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The important role of African emissions reductions in projected local rainfall changes

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Africa is highly vulnerable to climate change but emits a small portion of global greenhouse gases. Additionally, decarbonization might lead to a 'climate penalty' whereby reductions in cooling aerosols offset temperature benefits from CO_2 reductions for several decades. However, climate change impacts conditions other than temperatures, including precipitation. Using the NASA Goddard Institute for Space Studies climate model, we find that although African emissions cuts have weak impacts on projected African temperatures, they significantly impact rainfall. Whereas business-as-usual increasing emissions lead to substantial drying over tropical Northern Hemisphere Africa during local summer, that drying is essentially eliminated under a sustainable development pathway. The reduction in cooling aerosols is responsible for ~33–90% of the avoided drying in our model, with the remainder largely attributable to reduced absorbing aerosols. African policy choices may therefore greatly reduce regional African summer drying, giving parts of Africa substantial leverage over their own climate and air quality future.

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INTRODUCTION

Africa is developing rapidly, with rapid population growth, economic growth, and urbanization[1]. The African Union's Agenda 2063, the 'Africa We Want', articulates a vision for development where people have improved and sustainable livelihoods, live in clean environments with low air pollution, and where Africa ensures that it is climate resilient. Though African countries aim to play their role in limiting global climate change, as evidenced by their latest NDC submissions, the perception is that local efforts to address climate change are almost entirely about adaptation. This is because local mitigation is expected to have little impact on African climate change given that Africa emits less than 4% of global (2020) CO_2 emissions from fossil fuels and industry[2].

Cooling aerosols, including sulfates, ammonium, nitrates, and organic carbon, contribute to local air pollution and currently mask a portion of the warming from increased greenhouse gases (GHGs). Removal of these aerosols, either due to policies to improve air quality or to mitigate climate change, can thus have both beneficial and detrimental effects on society via changes in both air quality and climate. There is a large body of literature on the so-called 'climate penalty' attributable to reductions in cooling aerosols that unmask greenhouse gas warming[3–5]. For example, aerosol reductions that were implemented for the sake of air quality have contributed to observed local warming in the US[6], Europe[7] and China[8]. Although an instantaneous, global removal of all cooling aerosols would lead to a sharp rise in global warming[3], a realistic phaseout of fossil fuel usage would only lead to a modest (~0.02-0.10 °C) warming[9]. The knowledge that climate mitigation can lead to near-term warming has led some to a focus on strategies that prioritize the rapid reduction in emissions of short-lived climate pollutants (SLCPs), the strategy promoted by the Climate and Clean Air Coalition. Adoption of both sustainable development and SLCP reduction strategies provides a pathway for near-term mitigation of both warming and drying[10,11].

The climate scientific community continues to highlight the temperature penalty associated with the aerosol decreases that accompany GHG reductions. For instance, the latest Intergovernmental Panel on Climate Change (IPCC) report's Summary for Policy Makers highlights this 'climate penalty', stating that "In the low and very low GHG emissions scenarios, assumed reductions in anthropogenic aerosol emissions lead to a net warming"[12]. Similarly, that report's Frequently Asked Question 6.2 shows how emission reductions lead to one or more of four outcome categories: climate benefit, crop benefit, health benefit, and climate penalty, with reductions in cooling aerosols leading to health benefit and climate penalty impacts only. As Africa has a particularly large ratio of aerosol to CO_2 emissions, the climate penalty in response to African decarbonization might be expected to be especially large.

However, changing temperatures are only one aspect of climate change, and aerosols are known to also play an important role in regional precipitation changes[13–16]. Although many studies have examined the influence of changing aerosols over Europe, North America, and Asia, few have explored the role of African aerosols[17]. The local impacts of reduced African aerosol emissions may be especially important because the role of African greenhouse gas emissions relative to other regions is minor. Therefore, Africa's large aerosol emissions may have relatively greater influence on local future climate change than aerosol emissions reductions in other parts of the world. Additionally, the cooling aerosol changes could be particularly large as they include not only sulfate aerosols associated with coal-fired power plants and vehicles as in many other parts of the world, but also large quantities of organic carbon aerosols primarily from solid biofuel use[18]. Despite the potential for relatively large local climate impacts from changes in African aerosol emissions, few global climate modeling experiments have addressed this topic. Several modeling experiments suggest that historical rainfall over the

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Sahel has been affected by remote aerosol changes[19–22], but the role of future local African aerosol impacts is not clear.

We have therefore performed a suite of simulations with the NASA Goddard Institute for Space Studies (GISS) global climate model[23–25] designed to examine the role of emission changes on Africa's climate future, with a particular focus on African precipitation (see Online Methods). This work builds upon an Integrated Assessment of Air Pollution and Climate Change for Sustainable Development in Africa recently undertaken by the Climate and Clean Air Coalition in partnership with the United Nations Environment Programme and the African Union Commission (AUC)[26]. The Assessment examined the health, crop and climate benefits of an Agenda 2063 scenario constituting a broad shift toward sustainable development in Africa. Here we report on the results of additional modeling experiments that include all reductions from the Agenda 2063 scenario except for the aerosol decreases associated with decarbonization, which we call the 'No Decarbonization Aerosol Reductions' (NDAR) scenario. This NDAR scenario is designed to reveal the effect of reduced cooling aerosols emissions that occur as part of the sustainable transition on regional precipitation patterns. The results better illustrate how Africa's development choices can profoundly affect not only Africans' health via changes in air quality, but also local well-being via precipitation changes despite 'global warming' being largely outside of Africans' control.

