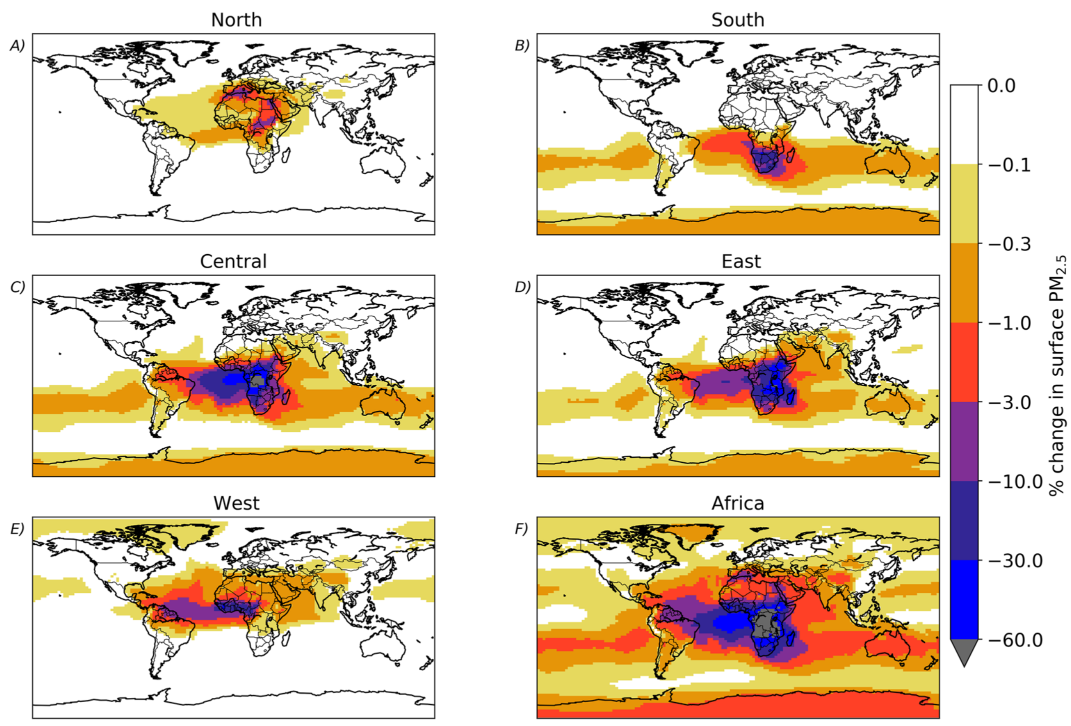

Figure 2. The percentage change in total surface $PM_{2.5}$ from removing all three solid-fuel combustion sources. Each panel (a–e) represents an individual simulation where all three solid-fuel sources were turned off by region of Africa and (f) for the whole continent.

error, mean error, and normalized mean bias (NMB). Hammer et al. (2020) estimates are provided at $0.1° \times 0.1°$ degree resolution, so we regridded the data to $2° \times 2.5°$ for the model-estimate comparisons.

3. Results and Discussion

3.1. Evaluation of Modeled $PM_{2.5}$

The global comparison of the Hammer et al. (2020) $PM_{2.5}$ estimates to the GEOS-Chem estimates for the BASE case are given in Figure 1. We acknowledge that the lack of continuous ground-based monitoring of $PM_{2.5}$ in Africa leads to uncertainty in estimated $PM_{2.5}$ concentrations. The choice and uncertainty of emission inventories may also lead to uncertainty in estimated $PM_{2.5}$ concentrations. Further uncertainty in the percentage of ambient $PM_{2.5}$ that is emitted from a certain source can lead to large uncertainties in premature mortality estimates in Africa according Kodros et al. (2018). On an annual global basis compared to Hammer et al. (2020), GEOS-Chem ambient global $PM_{2.5}$ estimates have a NMB of −6.9% (Figure 1) a R^2 of 0.776. The negative bias from our model ambient $PM_{2.5}$ will contribute to uncertainties in our $PM_{2.5}$-attributed premature mortality estimates from each of the three combustion sources covered in this study particularly as we cannot evaluate the bias in each source separately.

