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Improving present day and future estimates of anthropogenic sectoral emissions and the resulting air quality impacts in Africa

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The African continent is undergoing immense social and economic change, particularly regarding population growth and urbanization, where the urban population in Africa is anticipated to increase by a factor of 3 over the next 40 years. To understand the potential health impacts from this demographical shift and design efficient emission mitigation strategies, we used improved Africa-specific emissions that account for inefficient combustion sources for a number of sectors such as transportation, household energy generation, waste burning, and home heating and cooking. When these underrepresented emissions sources are combined with the current estimates of emissions in Africa, ambient particulate matter concentrations from present-day anthropogenic activity contribute to 13 210 annual premature deaths, with the largest contributions (38%) coming from residential emissions. By scaling both the population and the emissions for projected national-scale levels of growth, the predicted health impact grows to approximately 78 986 annual premature deaths by 2030 with 45% now resulting from emissions related to energy combustion. In order to mitigate this resulting increase in premature deaths, three scenarios have been developed which reduce sector-specific future emissions based on prior targets for technological improvements and emission controls in transportation, energy production and residential activities. These targeted potential mitigation strategies can avoid up to 37% of the estimated annual premature deaths by 2030 with the largest opportunity being a reduction of 10 868 annual deaths from switching half of the energy generation in South Africa to renewable technologies.

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As the population in Africa continues to grow at a high annual rate over the coming decades,[1] so too will the emissions of atmospheric pollutants from anthropogenic activity. With this growth in population and the resulting change in emissions, it is important to consider how ambient air quality will impact future climate and human health and which potential mitigation strategies may have the largest co-benefits. Ambient air pollution impacts human health causing approximately 2.9 million premature deaths globally[2] and aerosols and other short-lived climate pollutants (SLCPs) result in a net radiative forcing similar to that of CO_2,[3] although changes in emissions of these species result in more immediate climate impacts.[4]

According to data compiled by the Global Burden of Disease (GBD), since 2000 the percentage of deaths (from lower respiratory infections, ischaemic heart disease, and stroke) in Africa impacted by ambient concentrations of particulate matter smaller than 2.5 μm aerodynamic diameter ($PM_{2.5}$) has risen from 16.8 percent of the total global deaths to 19.3 percent in 2012.[2] Recent estimates of premature deaths due to ambient $PM_{2.5}$ air pollution from both natural and anthropogenic sources in Africa are 188 000 annual deaths, with approximately 38 percent occurring in Nigeria.[5] A large portion of these have been attributed to natural emissions, especially from the Sahara, although current estimates of premature deaths resulting from solid fuel cooking emissions in Africa alone are 11 800–14 300 annually.[6,7] Unlike human health, less information is available for the radiative impacts of sector specific African emissions. Instead prior work has focused on the changes in climate, both precipitation and surface temperature, over Africa from global emissions.

Due to the population growth rate in Africa and the associated air quality impacts, several regions have been targeted by decision makers as ones that could potentially benefit from improved technology and mitigation strategies. The Global Alliance for Clean Cookstoves (GACC) has a number of programs that attempt to provide clean cooking technology in Africa, although the main focus is to improve indoor air quality, which is not explicitly addressed in this work.[8] In addition, the United Nations Environmental Programme (UNEP) has explored several pathways for implementation of a carbon market in Africa, targeting reductions in greenhouse gas emissions through the African Carbon Asset Development Facility. Finally, the International Renewable Energy Agency (IRENA) has recently published a synthesis report on the availability of renewable energy throughout the continent, particularly in six countries that may have the opportunity to bypass traditional energy generation methods in favor of solar and wind electricity generation as the demands from a growing population increase.[9]

Initial estimates of the various health impacts from emissions sources in Africa lack sufficient information about present day emissions throughout Africa, especially as we move through the 21st century.[10,11] Marais and Wiedinmyer[11] provide an improved emissions inventory for inefficient combustion sources in Africa that in many cases differs from the current best estimates following global emissions inventories. Additional uncertainties in the estimates of health outcomes from air pollution in Africa result from other model parameterizations. Previous estimates of premature mortality have used modeled exposure to $PM_{2.5}$ at the coarse model resolution of approximately 1 degree.[5,6] Following Lee *et al.*[12] and Lacey *et al.*,[7] the work presented here uses satellite redistribution of $PM_{2.5}$ to the 0.1 by 0.1 degree resolution allowing for the relative risk from ambient air pollution to be estimated at the exposure relevant scales. This work also applies emissions mitigation scenarios that represent achievable goals for many regions in Africa over the next several decades. The combination of adjoint source attribution techniques with Africa-specific emissions factors and emission reductions strategies partially addresses the limitations of prior model studies and aids in determining the magnitude of air quality benefit pathways.