RESULTS

Surface air temperatures

We first examine the surface temperature changes over African land area. For the continent as a whole, the Baseline scenario shows a fairly constant rate of warming over the next 40 years (Fig. 1). The projected Baseline warming is virtually indistinguishable from that seen in GISS simulations of the Shared Socioeconomic Pathway 3_7.0 (SSP3_7.0) scenario performed for the Coupled Model Intercomparison Project phase 6 (CMIP6) with this same model (Fig. 1). The warming in the GISS SSP3_7.0 simulation in turn is very similar to the African warming under SSP3_7.0 in the CMIP6 multi-model mean ($N = 29$; CMIP6 models listed in Supplementary Table 1), with the projections from the GISS model falling near to or slightly above the multi-model mean and well within the projected range from the other models in the CMIP6 ensemble (Fig. 1). Under the Baseline scenario, the annual average Africa mean warming during 2050–2064 relative to 2015–2029 is 1.5 °C (±0.2 °C). There is a suggestion of modest (~0.05 °C) Africa mean warming under the Agenda 2063 simulation relative to the baseline simulation, and the Agenda 2063 simulations are approximately 0.07 °C warmer than the NDAR simulations on average, but the results are not statistically significant (Fig. 1). These weak temperature responses are consistent with the weak net forcings of 0.08 ± 0.08 and 0.16 ± 0.07 W m^{-2}, respectively, in those two cases (Table 1). Hence the aerosol reductions, which outweigh the greenhouse gas reductions and so cause the total

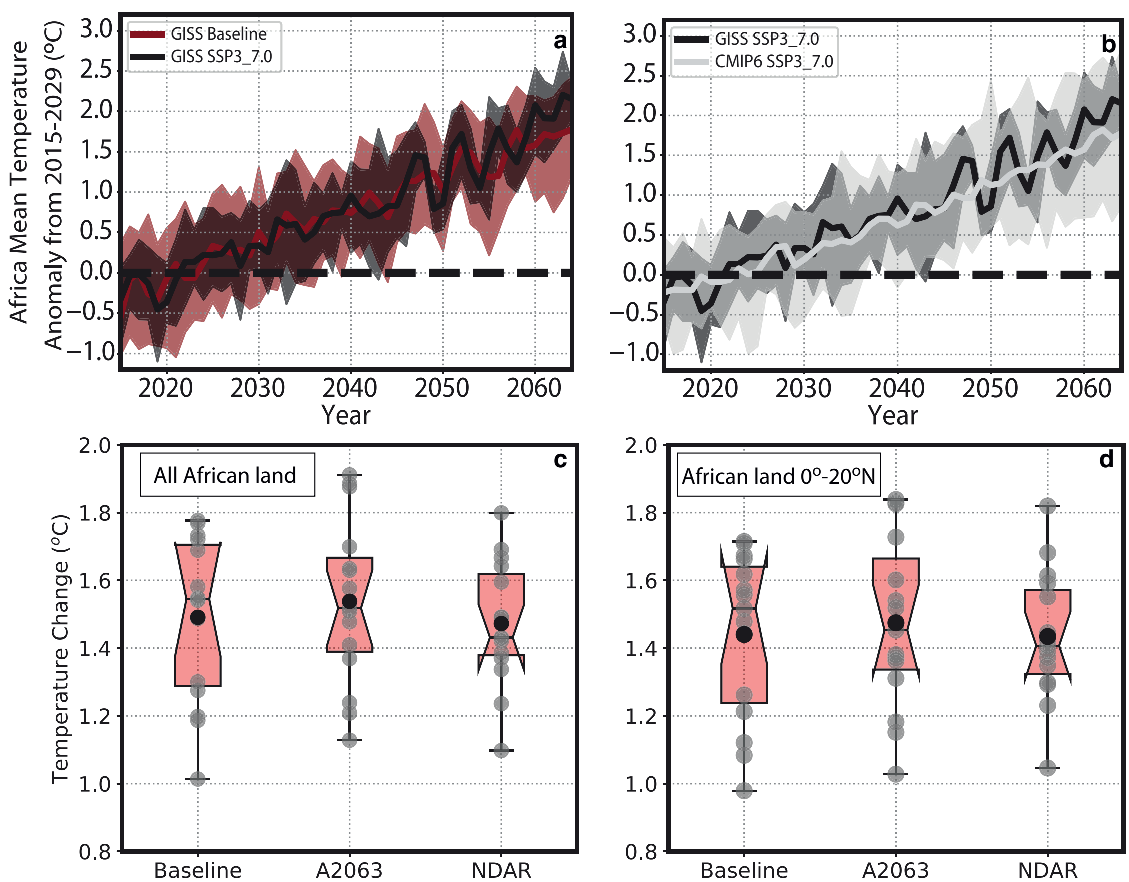

Fig. 1 Africa area-weighted annual mean surface air temperature changes. Values are shown for 2015–2064 relative to the 2015–2029 mean under the baseline scenario and under the SSP3_7.0 scenario in the GISS-E2.1-G model **a** and under SSP3_7.0 in the GISS model and in the CMIP6 SSP3_7.0 multi-model ensemble **b**, along with boxplots showing surface temperature changes averaged over all of Africa **c** and over Africa 0–20°N **d** under the indicated scenarios for 2050–2064 relative to 2015–2029. In panels a and b, solid lines show ensemble means and shaded areas show ranges across the ensembles. In panels c and d, colored boxes show interquartile range, whiskers show the full spread of data, horizontal black lines in boxes show medians, black dots show means, and grey dots show individual ensemble members. NDAR No Decarbonization Aerosols Reductions, A2063 Agenda 2063.

Table 1. Radiative forcing by component for 2050–2060 (W m^{-2}).

Name	Methane and CO_2	Ozone	Aerosol-radiation interaction	Aerosol total	Total
Agenda2063 vs. Baseline	−0.07	−0.07	0.10	0.22 ± 0.08	0.08 ± 0.08
Agenda2063 vs. NDAR	0.00	0.00	0.07	0.16 ± 0.07	0.16 ± 0.07

All values are global mean annual averages. Forcing values for methane and CO_2 are from offline calculations following IPCC AR6, ozone is from online double-call calculations and aerosol forcing is from analyses of shortwave fluxes removing the shortwave forcing attributable to ozone and feedbacks from sea-ice changes. Uncertainty ranges (90% confidence) are only shown for the total aerosol forcing (including cloud responses) as others are <0.01 W m^{-2}.

forcing to be positive (Table 1), may induce modest mean increases in annual mean temperatures over Africa, the traditional 'climate penalty', but this warming falls within the range of internal variability in the 10-member ensemble. These temperature results vary modestly across regions and seasons, with the clearest 'climate penalty' in terms of warming under Agenda 2063 relative to the NDAR simulations over Northwest Africa and the Horn of Africa for the annual average and especially June-August (Supplementary Figures 1–3).