3.2. Ambient $PM_{2.5}$ Impacts for All Three Combustion Sources

Figure 2 shows the percentage change in annual-average surface ambient $PM_{2.5}$ when all three combustion sources are removed. The annual-average percent changes in surface ambient $PM_{2.5}$ are presented in Table 2. Results are presented based on the region of Africa where the air pollution is emitted (i.e., North, Southern, East, West, Central) and the region that is impacted by the emissions. In addition to presenting the impacts across the five African regions, Table 2 also contains the percent change in ambient $PM_{2.5}$ concentrations due to emissions from each of the five regions to the entire African continent itself and outside of the African continent (Table 2). Although the Northern and Southern Hemisphere portions of Africa have different open BB seasons (Ramo et al., 2021), we present the annual-average changes in surface ambient $PM_{2.5}$ because the annual changes are used to estimate the impacts of chronic exposure to ambient $PM_{2.5}$.

Table 2
Percent Change in Annual-Average Surface Ambient $PM_{2.5}$ Attributed to Emissions of Each of the Three Combustion Sources and All Three Sources Combined (i.e., All Three Sources Off)

Source:	Trash					Residential					Biomass burning					All three sources off				
Region turned off:	North	South	East	West	Central	North	South	East	West	Central	North	South	East	West	Central	North	South	East	West	Central
Region impacted **Africa**	−0.26	−0.18	−0.28	−0.10	−0.09	−0.21	−0.60	−2.41	−0.83	−0.69	−0.55	−2.12	−7.91	−1.58	−10.16	−1.02	−2.90	−10.60	−2.51	−10.95
Total out	−0.02	0.00	−0.01	0.00	0.00	−0.01	−0.01	−0.08	−0.03	−0.01	−0.04	−0.06	−0.23	−0.20	−0.23	−0.07	−0.07	−0.32	−0.23	−0.25
North	−0.76	0.00	−0.05	−0.02	−0.01	−0.55	0.00	−0.72	−0.14	−0.13	−0.97	−0.01	−2.73	−0.53	−1.74	−2.29	−0.01	−3.50	−0.69	−1.88
South	0.00	−1.49	−0.16	0.00	−0.02	0.00	−4.77	−1.25	−0.01	−0.16	−0.02	−15.28	−8.77	−0.01	−8.13	−0.02	−21.60	−10.17	−0.02	−8.30
East	−0.05	−0.08	−1.16	0.00	−0.07	−0.07	−0.39	−9.21	−0.03	−0.46	−0.18	−1.64	−21.13	−0.30	−4.33	−0.29	−2.11	−31.52	−0.33	−4.85
West	−0.08	0.00	0.00	−0.33	−0.01	−0.09	−0.01	−0.07	−2.74	−0.06	−0.32	−0.02	−0.80	−4.49	−2.25	−0.49	−0.03	−0.88	−7.57	−2.32
Central	−0.08	−0.03	−0.26	−0.03	−0.45	−0.12	−0.23	−2.26	−0.23	−3.38	−0.94	−1.49	−17.04	−0.89	−45.11	−1.14	−1.75	−19.56	−1.15	−48.94

Note. The horizontal axis indicates the region where the emissions were turned off, while the vertical axes indicates the region where the percent change was calculated. In addition to the five regions (i.e., North, Southern, East, West, and Central), we calculated the percent change across the continent of Africa (indicated by the word Africa) and outside of Africa (indicated by the words Total out). Values are percent changes in units of $\mu g\ m^{-3}$.