1 Methods

1.1 Model description

To estimate the changes in atmospheric composition throughout Africa, the GEOS-Chem chemical transport model was used.[13] The GEOS-Chem model uses assimilated meteorology from the Goddard Earth Observing System (GEOS-5) in conjunction with online calculations of aerosol formation and fate, including hydrophilic aging of carbonaceous aerosol and secondary inorganic aerosol chemistry. While the standard forward GEOS-Chem model calculates gridded concentrations of aerosol and gaseous species, this particular work uses an adjoint model to efficiently estimate the sensitivities of a scalar model output with respect to changes in gridded emissions;[14] in this case to estimate human health impacts. The formulation of this model is fully described by Lee *et al.*[12] and uses disease-specific integrated exposure response curves[15] and national-scale baseline mortality rates[16] to estimate the relative risk of people to changes in ambient $PM_{2.5}$ exposure[17] at the sub-grid resolution. The sub-grid spatial distribution is done using the $PM_{2.5}$ estimates derived from satellite, model, and ground-based sources by van Donkelaar *et al.*[18] The model output of adjoint sensitivities allows for the efficient calculation of the change in human health impacts from an emissions perturbation as

$$R_{i,k,h,b} = \lambda_{i,k,h,b}\sigma_{i,k}, \tag{1}$$

where $\lambda_{i,k,h,b}$ is the spatially (i) distributed adjoint sensitivity of a particular species (k) calculated for a specific impact (h) and around a base atmospheric condition (b), $\sigma_{i,k}$ is as emissions perturbation and $R_{i,k,h,b}$ is the number of premature deaths globally associated with changes in ambient $PM_{2.5}$ exposure resulting from this perturbation in emissions. The adjoint sensitivities used here assume that there is a linear relationship from the health impact with respect to any emissions perturbation. This assumption has been validated for the aerosol mass concentration changes resulting from small emissions perturbations[14] and for the coupled health impact concentration response for a 10% change in emissions of each species when compared to finite-difference methods.[12] This assumption of a linear relationship holds best for directly emitted primary aerosol species such as carbonaceous aerosols although there are some additional uncertainties when evaluating secondary inorganic aerosol precursor emissions such as SO_2, NO_X, and NH_3. In terms of efficiency, adjoint models provide a significant benefit in terms of computational cost by reducing the model runs needed to generate the results presented here by several orders of magnitude.

1.2 Emissions

This work uses a combination of two emissions inventories in order to best represent the impacts of anthropogenic sources on atmospheric composition over Africa. The Diffuse and Inefficient Combustions Emission (DICE) inventory uses measured emissions factors along with observed changes in anthropogenic activity to provide gridded emissions for 2006 and 2013 from a number of combustion sources. These sector-specific emissions are shown in Table 1.[11] In order to most closely match our GEOS-Chem model runs which use both anthropogenic and natural emissions for the year 2005, this work considers emissions from DICE 2006 to represent the "present day" conditions. In addition to these newly available emissions, 2010 Hemispheric Transport of Air Pollutant (HTAP) emissions[19] are also considered as either replacements or supplemental emissions, based on sector, as shown in Table 1. These two emissions inventories are combined at the 0.1 by 0.1 degree resolution in the following manner: emissions from backup generators are added to the HTAP energy sector along with emissions from charcoal production, small scale oil refining and flaring emissions, and commercial fuelwood emissions being added to the industrial HTAP emissions. Other combustion sources considered in DICE were direct replacements for emissions from HTAP. These emissions included household (HH) solid-fuel use (fuelwood, charcoal, kerosene, and agricultural waste) as a replacement for residential emissions and four-wheel vehicle and motorcycle emissions as a replacement for the transportation sector.

Table 2 details the magnitude of emissions for each species throughout Africa, with the spatial distribution of the emissions shown in Fig. 1 and 2. A majority of the emissions of primary aerosol (OC and BC) are from the residential sector, while inorganic aerosol precursors (SO_2 and NO_X) are mainly emitted from the energy and industrial sectors. This Table also shows the contribution of DICE emissions to the total emissions for each sector. Both BC and OC are largely based on the emissions estimated in the DICE inventory, while SO_2 and NO_X emissions from DICE only contribute approximately 8% and 23% respectively.