Precipitation

Turning to precipitation, we focus on the regional and seasonal scales due to the temporal and spatial inhomogeneity of the responses. Whereas the mitigation of emissions within Africa alone in our scenarios had only weak effects on projected temperature increases, its impacts on June-August precipitation are comparable in magnitude, and opposite in sign, to the projected Baseline changes over much of tropical Northern Hemisphere Africa (Fig. 2a, d). The largest changes in June-August are seen over 0−20°N, with the Baseline precipitation projection showing an average June-August decrease across this region of 0.15 (±0.08; 95% CI) mm/day (Fig. 3) and values up to five times that large over parts of West Africa (Fig. 2a). To put these changes in context, the rainfall decrease over this same region producing the devastating droughts of the 1970s and 1980s relative to the 1940s and 1950s was 0.3 mm/day (using data from[27]). Adoption of the Agenda 2063 scenario eliminates this projected drying, even leading to a very modest projected increase in precipitation over this area with regional average impacts that are highly statistically significant (Fig. 3). This strong precipitation response is in marked contrast to surface temperatures, which were only weakly affected in this region by the Agenda 2063 scenario (Fig. 1). Comparing the Agenda 2063 and NDAR simulations shows that the decreased emissions of cooling aerosols appear to contribute about half of the total increase in precipitation and essentially all of the avoided drying in West Africa (Fig. 2d–f), though uncertainty ranges are large (Fig. 3). Hence rather than a 'climate penalty', the reduction in aerosols co-emitted with decarbonization is a critical component of reducing the magnitude of projected boreal summer drying of tropical Africa, and especially West Africa, in our modeling. In contrast, the reductions in cooling aerosols have minimal significant impact on winter precipitation in both southern Africa (Fig. 2a–c) and northern Africa (Supplementary Fig. 5).

DISCUSSION

Processes driving the rainfall responses

In our simulations, the emissions scenarios led to substantial differences in the aerosol burden over and near Africa (Supplementary Figure 6). Averaged over African land area from 10°S-10°N and 20°W-40°E, the ensemble spread of aerosol optical depth (AOD) in the 2015–2019 period is 0.34–0.38. By 2050–2060, it roughly doubles to 0.74–0.77 in the Baseline scenario. Under the Agenda 2063 scenario, AOD is 0.35–0.39 lower than the Baseline in 2050–2060, and under the NDAR scenario AOD is 0.27–0.31 lower than the Baseline. Therefore, the NDAR accounts for ~¾ of the Agenda 2063 reductions. Similarly, the well-characterized aerosol-radiation interaction forcing (direct effect) under the NDAR scenario is 70% of that in the Agenda 2063 scenario (Table 1). Given the very modest changes in other drivers (Tables 1 and 2), we infer that these aerosol changes are the primary driver of the precipitation results in both the NDAR and Agenda 2063 scenarios.

Prior studies of the impacts of regional aerosols on climate have focused on changes in European, North American, or Asian aerosols as those regions have the largest historical aerosol emissions[13,14,28]. Those that have examined the role of aerosols in Sahel precipitation changes, including the observed drought in the 1970s and 1980s, have likewise primarily examined the impacts of aerosols from outside Africa[13,29,30] or the impacts of global aerosols[15,19–22,31]. These studies have clearly shown that aerosol changes can strongly influence Sahel rainfall, in part via changes in meridional temperature gradients in the North Atlantic region and ensuing shifts in the location of the Inter Tropical Convergence Zone. This finding has led to a general conclusion that North American and European sulfate increases contributed to the increased Sahel drying over the 1950s to the 1980s and decreased sulfate contributed to increased precipitation thereafter. However, the role of aerosols from Africa itself has received less attention. Nevertheless, a prior study reported that European reflective aerosols that are transported over Africa scatter shortwave radiation and enhance cloud cover, cooling the surface and decreasing local rainfall[29]. This same mechanism would be expected to apply to emissions from Africa as well.

Our results suggest that both remote and local aerosol mechanisms are likely at work. We find a strong localized reduction in shortwave absorption in the atmosphere over tropical Northern Hemisphere Africa under the Agenda 2063 and NDAR scenarios (Fig. 4). The regional pattern is highly correlated with the precipitation responses in central and East Africa and stems primarily from reduced carbonaceous aerosols. This leads to decreased heating aloft in the troposphere and hence reduced atmospheric stability that drives enhanced convective precipitation relative to the baseline scenario[32]. Additionally, the decreases in scattering aerosols and associated cloud cover (Table 1) lead to greater shortwave flux reaching the surface, which can locally enhance land heating (e.g., in East Africa; Supplementary Fig. 3) and contribute to increased precipitation, as seen in prior studies[17,29]. However, we find that increases in both clear-sky (0.41 W m^{-2} global mean) and all-sky (0.49 W m^{-2}) shortwave fluxes reaching the surface over Africa are very similar to the reduction in clear-sky shortwave absorption (0.37 W m^{-2}; Supplementary Fig. 7), indicating that changes in scattering aerosols and cloud cover generally play a smaller role in comparison with changes in absorbing aerosols in our model. We also find a change in the meridional temperature gradient in the Atlantic under the Agenda 2063 scenario relative to the Baseline (Supplementary Fig. 4), though unlike the response to higher latitude aerosols[17] our response includes a substantial change in the Southern