Overall, these three combustion sources substantially impact ambient $PM_{2.5}$ across Africa, and they have a non-trivial impact outside of Africa. Across the African continent, these three sources contribute 28% of annual-average ambient $PM_{2.5}$ and 6% across the globe (Table 2, Figure 2f). Within Africa, the impact is largest over Central Africa, where these three combustion sources contribute 72% of the ambient $PM_{2.5}$ within Africa. These three sources have the smallest impact on ambient $PM_{2.5}$ over North Africa (8%).

Across all regions, local emissions from these three sources impact ambient $PM_{2.5}$ the most within the source region itself. For example, local emissions from these three combustion sources in Central Africa contribute 49% of the annual average surface ambient $PM_{2.5}$ within that region (Figure 2c), but <10% in the other four African regions. Emissions in Central Africa have the largest local impact on ambient $PM_{2.5}$. The contribution of local emissions from these three sources on annual-average ambient $PM_{2.5}$ concentrations over North Africa is the smallest (2%), and this is in part due to the large contribution of dust to ambient $PM_{2.5}$ and likely due to a lower population density across the Sahara Desert, which contributes to lower emissions in this region.

The impacts of emissions from one region on the annual-average ambient $PM_{2.5}$ in another region depends strongly on meteorology. For example, these three combustion sources in East Africa contribute 20% of the annual-average ambient $PM_{2.5}$ over Central Africa. This phenomenon is likely due to the trade winds at these latitudes primarily blowing from East to West. Consistent with this, these three combustion sources in Central Africa contribute only 5% of the annual average ambient $PM_{2.5}$ within East Africa. These three sources in Central Africa contribute 8% of ambient $PM_{2.5}$ concentrations in the Southern African region due to the close proximity of the Southern Africa region to open BB in the southern portion of the Central Africa region.

3.3. Ambient $PM_{2.5}$ Impacts for Trash Burning

The contribution of trash burning to annual average ambient $PM_{2.5}$ in each region of Africa is shown in Figure S3 in Supporting Information S1 and summarized in Table 2. Of the three sources investigated here, trash burning contributes the least to annual-average ambient $PM_{2.5}$ (Table 2). Southern Africa contributes the largest percentage of ambient $PM_{2.5}$ from trash burning (1.5% in Southern Africa) followed by East Africa (1.2% in East Africa). Although the regional percentages are small, highly populated regions of Africa can experience high local ambient $PM_{2.5}$ contributions from this source. Kodros et al. (2016) estimated that the local percent changes of ambient $PM_{2.5}$ from waste combustion within Africa ranged from 0% to ∼30% in the year 2010. The range of our local percent changes (0%–30%) is the same despite using different emissions inventories. The inventories are different because of the assumptions of waste/trash emissions of the $CEDS_{GBD-MAPS}$ (McDuffie et al., 2020) used in our study. Although $CEDS_{GBD-MAPS}$ incorporated the Wiedinmyer et al. (2014) waste combustion inventory, only 30% of generated waste was assumed to be combusted as opposed to 60%, as was used in Kodros et al. (2016). The reduction was based on a literature survey conducted to understand the fraction of residential waste that is combusted resulting in the assumption of 30% of uncollected waste is burnt by weight in $CEDS_{GBD-MAPS}$ (McDuffie et al., 2020).

Transported air pollution from trash burning had only minor impacts on ambient $PM_{2.5}$ concentrations outside of the region where the emissions originated from due to the small magnitude of this source. Consistent with the impacts of transport for all three combustion sources combined, trash emissions from East Africa have the largest relative impact on ambient $PM_{2.5}$ in Central Africa, but even this impact is minor (∼0.3% of annual average ambient $PM_{2.5}$).