Table 1 Treatment of DICE and HTAP emissions over continental Africa. In grid cells where DICE emissions are present they are treated as either additive or a complete replacement for the corresponding HTAP sectors as denoted in column 3

DICE sector	HTAP sector	Combination method
Backup generators	Energy	Additive
Charcoal production	Industry	Additive
Oil refining	Industry	Additive
Other fuelwood	Industry	Additive
Flaring	Industry	Additive
HH fuelwood	Residential	Replacement
HH charcoal	Residential	Replacement
HH kerosene	Residential	Replacement
HH Ag. waste	Residential	Replacement
4W vehicles	Transportation	Replacement
Motorcycles	Transportation	Replacement

Table 2 Sector-specific emissions for all of Africa in Gg per year

Sector	BC	OC	NO_X	SO_2	NH_3
Transportation	28	554	433	73	8
Energy	16	2	1627	1481	3
Industry	60	254	449	586	408
Residential	567	1001	159	92.3	61
Total	672	1810	2668	2233	480
HTAP only sector-specific emissions in Gg per year					
Transportation	21	13	1649	45	8
Energy	16	2	122	1505	1477
Industry	14	121	434	575	397
Residential	963	1994	688	357	15
Total	1014	2130	4276	2455	424
DICE only sector-specific emissions in Gg per year					
Transportation	27	552	315	64	0
Energy	0	0	122	4	0
Industry	46	132	15	11	11
Residential	564	994	156	90	61
Total	637	1679	608	169	72

As is shown in Fig. 1, the emissions for OC that are contained within the DICE inventory are from the residential sector due to the use of solid fuels for cooking and home heating, with Nigeria contributing approximately 20% of the total OC residential emissions. The present-day transportation sector in Africa also emits a large amount of primary OC, which differs from current vehicle emissions

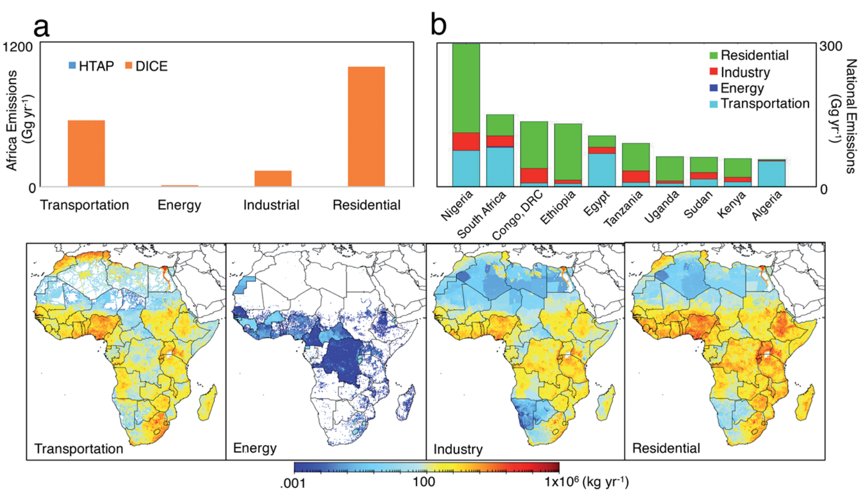

Fig. 1 Sector-specific OC emissions for present day (combination of 2006 DICE and 2010 HTAP) by inventory used (a) and breakdown of sectoral emissions for the top 10 emitting African countries (b). The plots on the bottom show the spatial distribution of emission by sector (log axis). While included in all sectors, HTAP OC emissions contribution is negligible when compared to the contribution from DICE emissions.

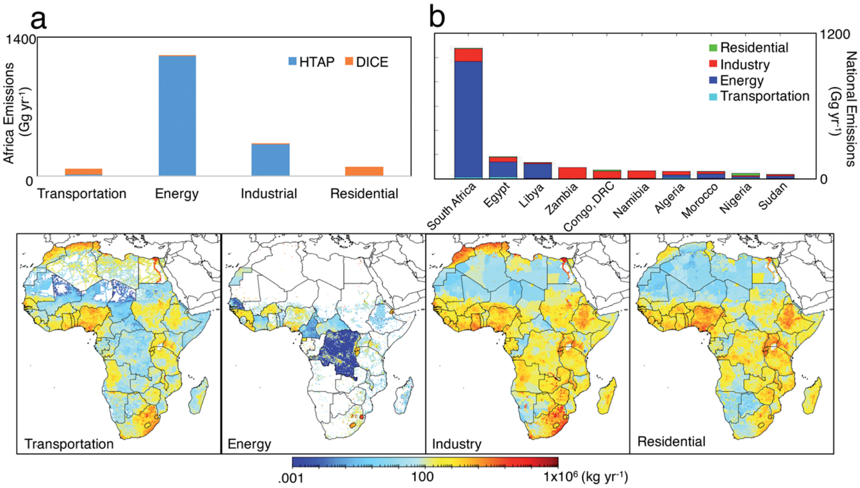

Fig. 2 Sector-specific SO_2 emissions for present day (combination of 2006 DICE and 2010 HTAP) by inventory used (a) and breakdown of sectoral emissions for the top 10 emitting African countries (b). The plots on the bottom show the spatial distribution of emission by sector (log axis).