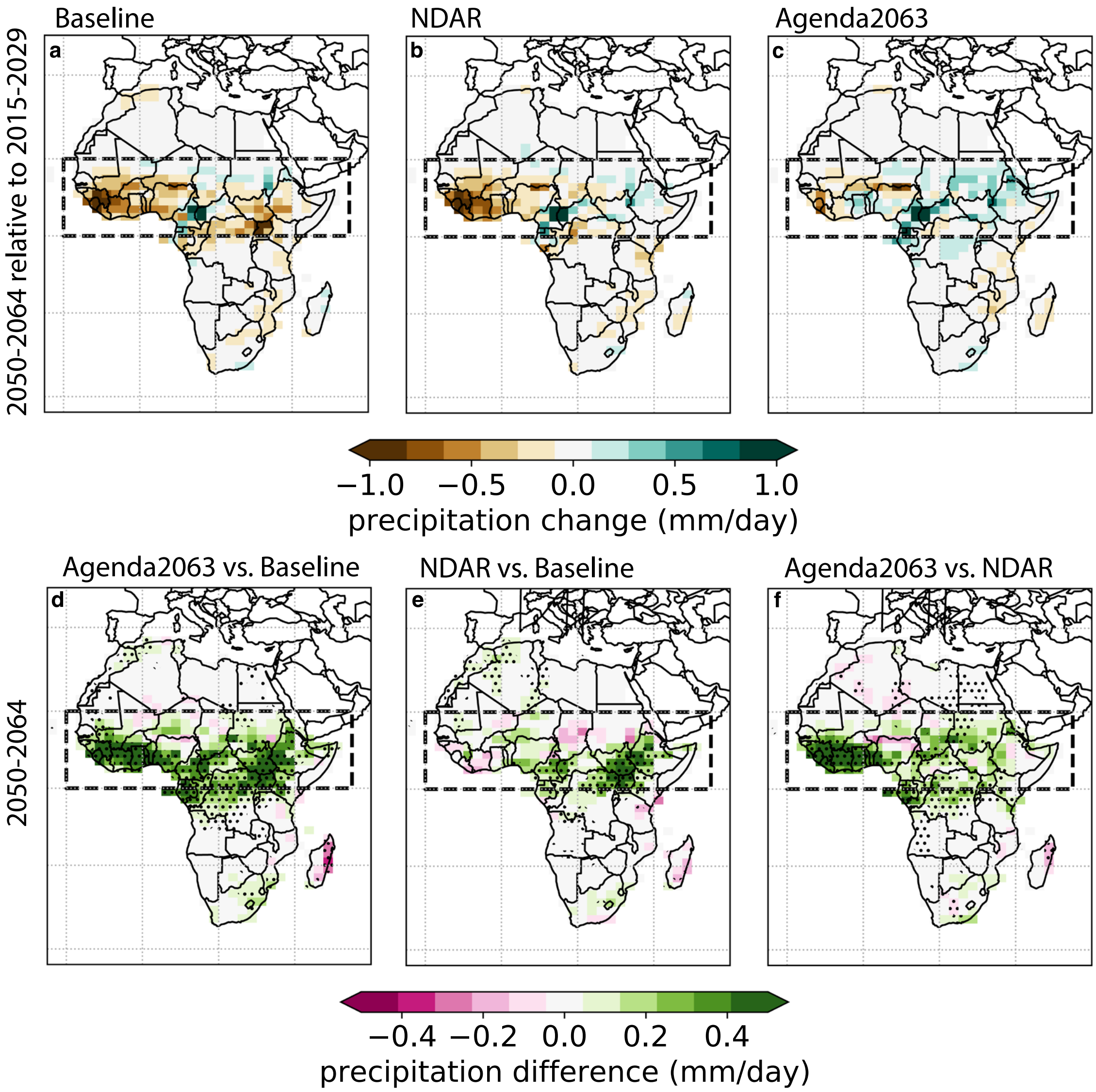

Fig. 2 June–August precipitation changes for 2050–2064. Values are shown for precipitation relative to 2015–2029 under the Baseline **a**, the No Decarbonization Aerosols Reductions (NDAR) **b**, and the Agenda2063 **c** scenarios and the differences are shown during 2050–2064 between Agenda2063 and Baseline **d**, NDAR and Baseline **e**, and Agenda2063 and NDAR **f**. Statistically significant differences at the 95% confidence level between scenarios **d**–**f** over the ensemble of simulations are stippled. The 0°–20°N area discussed in the text is outlined.

Hemisphere as well as the Northern. These results suggest that the local aerosol effect on precipitation dominates for most of Africa, whereas remote effects such as the Atlantic meridional gradient changes may also affect far West Africa given the stronger precipitation response there under the Agenda 2063 scenario relative to the NDAR scenario despite very similar local absorption changes (Figs. 2f and 4c). This implies that reductions in both scattering and absorbing aerosols contribute to the increased African precipitation under the Agenda 2063 scenario, depending upon the region.

Contextualization of results

Consistent with the mechanism whereby aerosols affect precipitation locally via radiative impacts, prior work[17] report that the direct (atmospheric) effect of increased African aerosols was to cause Sahel drying from the 1970s to the 2000s (outweighed by their ocean-mediated wetting, with GHGs contributing to the oceanic component as well from the 1970s onwards). That study shows changes in clear-sky shortwave absorption patterns that are qualitatively similar to those reported here (though smaller in magnitude as that work focused on scattering aerosols), which therefore provides some precedence for African aerosols causing drying. However, those results were from an atmosphere-only model and focused on a historical period when observations showed increased rather than decreased rainfall. In contrast, our study examines the future with substantially larger aerosol forcing and uses a coupled model with both atmospheric and oceanic responses.

The only multi-model simulations that examined the response to African aerosol emissions that we are aware of studied the impact of decreases in biomass burning aerosols in three composition-climate models[13]. They found that decreases in biomass burning led to an increase in June–September Sahel rainfall in all three models, but with substantial diversity in the magnitude of the response. The GISS model used here, which also was used in the prior study[13], fell approximately at the mean for that specific impact. This suggests that the results reported here