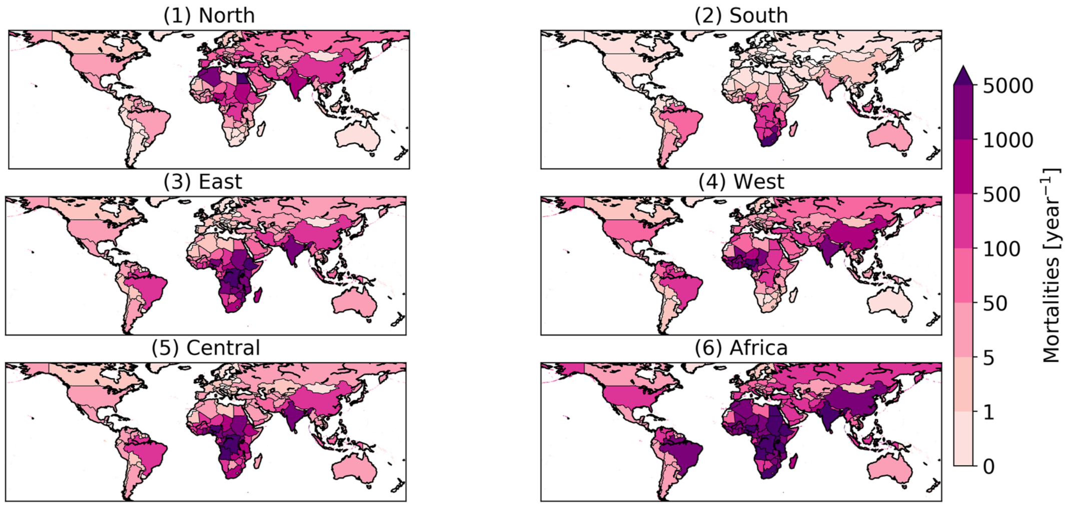

Figure 3. Annual $PM_{2.5}$-related mortalities attributable from all three combustion sources by each African region.

3.4. Ambient $PM_{2.5}$ Impacts for Residential Solid-Fuel Burning

The contribution of residential solid biofuel burning to annual-average ambient $PM_{2.5}$ is shown in Figure S4 in Supporting Information S1 and summarized in Table 2. Residential combustion is the second largest contributor to annual-average surface ambient $PM_{2.5}$ (5%) over Africa when compared to trash (1%) and open BB (22%). Residential combustion in East Africa makes the largest local contribution to annual-average surface ambient $PM_{2.5}$ (9% in East Africa) followed by Central Africa (2% in Central Africa). Emissions from this source make only a minor contribution (1%) to annual-average surface ambient $PM_{2.5}$ in North Africa. The largest changes in regions outside of a source region due to transport were again from emissions in East Africa, where East Africa contributes 2% and 1% of the annual average ambient $PM_{2.5}$ over Central Africa and Southern Africa, respectively.

3.5. Ambient $PM_{2.5}$ Impacts for Open BB

Maps showing the contribution of open BB to annual-average ambient $PM_{2.5}$ in Africa are displayed in Figure S5 in Supporting Information S1 with the percentage changes summarized in Table 2. Of the three sources investigated here, open BB in Africa makes the largest contribution to annual-average surface ambient $PM_{2.5}$ across Africa (22%) and globally (5%). Across all the regions, open BB in Central Africa makes the largest local contribution to annual-average ambient $PM_{2.5}$ (45% in Central), followed by meaningful contributions in East (21% in East) and Southern Africa (15% in Southern). In contrast, the contribution is much smaller over West (5% in West) and North Africa (1% in North). Roberts et al. (2009) reported that most open BB in Africa occurs in woodland regions, which is the land cover type primarily found in Central Africa.

Compared to the other two combustion sources, open BB emissions makes a larger contribution to annual-average surface ambient $PM_{2.5}$ concentrations outside of individual source regions. For example, turning off open BB emissions in Central Africa decreased ambient $PM_{2.5}$ concentrations in Southern Africa by 8%, and turning off emissions in East Africa reduced ambient $PM_{2.5}$ concentrations in Central Africa by 17%. Open BB has larger impacts because the emissions are greater than trash and residential solid-fuel combustion and because emissions from open BB may be lofted to outside of the planetary boundary layer resulting in a longer atmospheric lifetime, which increases the likelihood that they will be transported over longer distances (Paugam et al., 2016).