factors in the US and Europe, although vehicles in the US prior to 1990 also have similar high emission rates of primary organic carbon due to less stringent emissions controls.[20] The relatively small component of OC emissions in the industry sector results mainly from the use of solid fuels for commercial cooking at markets.[11]

Emissions of SO_2, as shown in Fig. 2, represent a much different mix of sectors. Here we see a much smaller contribution from the addition of DICE emissions (although they are still present in the residential and transportation sectors), but instead larger emissions from the HTAP inventory, particularly from coal-fired power plants in South Africa. These power plant emissions are included in HTAP as point sources which makes them difficult to identify on the spatial maps at the 0.1 by 0.1 resolution, especially in countries like Egypt, Algeria, and Morocco which have power in major cities, but appear blank in the spatial distribution. Other countries such as Zambia, Namibia and the Democratic Republic of Congo also show relatively large contributions from their mining industry, and both the Democratic Republic of Congo and Nigeria have a small residential component from the use of coal as a solid fuel for cooking.

1.2.1 Future emissions. For this work future emissions are considered following two pathways. The first is used for the GEOS-Chem modeling and represents changes in future global emissions following the 2030 Representative Concentration Pathway 4.5 (RCP4.5) emissions, which is a socioeconomic analysis of changes in anthropogenic activity throughout the 21st century and provides estimates of resulting emissions changes from this shift in human behavior along with population growth.[21,22] These emissions are aggregated to the model scale of 2 by 2.5 degrees and used to estimate the adjoint sensitivities of premature death from ambient $PM_{2.5}$ with respect to emissions in each grid cell.

The second emissions pathway is used to calculate baseline future impacts on human health using the modeled adjoint sensitivities using GEOS-Chem. This inventory scales the combined Africa-only HTAP and DICE emissions by national-scale population growth from the United Nation World Population Prospects,[1] at the 0.1 by 0.1 degree resolution. This baseline estimate is needed in order to understand the impacts of both shifting population and shifting anthropogenic activity in Africa on the net national-scale contributions to premature death from changes in ambient $PM_{2.5}$ concentrations.

1.3 Emissions mitigation scenarios

This work not only considers updates to the current and future baseline emissions in Africa, but also considers various realistic mitigation strategies in order to better understand how ambient air quality can be improved in the 21st century. In particular, we have considered three different scenarios in which different emissions sectors and locations undergo changes in emissions based on realistic scenarios that have been proposed in a number of recent synthesis reports and work from various non-governmental organizations that are exploring air quality mitigation technologies throughout Africa.

The first scenario considers the reduction in transportation emissions throughout Africa, hereafter referred to as *S:TRA*. Currently, there exist few regulations on the emissions from the transportation sector in African countries with several countries instead relying on limiting the model year of imported vehicles. The emissions estimated from this sector are based on measurements made in developing cities.[11] A scenario has been developed that assumes that the emissions from gasoline and diesel vehicles are controlled in the future and therefore have reduced emissions of CO, NO_X, SO_2, NMHC, and OC and BC. Reductions in this sector were made *via* the species-specific scaling of current DICE emission factors to represent those emission factors currently applied under the Euro 6 emission standards. For the gaseous pollutants, this scaling was accomplished assuming that the current DICE transport emission factors were represented by the earliest Euro standard emission factors available. For OC and BC, we used the scaling of emission factors from developing to developed countries as was assigned by Liousse *et al.*[10] Not only were emission factors for all pollutants reduced under these assumptions, but the ratio of the various pollutant emissions changed dramatically in this scenario. The resulting scaled emission factors were combined with the gasoline and diesel usage by country to develop new emission estimates for the 2030 population. The highest levels of emissions reductions are clustered near cities and roadways spread across Africa, particularly along the Nile River in Egypt, along with other densely populated areas in Nigeria, Algeria, and South Africa.

The second scenario, referred to here as *S:ENE*, considers national-scale availability of renewable energy resources and the projected electricity demands for each country; as developed by IRENA and Lawrence Berkeley National Laboratory.[9,23] Wu *et al.*[9] has specifically highlighted eight countries that have an excess of renewable energy resources and would potentially have the opportunity to bypass traditional power generation fuels (coal, natural gas, nuclear) through the use of solar and wind power. These countries are: Angola, Egypt, Ethiopia, Kenya, South Africa, Tanzania, Zambia, and Zimbabwe. Since a 100% conversion to renewable energy methods is not feasible by 2030, the emissions reduction here consider that each of these countries supplies 50% of their energy need through the use of renewable technology. The remaining energy emissions match those from the baseline future emissions explained above. Due to the use of coal-fired power plants, SO_2 is the dominant emission and as shown in Fig. 2 the emissions are highest at point sources that correspond to the locations of power plants in each country. While these sources are spatially discrete, unlike those from transportation, the emissions magnitude is still significant and results in a total reduction of 642 Gg SO_2.