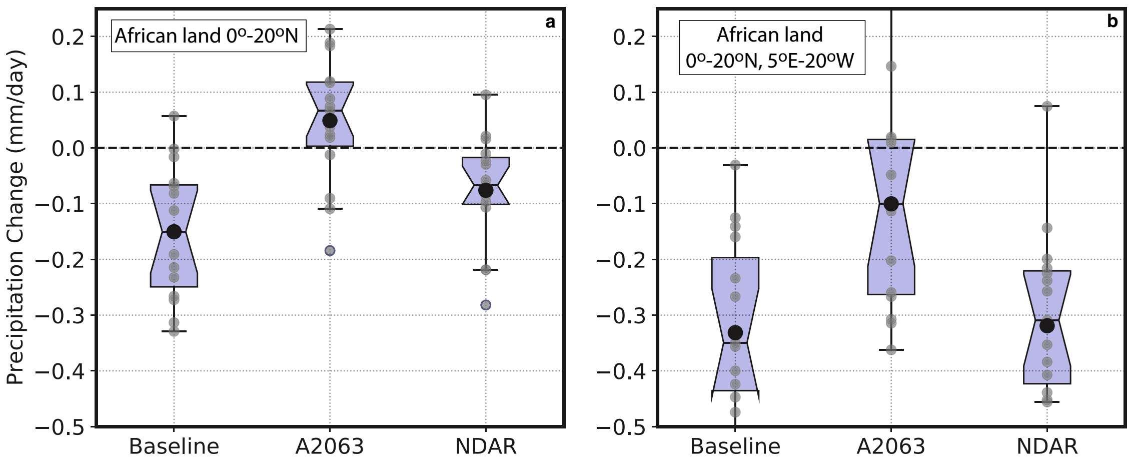

Fig. 3 Distribution of modeled June–August precipitation changes over Northern Africa. Values are averaged over 0°–20°N African land area **a** and over that land area between 5°E and 20°W **b** under the indicated scenarios for 2050–2064 relative to 2015–2029. Colored boxes show interquartile range, whiskers show full spread of data, horizontal black lines in boxes show medians, black dots show means, and grey dots show individual ensemble members. The horizontal dashed line marks zero precipitation change. The difference between NDAR to Agenda 2063 reflects the impact of decarbonization aerosol reductions.

Table 2. Scenarios used in this study and changes in major emissions and concentrations for 2050–2060.

Name	SO_2 emissions	NO_x, CO, OC, BC emissions	NH_3 emissions	Methane (global conc.)	CO_2 (global conc.)
Baseline (vs 2015–2019)	+200%	+125–300%	+300%	+37%	+40%
Scenarios vs Baseline 2050–2060					
Agenda2063	−57%	−70–75%	−63%	−5%	−1%
No Decarbonization Aerosols Reductions (NDAR)	−9%	−60–65%	−37%	−5%	−1%

Notes: Emissions are for Africa. N_2O trends are similar to, though slightly larger than, those for CO_2. *conc* concentration.

may be 'middle-of-the-road' relative to other climate models, though we note that the Sahel precipitation response of this model to aerosol changes in other regions was not always near the mean. As the aerosol perturbations imposed in the Agenda 2063 simulations were anthropogenic, they will also have different geographic patterns and composition from those associated with biomass burning.

To contextualize the results from our specific climate model, we note that the CMIP6 models show substantial model-to-model variability in patterns of rainfall change under a warming climate, but for boreal summer they typically show decreased precipitation in northwest and southern Africa with increases in central Africa north of the equator, in east Africa, and in the eastern flank of west Africa[33,34]. The GISS model similarly shows decreases in the northwest and southern Africa, but the increases it produces in central and east Africa extend over a smaller area than in the CMIP6 multi-model mean. The GISS west Africa drying also extends further east. In austral summer, the CMIP6 multi-model mean shows drying over north and west Africa as well as in the western half of southern Africa, with precipitation increases over central and especially east Africa. The GISS model's Baseline results are generally consistent with these patterns, although this model shows less drying over north Africa and more drying over Madagascar. We also note that this version of the GISS model shows a global aerosol optical depth 12–33% low relative to multiple analyses of ground-based and satellite observations[35]. Finally, we note that CMIP6 models also show some evidence that the 'climate penalty' of local warming in response to non-methane short-lived forcer reductions can be present in some regions, but precipitation changes can be positive (and offset drying trends in the Baseline), e.g., for Latin America, Europe and southern Africa[15]. However, that study examined the responses to global changes in aerosols and ozone precursors rather than regional emissions changes and reported that the emissions changes led to warming and increased precipitation in every region, suggesting that they may largely reflect warmer air holding more water vapor rather than local precipitation shifts due to inhomogeneous aerosol changes.

Implications for future research and policy

Using an ensemble of simulations with the GISS climate model, we have demonstrated that many of the aerosol-driven precipitation changes in our model are robust. However, the use of additional climate models to test the consistency of this response to African aerosol changes would be valuable because there is substantial diversity in the precipitation response to regional aerosol changes across climate models.[13,14] We note that there is also substantial diversity in the precipitation response to increasing GHGs, so this is not an issue unique to aerosols (e.g.[20]). There is some agreement from prior studies that reductions in African aerosols lead to precipitation increases in the Sahel, though the magnitude is quite model dependent. Furthermore, the aerosol changes under our scenarios are at the large end of those in the literature given our comparatively high baseline SO_2 emissions, as discussed in the Methods, so that the simulated precipitation response we report may also be towards the upper end. Hence the conclusion