3.6. $PM_{2.5}$-Attributable Mortality

The annual $PM_{2.5}$-related premature mortalities attributable to emissions from all three combustion sources from each of the African regions and the entire continent are shown in Figure 3. Table 3 is similar to Table 2 but shows results for annual $PM_{2.5}$-related premature mortalities, rather than changes in ambient $PM_{2.5}$. Using our base-case scenario, we find that there are 7.6 million (95% confidence interval: 5.3–9.4) annual $PM_{2.5}$-attributable premature mortalities globally from the five causes of death explored here (see Section 2.2). Our global annual

Table 3
Annual Premature $PM_{2.5}$-Mortality Due To Emissions From Each of the Three Combustion Sources and All Three Sources Combined (i.e., All Three Sources Off)

Source:		Trash					Residential					Biomass burning					All three sources off				
Region turned off:		North	South	East	West	Central	North	South	East	West	Central	North	South	East	West	Central	North	South	East	West	Central
Region impacted	**Africa**	5279	1122	1830	2345	627	3334	2803	16385	21976	4627	3436	5933	28694	19860	48286	12068	9896	46960	44349	53559
	Total out	899	3	814	98	138	624	17	8747	599	1202	2044	205	8808	5035	4401	3566	228	18375	5730	5746
	North	5006	0	52	21	11	2991	2	674	165	132	2012	8	2394	568	1737	10026	10	3121	755	1879
	South	0	1083	50	0	3	0	2607	288	1	19	2	4997	1649	2	1073	3	8727	1985	3	1095
	East	44	31	1418	2	163	72	134	12949	20	1000	145	544	11678	157	2994	261	707	26101	180	4162
	West	192	4	18	2311	22	212	39	282	21700	236	836	159	3471	18745	12079	1241	202	3772	42924	12337
	Central	38	10	350	11	446	60	68	2486	90	3315	449	382	11184	393	30840	547	458	14015	493	34615

Note. The horizontal axis indicates the region where the emissions were turned off, while the vertical axis indicates the region where the mortality was calculated. In addition to the five regions (i.e., North, Southern, East, West, and Central), we calculated the mortality across the continent of Africa (indicated by the word Africa) and outside of Africa (indicated by the words Total out). Units are in attributable mortalities per year.

global premature mortality estimates are similar to R. Burnett et al. (2018) of 8.9 million (7.5–10.3) and Lelieveld et al. (2020) of 8.8 million (7.11–10.41) deaths. Of these 7.6 million $PM_{2.5}$-attributable premature deaths, we find that 203,000 (95% confidence interval: 133,000–259,000) annual global premature mortalities are attributable to emissions from the combination of three combustion sources in Africa, or 10% of total global ambient $PM_{2.5}$ premature mortalities. Of the 203,000 annual mortalities attributable to these three sources, 167,000 of these annual mortalities are within the African continent, which represents 25% of total $PM_{2.5}$ related premature mortalities in Africa. The $PM_{2.5}$-attributable premature moralities from these sources represent 2% of total annual $PM_{2.5}$-related premature moralities in North Africa, 5% in Southern Africa, 10% in East Africa, 49% in West Africa, and 10% in Central Africa.

Following the changes in ambient $PM_{2.5}$, we found that annual $PM_{2.5}$-attributable premature mortalities were mainly driven by emissions within their own region, while transported ambient $PM_{2.5}$ to the surrounding regions resulted in fewer premature mortalities. The largest ambient $PM_{2.5}$ emissions are in West Africa, and these led to the highest number of local mortalities when considering all three combustion sources, that is, 43,000 $PM_{2.5}$-attributable mortalities per year in this region. In contrast, Central Africa also has a large number of annual $PM_{2.5}$-attributable mortalities (35,000 mortalities per year) despite the fact that these three combustion sources are responsible for larger contributions to ambient $PM_{2.5}$, compared to other regions. This is due to the larger population numbers. Further, despite contributing to a relatively large percent of ambient $PM_{2.5}$ in Southern Africa, these three sources only cause 9,000 annual $PM_{2.5}$-attributable deaths in the region.