The third, and final, scenario (*S:RES*) considers the use of liquified petroleum gas (LPG) for cooking in the urban regions throughout Africa. The adoption of clean cookstoves and fuels in urban regions alone is based on empirical data showing the availability of fuel and familiarity of users with LPG technology greatly influence the consumers' decisions of what stove they adopt.[24,25] The fraction of urban population was calculated following Marais and Wiedinmyer[11] and aggregates the 2013 LandScan™ gridded world population to the 0.1 by 0.1 degree resolution. Here we have considered 1000 people per square kilometer to be the threshold for urban population in Africa. Since solid fuel cooking is the dominant activity for this sector,[24] large emissions reductions of carbonaceous aerosols are seen over the African continent. Fig. 1 shows the reductions in these primary organic carbon emissions over well-populated areas from the introduction of LPG stoves.

The total emissions reductions throughout Africa for each of these scenarios are shown in Table 4 and represent a range of emissions reductions from 2030 baseline emissions levels described in the Future emissions section of this paper. While the largest emissions reduction is seen in OC with contributions from improvements in both transportation and residential emissions sources, smaller reductions are seen for all other sectors and species, with the complete breakdown shown in Fig. 4.

2 Results

2.1 Continental Africa impacts

In order to consider the impacts from the mitigation strategies outlined above, we must first evaluate the baseline health impacts associated with anthropogenic emissions at the national scale throughout Africa. This is done by multiplying the adjoint sensitivities modeled for the present day and for 2030 by the sector and species-specific emissions from the combined DICE and HTAP inventory. Here the agricultural emissions are neglected in this analysis for several reasons. First, these emissions are not impacted by the addition of DICE emissions and second, these emissions are not considered with any of the proposed mitigation strategies. In contrast, although the industrial emissions are also not included in any of the mitigation scenarios, these emissions are impacted by DICE emissions and this analysis provides an improved understanding of the impacts from the updated emissions.

Fig. 3 shows the contribution of each country's emissions to changes in ambient $PM_{2.5}$ concentrations and the resulting premature deaths from this change in air quality for both the present day and following future emissions trends into 2030. Continent-wide there is an increase in the total number of

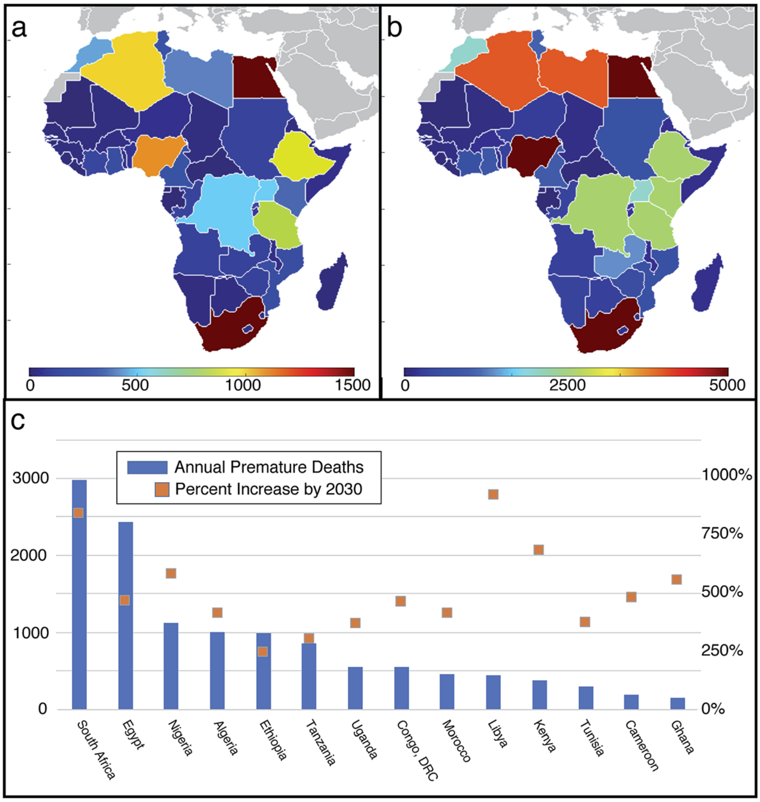

Fig. 3 The African countries colored by their contribution to premature deaths in 2006 (a) and 2030 (b) caused by baseline national-scale anthropogenic (minus agriculture) emissions. (c) Shows the countries with the largest contributions to premature death impacts. The solid bars (left y-axis) represent the total number of premature deaths attributed to anthropogenic activity (minus agriculture) and the square markers represent the percent increase from 2006 to 2030 (right y-axis). Deaths in 2030 due to emissions in Nigeria (6885), Egypt (11 400), and South Africa (27 110) are outside of the plot scale.