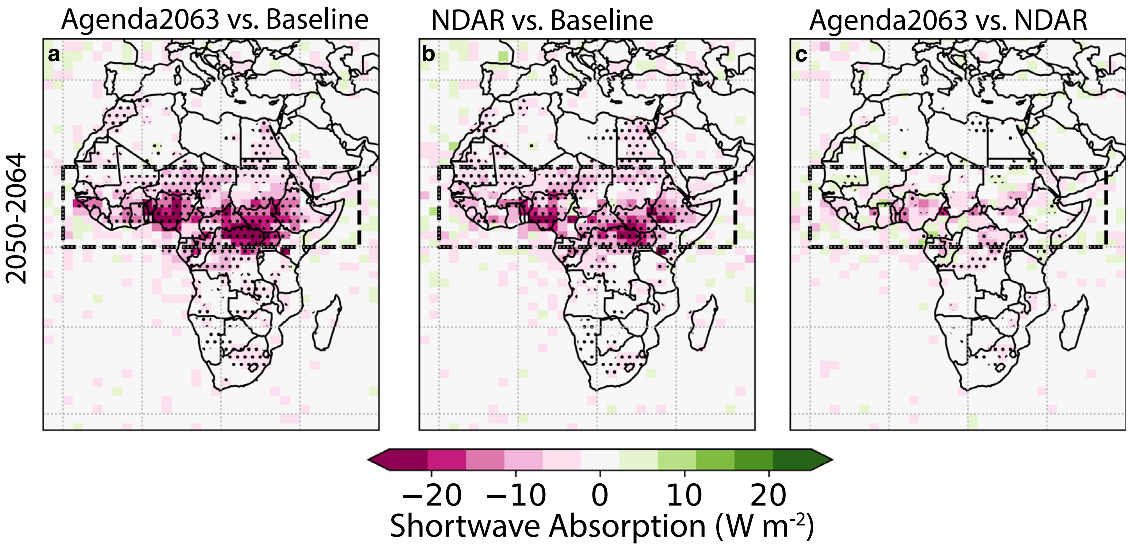

Fig. 4 June–August changes in atmospheric shortwave clear-sky absorption. Values are averaged over 2050–2064 between Agenda 2063 and Baseline **a**, NDAR and Baseline **b**, and Agenda 2063 and NDAR **c**. Statistically significant differences at the 95% confidence level between scenarios over the ensemble of simulations are stippled. The 0–20°N area discussed in the text is outlined.

of this study that future African aerosol emissions, both absorbing and scattering, can play a large role in Africa's future rainfall should be regarded as plausible and qualitatively in agreement with the limited prior literature, but the quantitative results presented here should be treated with caution. The finding that the sustainable development policies under Agenda 2063, including the aerosol reductions therein, have the potential to prevent a projected drying of comparable magnitude to that which occurred during the 1970s and 1980s indicates there would be great value in additional efforts to quantify this impact. Furthermore, rainfall changes in this region appear to exhibit substantial irreversibility (defined as hysteresis in response to warming and cooling[36]), so that avoiding GHG-induced drying in the near-term might have long lasting benefits.

These findings suggest that Africa might benefit greatly from avoided rainfall decreases by adopting sustainable development strategies emphasizing shifting away from fossil fuels, reducing food waste, and moderating the projected growth in meat consumption, even if the resulting aerosol changes lead to modest near-term warming. The strong role of reduced aerosol emissions on aspects of local climate other than temperature suggests that the widespread 'climate penalty' paradigm holds only when narrowly focusing on temperature. Instead, reduced aerosol emissions may provide climate benefits via reduced disruption of precipitation patterns due to global climate change. In addition to considering the large public health benefits of aerosol reductions (e.g.[26,37]). African policy makers should weigh the potentially large rainfall and crop benefits against the traditional temperature-based 'climate penalty'.

METHODS

Emissions

An Africa-wide model with national-scale resolution was constructed primarily within the Low Emissions Analysis Platform (LEAP)[38], and was used to explore several scenarios: a baseline "business-as-usual" scenario with no additional climate or air pollution policies, a scenario representing the decarbonization and sustainable development goals under the African Union's Agenda 2063 plan[1], and a scenario incorporating a subset of the Agenda 2063 policies focused on the mitigation of SLCPs that cause warming, such as methane, black carbon (BC), hydrofluorocarbons, and the ozone precursors CO and VOCs. The SLCP scenario includes: vehicle emissions controls and hybrid and electric vehicles in the transportation sector; clean lighting and cookstoves in the residential sector; methane capture from the fossil fuel industry and efficient charcoal making in the energy sector; reductions in methane from rice and livestock and elimination of agricultural waste burning in the agricultural sector; and improved methane capture at landfills and wastewater facilities in the waste sector[26]. The Agenda 2063 scenario implemented additional measures (37 in total), and also includes: public and active transport as well as rail and road traffic electrification; residential, industrial, and power sector efficiency improvements; renewable energy; carbon capture and sequestration; behavioral changes to reduce food waste and meat consumption; and organic waste diversion from landfills. Outside of Africa, all anthropogenic emissions follow the Shared Socioeconomic Pathway 3 with ~7.0 W m^{-2} radiative forcing in 2100 (SSP3_7.0), which is a high-emissions 'regional rivalry' reference case widely used in climate research[39]. The model also includes internally generated climate-sensitive emissions from several natural sources such as NO_x from lightning, biogenic VOCs, windblown dust and sea-salt emissions, whereas wildfire emissions are prescribed (i.e., not climate-sensitive). Note that given the small share of Africa's CO_2 emissions, the long ramp-up time for reductions relative to other pollutants (e.g., 2040 emissions are ~0.5 Pg lower, ~15%) and the slow carbon cycle response to emissions changes, African CO_2 emissions cuts have minimal impact on CO_2 concentrations by mid-century. This is the case even under the ambitious Agenda 2063 scenario that achieves >50% reductions by 2063 (Table 2).

In the LEAP model's baseline scenario, African SO_2 emissions grow rapidly, reaching 16.2 Tg/yr in 2060. This is higher than the highest SSP, SSP5–8.5, that has emissions of approximately 13.5 Tg/yr followed by SSP4–6.0 and SSP3–7.0 that have emissions of 9.5 and 8.9 Tg/yr, respectively (the SSP5–8.5 data reports combined emissions from the Middle East and North Africa (MENA), so the North African portion is estimated by scaling the projected value by the 2015 ratio of North African/MENA emissions). The increased sulfur emissions are primarily attributable to increased use of coal in electricity generation

(~100,000 MW in 2060), which is not accompanied by increased air pollution controls, along with a growth in diesel fuel use and continued coal liquification. Note that coal remains a relatively small portion of Africa's electricity generation portfolio, about 11% of capacity, but combined with coal use by industry, the total SO_2 emissions attributable to coal are ~8 Tg/yr by 2060. Most of the remaining SO_2 emissions come from diesel vehicles, particularly heavy-duty trucks and buses. These trends are somewhat similar to those in the SSP5–8.5 scenario that also show large increases in energy-sector SO_2 emissions though those are accompanied by fairly constant industry-sector emissions and decreases from the transport sector. In contrast, under SSP3–7.0 energy-related SO_2 emissions stay near current levels and the future growth is almost entirely driven by the industrial sector. The disparities in trends seem to be associated with assumptions about the levels of pollution controls that are likely to be applied under baseline scenarios with growing income in these three sectors, especially in energy. Many models assume the existence of an environmental Kuznet's curve that leads to application of air pollution controls as incomes pass a defined level. Though observational evidence for such a relationship is fairly strong for SO_2 from the energy sector, integrated assessment models tend to show emissions declines happening faster and at lower incomes than observations[40]. By contrast, the Africa model does not assume such controls would occur without new policy measures, and hence none are put in place in the baseline scenario.