3.7. $PM_{2.5}$-Attributable Mortality From Trash Burning

The map of our estimates of premature mortalities attributed to trash-burning ambient $PM_{2.5}$ is shown in Figure S6 in Supporting Information S1 with results summarized in Table 3. We find that 11,200 premature mortalities are attributable to ambient $PM_{2.5}$ from trash combustion across Africa. Of the five regions, the largest number of $PM_{2.5}$-attributable premature mortalities occurs in North Africa (~5,000 deaths). Kodros et al. (2016) attributed 19,000 premature adult mortalities to waste combustion $PM_{2.5}$ in Africa for the year of 2010. This estimate is relatively close to the premature mortalities found in our study. These are a few differences in the emissions inventories used between the two studies and they also used a different concentration-response function. On the other hand, when we compared our estimates to McDuffie et al. (2021) which also used $CEDS_{GBD-MAPS}$, our estimates are close to their premature mortality estimates of 16,000 deaths. Although McDuffie et al. (2021) used the same inventory and GEMM concentration-response function, they attributed premature mortality estimates to six causes of premature death (IHD, stroke, COPD, LC, LRI, and type II diabetes), whereas we use five causes of death for all age groups in our estimates.

3.8. $PM_{2.5}$-Attributable Mortality From Residential Burning

We attribute 49,000 annual premature mortalities to ambient $PM_{2.5}$ from residential solid-fuel burning in Africa. The regional map of premature mortalities attributed to this source of ambient $PM_{2.5}$ is shown in Figure S7 in Supporting Information S1. Residential combustion contributes to the fewest number of $PM_{2.5}$-attributable mortalities in Southern Africa. On the other hand, residential combustion leads to the most premature mortalities in West Africa (21,700 mortalities per year). The relatively large population in this region contributes to the higher mortality estimates. The effect of population is evident between the contrast of Table 2 with Table 3. When residential biofuel burning was removed in West Africa $PM_{2.5}$ concentrations were only reduced by 3% within the region (second smallest of any region's self-effect). However, this removal led to the most premature mortalities within the source region of any of the five regions. The West Africa region is one of the largest populated regions in Africa.

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3.9. $PM_{2.5}$-Attributable Mortality From Open BB

Following the effects on ambient $PM_{2.5}$ concentrations, open BB contributes to the largest number of annual $PM_{2.5}$-attributable premature mortalities (Figure S8 in Supporting Information S1, Table 3). In Africa, this source amounts to 106,200 annual premature mortalities, and outside of Africa, it amounts to 20,500 annual premature mortalities. Bauer et al. (2019) estimated that open BB leads to 43,000 annual premature deaths in Africa, which is lower than our findings. We found that emissions from open BB in Central Africa lead to the largest number of annual $PM_{2.5}$-attributable mortalities within that region (31,000 in Central Africa), and contribute to the largest number of $PM_{2.5}$-attributable premature mortalities across all of Africa (48,300 mortalities per year). Open BB in West Africa leads to the second largest number of annual $PM_{2.5}$-attributable mortalities across the continent, with 18,700 in West Africa and 19,900 across all of Africa. Additionally, compared to the other regions, open BB in East Africa leads to the largest number of $PM_{2.5}$-attributable mortalities outside of Africa (8,800 mortalities per year).