premature deaths from 13 743 in 2006 up to 80 192 premature deaths in 2030. This large increase in estimated premature deaths is driven by the growing population in Africa. The population growth impacts these calculations in several ways. First, as the population grows so do the emissions from each sector. This leads to more aerosols and aerosol precursors being released into the atmosphere, thereby increasing the background concentrations of $PM_{2.5}$. The resulting modest increases in $PM_{2.5}$ in relatively clean regions would result in a surprisingly large increase in mortality due to the nonlinear concentration–response relationship.[26] Second, the population growth increases the number of people exposed to these higher concentration levels, leading to more premature deaths. In an effort to isolate the importance of these two variables we have estimated the number of premature deaths resulting from present day emissions with 2030 population to be 66 422. This means that the number of people exposed tends to be the driving parameter when considering health impacts throughout Africa, although changes in emissions are not negligible. Table 3 shows the premature

Table 3 Sector and species-specific premature death estimates due to ambient $PM_{2.5}$ exposure

Sector	BC	OC	NO_X	SO_2
Annual premature deaths for 2006				
Transportation	73	3382	0.2	75
Energy	91	28	0.6	1656
Industry	116	1083	0.2	442
Residential	1015	4040	0.0	59
Total	1295	8532	1.1	2232
Annual premature deaths for 2030				
Transportation	165	7446	249	1703
Energy	177	54	1419	33 813
Industry	298	2994	279	9938
Residential	2965	11 826	87	2161
Total	3604	22 320	2034	47 614

deaths due to exposure to ambient $PM_{2.5}$ for each sector and species for both the base year 2006 and the endpoint of 2030. The increase in the number of deaths from primary emissions (OC and BC) is relative to the population growth while the presence of more aerosol precursors, especially in countries with large population growth, tends to increase the deaths from secondary inorganic aerosol formation at a much higher rate, especially from emissions of NO_X due the increased likelihood of nitrate formation.

2.2 Scenario specific results

This work evaluates the impacts of the three control strategies outlined in the Methods section (Table 4). Panel a of Fig. 4 shows the scenario-specific emissions reductions disaggregated to the individual species. For the residential emissions scenario, the reductions are dominated by primary carbonaceous aerosol, with a much smaller inorganic aerosol precursor component. For the energy sector scenario, the opposite is true. Combustion emissions from power plants consists of almost 100% gaseous aerosol precursors (SO_2 and NO_X), which go on to form

Table 4 Sector-specific emissions for all of Africa in Gg per year

Sector	BC	OC	NO_X	SO_2	NH_3
Emissions reductions (Gg per year)					
S:TRA	23	500	317	73	8
S:ENE	7	1	568	573	1
S:RES	176	300	48	48	18
Total	206	801	933	672	27
Premature deaths avoided (annual deaths)					
S:TRA	141	7224	203	1850	335
S:ENE	86	26	607	1364	32
S:RES	1167	4405	31	705	176
Total	1394	11 655	842	16 191	543

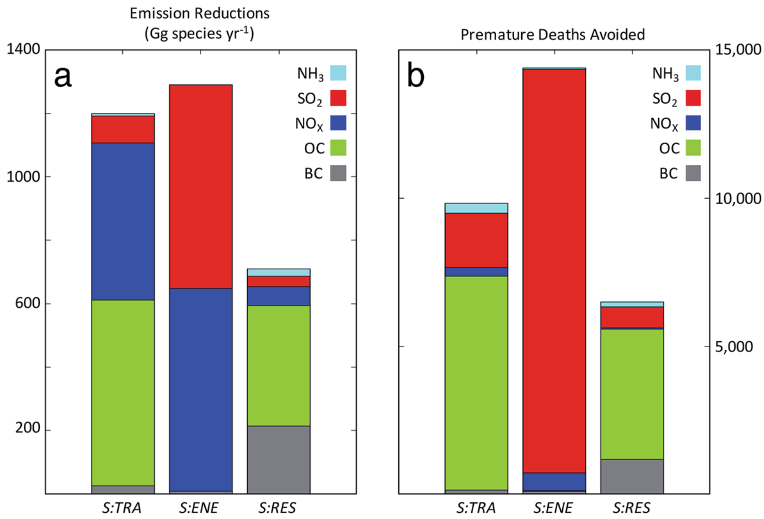

Fig. 4 (a) Mitigation-specific emissions reductions by 2030 for transportation (*S:TRA*), energy (*S:ENE*) and residential (*S:RES*) and (b) the resulting avoided premature deaths.