To examine the influence of aerosols associated with decarbonization we created a scenario incorporating all reductions from the Agenda 2063 scenario except those for aerosols and ozone precursors, which were instead set to their values under the SLCP scenario. This separates out the changes in aerosols and ozone precursors due to deliberate efforts to reduce SLCPs from those that occur indirectly because of decarbonization. We call this the 'No Decarbonization Aerosol Reductions' (NDAR) scenario, and the difference between Agenda 2063 and NDAR reflects the influence of reductions in co-emitted cooling aerosols. In practice, the Agenda 2063 decarbonization/sustainable development scenario has by far the largest effect on short-lived species beyond those in the SLCP scenario for SO_2, which at mid-century (2050–2060) is ~50% less under Agenda 2063, followed by ammonia (25%), and organic carbon (15%), with more modest emissions decreases for BC, CO, and NO_x (10%) (Table 2). Sulfur changes are driven largely by the transition from coal to renewables and improved industrial efficiency, ammonia decreases by reductions in food waste and meat consumption (meaning NDAR is not exclusively decarbonization but includes ammonia changes associated with behavioral changes in the food system), and organic carbon by the shift from solid biofuels to liquified petroleum gas or electricity for cooking.

Composition-climate modeling

These emissions scenarios were used as input to GISS-E2.1-G; the same model version used in Coupled Model Intercomparison Project phase 6 (CMIP6[41]). This version of the GISS model realistically captures many observed meteorological quantities, atmospheric composition, and associated trends[23–25]. The horizontal resolution of the atmosphere is $2° \times 2.5°$ latitude/longitude, and the ocean resolution is $1° \times 1.25°$, with 40 vertical layers in both components, and the atmospheric model having a top at 0.1 hPa. The aerosol model includes representations of sulfate, black and organic carbonaceous aerosols, nitrate, ammonium, dust, and sea-salt in a mass-based scheme (with fixed size distributions other than for dust and sea-salt). Aerosols affect cloud albedo but not cloud lifetime in this model. The chemistry scheme includes around 200 chemical reactions among ~40 species.

We performed ensembles of 10 simulations from 2015 through 2064 for all scenarios. These simulations began from starting conditions at the end of 2014 taken from 10 independent historical simulations with the GISS-E2.1-G model, which in turn began from starting conditions taken from widely spaced years of a long preindustrial control simulation[42]. Note that although the simulations end in 2064, the net radiation is positive at that time, indicating that warming would continue until energy balance is restored. Unless otherwise noted, all uncertainty ranges show the 95% confidence interval about the 10-member ensemble mean assuming $n = 9$ degrees of freedom. We use the monthly output from these simulations, including monthly mean 2-m air temperature (referred to simply as 'surface temperature') and precipitation.

DATA AVAILABILITY

CMIP6 data, from GISS and other modeling centers, is available at the Earth System Grid Federation (https://esfg-node.llnl.gov/projects/cmip6/). The GISS model is available at https://www.giss.nasa.gov/tools/modelE/. GPCC data is available from NOAA (https://psl.noaa.gov/data/gridded/data.gpcc.html). The data shown in Figs. 1–4 are available at doi: 10.5281/zenodo.7897051 along with the python notebooks used in creating the plots.

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REFERENCES

1. African Union. Agenda 2063: The Africa We Want. Addis Ababa, Ethiopia. p. ISBN: 978-92-95104-23-5, (2013).
2. Friedlingstein, P. et al. Global carbon budget 2021. *Earth Syst. Sci. Data* **14**, 1917–2005 (2022).
3. Lelieveld, J. et al. Effects of fossil fuel and total anthropogenic emission removal on public health and climate. *Proc. Natl Acad. Sci. USA* **116**, 7192–7197 (2019).
4. Ramanathan, V. & Xu, Y. The copenhagen accord for limiting global warming: criteria, constraints, and available avenues. *Proc. Natl Acad. Sci. USA* **107**, 8055–8062 (2010).
5. Stohl, A. et al. Evaluating the climate and air quality impacts of short-lived pollutants. *Atmos. Chem. Phys.* **15**, 10529–10566 (2015).
6. Leibensperger, E. et al. Climatic effects of 1950-2050 changes in US anthropogenic aerosols - Part 2: climate response. *Atmos. Chem. Phys.* **12**, 3349–3362 (2012).
7. Turnock, S. T. et al. The impact of European legislative and technology measures to reduce air pollutants on air quality, human health and climate. *Environ. Res. Lett.* **11**, 024010 (2016).
8. Dang, R. J. & Liao, H. Radiative forcing and health impact of aerosols and ozone in China as the consequence of clean air actions over 2012–2017. *Geophys. Res. Lett.* **46**, 12511–12519 (2019).
9. Shindell, D. & Smith, C. J. Climate and air-quality benefits of a realistic phase-out of fossil fuels. *Nature* **573**, 408–411 (2019).
10. Shindell, D. et al. Simultaneously mitigating near-term climate change and improving human health and food security. *Science* **335**, 183–189 (2012).
11. Dreyfus, G., Xu, Y., Shindell, D. T., Zaelke, D. & Ramanathan, V. Mitigating climate disruption in time: a self-consistent approach for avoiding both near-term and long-term global warming. *Proc. Natl Acad. Sci. USA* **119**, e2123536119 (2022).
12. IPCC, Summary for Policymakers, in Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, (Eds Masson-Delmotte, V. et al.) (Cambridge University Press, New York, 2021).
13. Westervelt, D. M. et al. Connecting regional aerosol emissions reductions to local and remote precipitation responses. *Atmos. Chem. Phys.* **18**, 12461–12475 (2018).
14. Liu, L. et al. A PDRMIP multimodel study on the impacts of regional aerosol forcings on global and regional precipitation. *J. Clim.* **31**, 4429–4447 (2018).
15. Allen, R. J. et al. Climate and air quality impacts due to mitigation of non-methane near-term climate forcers. *Atmos. Chem. Phys.*, **20**, 9641–9663 (2020).
16. Wilcox, L. J. et al. Accelerated increases in global and Asian summer monsoon precipitation from future aerosol reductions. *Atmos. Chem. Phys.* **20**, 11955–11977 (2020).
17. Hirasawa, H., Kushner, P. J., Sigmond, M., Fyfe, J. & Deser, C. Evolving Sahel rainfall response to anthropogenic aerosols driven by shifting regional oceanic and emission influences. *J. Clim.* **35**, 3181–3193 (2022).
18. Bond, T. C. et al. Bounding the role of black carbon in the climate system: a scientific assessment. *J. Geophys. Res.-Atmosph.* **118**, 5380–5552 (2013).