While previous studies have not investigated all three of these three sources in Africa directly, several studies have looked at similar sectors or have included one or more of these sources in health-impact assessments. Lacey et al. (2017) estimated 13,210 annual premature deaths from anthropogenic activity (including transportation, household energy generation, waste burning, and home heating and cooking but not open BB) in Africa by implementing the Diffuse and Inefficient Combustion Emissions in Africa (DICE-Africa) (Marais & Wiedinmyer, 2016) and the 2010 Hemispheric Transport of Air Pollutant emissions inventories for 2006. The Lacey et al. (2017) study used the Integrated Exposure-Response model (IER) (R. T. Burnett et al., 2014) that incorporates relative risk information from ambient air pollution, second tobacco smoke, household solid fuel for cooking, and active smoking to estimate premature mortalities for five causes of death including IHD, stroke, COPD, and LC. The IER generally produces lower $PM_{2.5}$-attributable mortality estimates than the GEMM function that we used in this study. Hence, these lower annual premature mortality estimates from Lacey et al. (2017) attributed to anthropogenic activity may be due to the use of this IER model in addition to not including BB. On the other hand, Bauer et al. (2019) estimated 780,000 premature deaths annually from $PM_{2.5}$ from desert dust, all anthropogenic activity, and BB in Africa for 2016. In the terms of premature mortalities due to fossil-fuel combustion in Africa (not covered in our study), Vohra et al. (2021) calculated 194,000 premature mortalities annually in Africa due to fossil-fuel combustion from power generation, industry, ships, aircraft, ground transportation, backup generators, kerosene, and oil/gas extraction for the year 2012. Marais et al. (2019) attributed 79,000 premature deaths from exposure to ambient $PM_{2.5}$ fossil fuel use from 2015 emissions in Africa. None of these studies are directly comparable to ours due to factors such as differences in sources investigated, emissions inventories, atmospheric models, and concentration-response functions. However, despite these differences, the estimated number of annual $PM_{2.5}$-related premature mortalities provided here are similar in magnitude, supporting the validity of our results.

4. Conclusion

We use the GEOS-Chem chemical-transport model to estimate the annual-average surface ambient $PM_{2.5}$ concentrations and annual $PM_{2.5}$-attributable premature mortalities from three combustion sources (trash burning, residential solid-fuel use, and open BB) across Africa for 2017. We estimate the impacts of these three combustion sources across five regions of Africa (as defined by the GBD), including both the impacts of emissions from each region to each of the African regions as well as outside of Africa. Via a set of sensitivity simulations, we show that these sources lead to 203,000 annual $PM_{2.5}$-attributable premature mortalities globally and 167,000 annual premature mortalities in Africa. Ambient $PM_{2.5}$ from these three combustion sources leads to a substantial number of premature mortalities in Africa compared to the deaths from communicable diseases, such as the Ebola Virus (~11,000 deaths from 2014 to 2016) (Bell, 2016). To our knowledge there are very few health impact assessments in this region of the world that are focused on the three combustion sources we examined here.

Overall, the largest impact of $PM_{2.5}$ emissions occurs in the region of Africa where the emissions occur. However, emissions from some regions have substantial impacts on neighboring regions. For example, in East Africa these three combustion sourced had substantial impacts on $PM_{2.5}$ concentrations in Central Africa due to the predominant East-West wind patterns in the tropics. Of the three sources, open BB has the largest impact on ambient $PM_{2.5}$ and annual $PM_{2.5}$-attributable premature mortalities in Africa (106,000 per year), followed by residential solid-fuel combustion (49,000 per year), and trash combustion (11,000 per year).

Overall, Africa has a unique ambient air pollution profile because sources such as windblown dust and BB contribute strongly to $PM_{2.5}$ levels and $PM_{2.5}$-related mortality. Although open BB has the largest health impacts, this source is probably one of the most difficult of three sources to control or regulate in Africa. Trash and residential solid-fuel emissions may be mitigated more easily through financial investments in municipal trash collection programs and/or assistance programs that help finance conversions from residential solid-fuel use to electric stoves (as well as electrification of rural/remote African regions in general).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The version of GEOS-Chem used in this manuscript can be found on Zenodo (https://doi.org/10.5281/zenodo.3507501) and details of the meteorological and emissions inputs can be found in the manuscript. The latest version of the GEOS-Chem input files along with the files used for data analysis is archived on Zenodo (https://doi.org/10.5281/zenodo.6611767).

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