atmospheric sulfate and nitrate, contributing to ambient $PM_{2.5}$ concentrations. Due to the lack of current control technologies on vehicles in Africa, the implementation of Euro V controls would lead to an emissions reduction of a mix of carbonaceous aerosols (primarily OC) and NO_X. As is shown in Panel b of Fig. 4, the magnitude of the emissions do not directly translate to their respective contributions to premature death. The sensitivities of premature deaths due to SO_2 emissions over Africa tend to be the largest per kg emission, while NO_X tends to be the smallest. This is due to NO_X competing with, but being less likely to form nitrate aerosol when compared to sulfate formation rates from SO_2 in the presence of NH_3.[27] The deaths resulting from primary emitted species, BC and OC, tend to be much more sensitive to emissions location with respect to nearby population and meteorological conditions instead of the surrounding atmospheric composition.

For these reasons we see the largest number of avoided deaths comes from *S:ENE*, where the SO_2 emissions reductions in densely populated parts of South Africa and Egypt contribute to a majority of these avoided deaths. The spatial distribution of the total avoided deaths and the sectors that contribute the most are shown in Fig. 5. While *S:ENE* has the largest contribution to the estimated health impacts from changes in ambient particulate concentrations, a majority of these avoided deaths result from emissions changes in a very small subset of grid cells, as seen in Fig. 5(b). Also, while *S:TRA* appears to be the best mitigation option based on number of grid cells in which it has the largest impacts, this scenario is the only one that was applied without any spatial constraints, unlike the urban-only *S:RES* and the specific countries in *S:ENE*.

The sector-specific contributions to avoided premature deaths can also be aggregated to the national scale. Fig. 6 shows the spatial distribution of scenario-specific premature deaths avoided (Panels b–d) along with the top 10 countries where emissions reductions have the largest contribution to avoided deaths

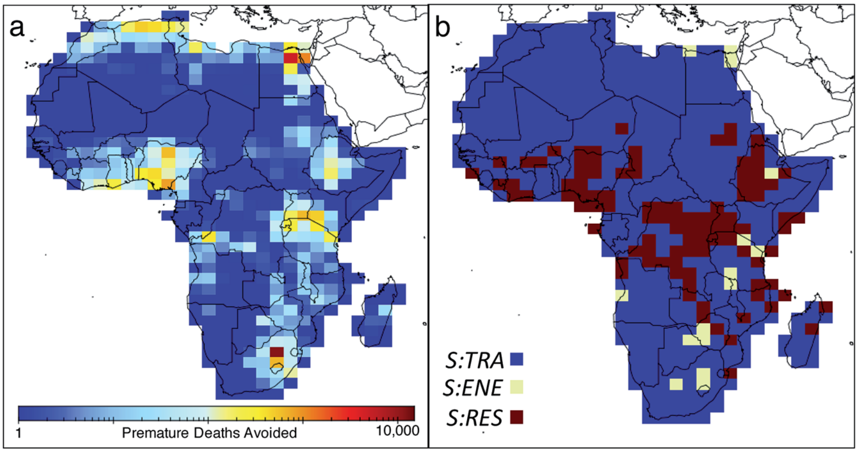

Fig. 5 (a) Total avoided annual deaths due to the reduction of each grid cell's emissions for all scenarios plotted on a log axis. (b) This plot shows which of the three emission reduction scenarios contributed the most to that grid cell's contribution to total avoided deaths.

(Panel a). Of the total number of deaths avoided through the proposed scenarios, ≈35% results from SO_2 emissions reductions in South Africa. South Africa is responsible for 3% of the global coal consumption and 90% of Africa's consumption in 2015, which is projected to increase to 3.5% of global by 2030.[28] This major emissions source is the reason for the large contribution to premature deaths from South Africa's emissions reductions. In countries targeted for a reduction in energy emissions, the trend of *S:ENE* being the largest contributor to avoided annual deaths is not seen in all countries. In Kenya, where all three scenarios are applied, the largest number of avoided annual deaths is seen from reductions following *S:RES* instead. This is due to the higher percentage of the population using solid-fuels for cooking in Kenya (80% in 2010) *versus* South Africa (15% in 2010).