19. Giannini, A. & Kaplan, A. The role of aerosols and greenhouse gases in Sahel drought and recovery. *Clim. Change* **152**, 449–466 (2019).
20. Biasutti, M. Rainfall trends in the African Sahel: characteristics, processes, and causes. *Wiley Interdiscip. Rev.-Clim. Change* **10**, e591 (2019).
21. Hua, W. J., Dai, A., Zhou, L., Qin, M. & Chen, H. An externally forced decadal rainfall seesaw pattern over the Sahel and Southeast Amazon. *Geophys. Res. Lett.* **46**, 923–932 (2019).
22. Deser, C. et al. Isolating the evolving contributions of anthropogenic aerosols and greenhouse gases: a new CESM1 large ensemble community resource. *J. Clim.* **33**, 7835–7858 (2020).
23. Bauer, S. E. et al. Historical (1850-2014) aerosol evolution and role on climate forcing using the GISS ModelE2.1 contribution to CMIP6. *J. Adv. Modeling Earth Syst.* **12**, e2019MS001978 (2020).
24. Kelley, M. et al. GISS-E2.1: configurations and climatology. *J. Adv. Modeling Earth Syst.* **12**, e2019MS002025 (2020).
25. Seltzer, K. M., Shindell, D. T., Faluvegi, G. & Murray, L. T. Evaluating modeled impact metrics for human health, agriculture growth, and near-term climate. *J. Geophys. Res.-Atmosph.* **122**, 13506–13524 (2017).
26. UNEP, CCAC and AUC. Integrated Assessment of Air Pollution and Climate Change for Sustainable Development in Africa, United Nations Environment Programme: Nairobi, Kenya, (2022).
27. Schneider, U., Becker, A., Finger, P., Rustemeier, E. & Ziese, M. GPCC Full Data Monthly Product Version 2020 at 2.5°: Monthly Land-Surface Precipitation from Rain-Gauges built on GTS-based and Historical Data. Global Precipitation Climatology Centre (GPCC) at Deutscher Wetterdienst, (2020). https://doi.org/10.5676/DWD_GPCC/FD_M_V2022_250. (accessed Nov. 2022).
28. Collins, W. J. et al. Global and regional temperature-change potentials for near-term climate forcers. *Atmos. Chem. Phys.* **13**, 2471–2485 (2013).
29. Dong, B., Sutton, R. T., Highwood, E. & Wilcox, L. The impacts of European and Asian anthropogenic sulfur dioxide emissions on Sahel rainfall. *J. Clim.* **27**, 7000–7017 (2014).
30. Undorf, S., Bollasina, M. A. & Hegerl, G. C. Impacts of the 1900-74 increase in anthropogenic aerosol emissions from North America and Europe on Eurasian Summer Climate. *J. Clim.* **31**, 8381–8399 (2018).
31. Zhang, S. P., Stier, P., Dagan, G. & Wang, M. Anthropogenic aerosols modulated 20th-century Sahel rainfall variability via their impacts on North Atlantic Sea surface temperature. *Geophys. Res. Lett.* **49**, e2021GL095629 (2022).
32. Samset, B. H. et al. Fast and slow precipitation responses to individual climate forcers: a PDRMIP multimodel study. *Geophys. Res. Lett.* **43**, 2782–2791 (2016).
33. Almazroui, M. et al. Projected change in temperature and precipitation over Africa from CMIP6. *Earth Syst. Environ.* **4**, 455–475 (2020).
34. Lee, J.-Y. et al. Future Global Climate: Scenario-Based Projections and Near-Term Information, in Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, (eds Masson-Delmotte, V. et al.) p. 553–672 (Cambridge University Press, New York, 2021).
35. Gliss, J. et al. AeroCom phase III multi-model evaluation of the aerosol life cycle and optical properties using ground- and space-based remote sensing as well as surface in situ observations. *Atmos. Chem. Phys.* **21**, 87–128 (2021).
36. Kim, S. K. et al. Widespread irreversible changes in surface temperature and precipitation in response to CO_2 forcing. *Nat. Clim. Change* **12**, 834–840 (2022).
37. Shindell, D., Faluvegi, G., Parsons, L., Nagamoto, E. & Chang, J. Premature deaths in Africa due to particulate matter under high and low warming scenarios. *Geohealth* **6**, e2022GH000601 (2022).
38. Heaps, C. G. LEAP: The Low Emissions Analysis Platform. [Software version: 2020.1.81] Stockholm Environment Institute. Somerville, MA, USA, https://leap.sei.org, (2022).
39. Fujimori, S. et al. AIM implementation of shared socioeconomic pathways. *Glob. Environ. Change* **42**, 268–283 (2017).
40. Ru, M., Shindell, D., Seltzer, K., Tao, S. & Zhong, Q. The long-term relationship between emissions and economic growth for SO_2, CO_2 and BC. *Env. Res. Lett.* **13**, 124021 (2018).
41. Eyring, V. et al. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Dev.* **9**, 1937–1958 (2016).
42. Miller, R. et al. CMIP6 Historical Simulations (1850-2014) with GISS-E2.1. *J. Adv. Model. Earth Syst.* **13**, e2019MS002034 (2021).

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AUTHOR CONTRIBUTIONS

D.S. designed and led the study. C.H. created the emissions scenarios. G.F. performed the GISS simulations. L.P. and G.F. analyzed the simulations. All authors contributed to writing the paper.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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