3 Discussion and conclusions

The work presented here combines existing emissions inventories over Africa in order to better understand the impacts of anthropogenic activity on human health for both the present and future, along with developing potential mitigation scenarios to address these changing impacts. As shown in Marais and Wiedinmyer,[11] the current estimates of combustion emissions are underestimated and this work shows that the updated emissions inventory estimates 13 210 annual premature deaths from all anthropogenic sectors across the continent for present day. Based on the rate of population change predicted in Africa, the emissions, and therefore the modeled mortality, increase up through 2030. Based on the emissions scaling and the use of adjoint sensitivities, the future ambient $PM_{2.5}$ related deaths is 78 986 from anthropogenic activity in 2030. In order to overcome this increase in projected mortality, three emissions reductions scenarios were developed targeting the transportation, energy, and residential

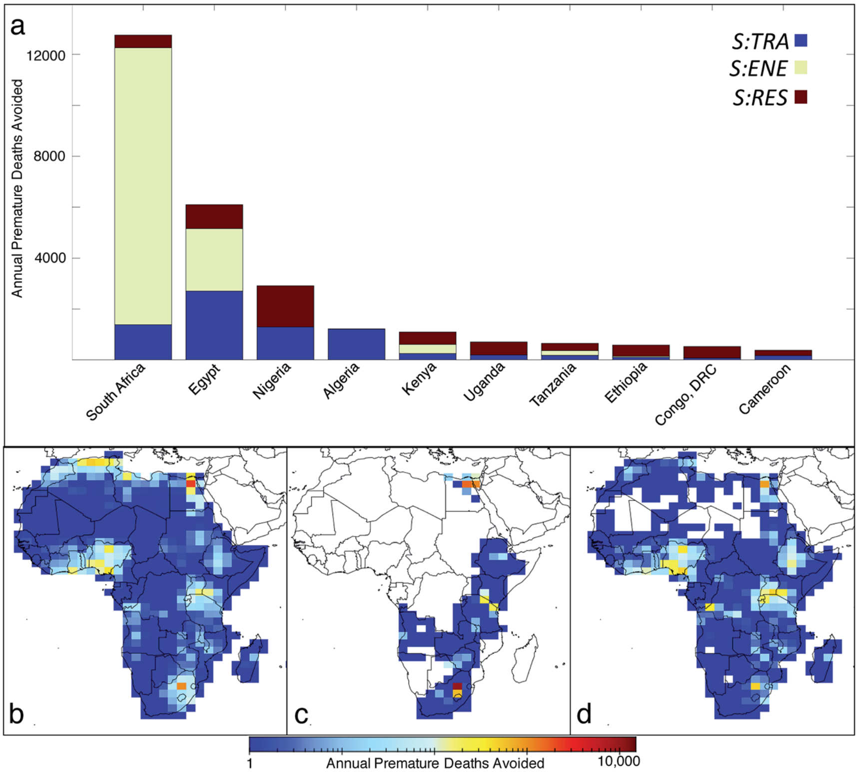

Fig. 6 Breakdown of impacts aggregated to the national scale for the top ten contributing countries (a) and the scenario-specific spatial distribution of emissions reductions and the resulting contribution to annual avoided deaths, plotted on a log-axis for *S:TRA* (b), *S:ENE* (c), and *S:RES* (d).

sector emissions. The total impact of all of the outlined mitigation efforts will result in a reduction in the annual premature deaths of 30 625 (9735 from *S:TRA*, 14 388 from *S:ENE*, and 6485 from *S:RES*) or a 38% reduction. Based on the spatial distribution of these deaths, reductions in energy emissions in South Africa have the largest overall contribution at 10 868 deaths avoided, while the next most impactful scenario is due to mitigation of transportation emissions in Egypt, resulting in 2697 avoided deaths. For the *S:RES*, the largest contribution comes from Nigeria at 1620 avoided deaths.

Due to model constraints and lack of scientific agreement on model representations of specific atmospheric processes detailed here, these numbers represent a conservative estimate of the total health impacts from anthropogenic emissions. First, this analysis does not consider the additional health burden due to secondary organic aerosol or ozone formation. Both of these species are strongly region dependent regarding their formation and lifetime and not well-studied with regards to formation rates over Africa.[29–31] For this reason, the work presented here does not use the same SOA parameterization used in Lacey *et al.*,[7] which represents a global average representation of SOA formation, but following these global tendencies would result in an increase in the overall deaths from OC by 18%. While the ozone concentrations in Africa have been modeled, the health response to ozone is less certain. Recent work from Turner *et al.*[32] has used cohort studies to show that the current integrated exposure response functions for ozone tend to under-predict the total number of premature deaths due to ozone exposure. Therefore, we would expect additional premature deaths for both the baseline and mitigation scenarios due to exposure to tropospheric ozone. This study also does not account for the deaths due to emissions impacts on climate change, where Africa is a region that is most susceptible to changing water security and crop losses.

Overall, this work offers an improved estimate of the $PM_{2.5}$ related deaths in Africa by using updated emission inventories and human health impact calculations at the exposure relevant scales of 100 km^2. This work has identified several important regions and emissions that can be targeted to provide an improvement in the changing future ambient air quality in Africa and provide guidance about where new policies and mitigation efforts can have the largest impact on human health outcomes.

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