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Effects of fossil fuel and total anthropogenic emission removal on public health and climate

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Anthropogenic greenhouse gases and aerosols are associated with climate change and human health risks. We used a global model to estimate the climate and public health outcomes attributable to fossil fuel use, indicating the potential benefits of a phaseout. We show that it can avoid an excess mortality rate of 3.61 (2.96–4.21) million per year from outdoor air pollution worldwide. This could be up to 5.55 (4.52–6.52) million per year by additionally controlling nonfossil anthropogenic sources. Globally, fossil-fuel-related emissions account for about 65% of the excess mortality, and 70% of the climate cooling by anthropogenic aerosols. The chemical influence of air pollution on aeolian dust contributes to the aerosol cooling. Because aerosols affect the hydrologic cycle, removing the anthropogenic emissions in the model increases rainfall by 10–70% over densely populated regions in India and 10–30% over northern China, and by 10–40% over Central America, West Africa, and the drought-prone Sahel, thus contributing to water and food security. Since aerosols mask the anthropogenic rise in global temperature, removing fossil-fuel-generated particles liberates 0.51(±0.03) °C and all pollution particles 0.73(±0.03) °C warming, reaching around 2 °C over North America and Northeast Asia. The steep temperature increase from removing aerosols can be moderated to about 0.36(±0.06) °C globally by the simultaneous reduction of tropospheric ozone and methane. We conclude that a rapid phaseout of fossil-fuel-related emissions and major reductions of other anthropogenic sources are needed to save millions of lives, restore aerosol-perturbed rainfall patterns, and limit global warming to 2 °C.

air pollution | greenhouse gases | health impacts | climate change | hydrologic cycle

Air pollution makes a major contribution to excess mortality from cardiovascular, respiratory, and other diseases (1–3). Significant excess death rates are related to fossil energy use, as combustion emissions from traffic, power generation, and industry typically occur in densely populated regions (4, 5). The Paris Agreement that aims to limit climate change in the 21st century to 1.5–2 °C above preindustrial levels requires the phaseout of fossil fuels, which may need to be augmented by negative emissions of CO_2, i.e., removal from the atmosphere, or other geoengineering measures (6). Based on the two middle scenarios of the Intergovernmental Panel on Climate Change (IPCC) there is an estimated 5% chance that the temperature increase in this century can be limited to 2 °C, but the likelihood increases when greenhouse gas emissions are curbed sharply in the near term (7). The timing of mitigation actions is critical, especially if currently unproven geoengineering options are to be avoided. Clearly, the switch from fossil to renewable, clean energy sources has the potential to prevent morbidity and mortality from aerosol pollution. Because the particles have a net climate cooling effect, removing them will lower the prospects of meeting the goals of the Paris Agreement, but the public health gain is nevertheless a strong motivation for emission controls (8, 9). Here we present the health benefits achieved by removing fossil-fuel-related and all air pollution emissions, applying hazard ratio functions that connect fine particulate matter to nonaccidental mortality (10). We consider the repercussions for climate change of policies and technologies which focus on air-quality improvement using traditional control methods such as filters, catalytic converters, and cleaner fuels, but also concurrently with greenhouse gas mitigation strategies which improve air quality.

Methods

We applied an atmospheric chemistry–general circulation model to calculate the impacts of air pollution on climate and public health (*SI Appendix*, *SI Methods*). The model comprehensively accounts for emissions, multiphase chemistry, and other processes that control atmospheric composition. Model results include concentrations of ozone (O_3) and particulate matter, including $PM_{2.5}$ (particulates with a diameter <2.5 μm), being the main cause of morbidity and mortality (2, 9). The results for $PM_{2.5}$ and O_3 served as input to the health impact calculations, based on the Global Burden of Disease methodology (2). We applied a Global Exposure Mortality Model (GEMM) for $PM_{2.5}$ that is based on an unmatched large number of cohort studies in many countries, and accounts for additional causes of death than considered previously (10). The GEMM calculations were complemented with those for O_3, accounting for about 3% of the total excess mortality rate. The atmospheric chemistry model was initially run for 20 y (excluding 5-y spin-up) with prescribed ocean temperatures to analyze health impacts and climate forcings, following IPCC recommendations (11), including changes in cloud reflectivity through the effects of aerosols on cloud condensation nuclei (CCN) (12). Uniquely, we included the increase in CCN activity of aeolian (wind-blown) dust particles is due to interaction with air pollution (chemical "aging"), which generally increases their ability to take up water. *SI Appendix*, Fig. S1 shows a comparison between modeled and satellite observed aerosol optical depth, *SI Appendix*, Fig. S2 for rainfall, *SI Appendix*, Fig. S3

Significance

We assessed the effects of air pollution and greenhouse gases on public health, climate, and the hydrologic cycle. We combined a global atmospheric chemistry–climate model with air pollution exposure functions, based on an unmatched large number of cohort studies in many countries. We find that fossil-fuel-related emissions account for about 65% of the excess mortality rate attributable to air pollution, and 70% of the climate cooling by anthropogenic aerosols. We conclude that to save millions of lives and restore aerosol-perturbed rainfall patterns, while limiting global warming to 2 °C, a rapid phaseout of fossil-fuel-related emissions and major reductions of other anthropogenic sources are needed.

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for $PM_{2.5}$ and dust aerosol optical depth, and *SI Appendix*, Figs. S4 and S5 present the calculated aerosol radiative forcing of climate, which match the IPCC ensemble model estimates (11). Subsequently, the same model was rerun for 30-y periods (excluding 5-y spin-up) with an interactive ocean to compute equilibrium climate responses. We accounted for air pollution and greenhouse gases in idealized scenario calculations to characterize the public health and climate impacts of a hypothetical phaseout from fossil-fuel-related and other anthropogenic emissions, a distinction that could be essential for policy-making.

Results

Table 1 presents the excess mortality rate attributed to air pollution and the associated years of life lost (YLL), and the 15 countries that lead the ranking. *SI Appendix*, Tables S1 and S2 itemize the excess mortality and YLL for different countries and disease categories, including uncertainty ranges, and *SI Appendix*, Fig. S6 shows a global map of the excess mortality. We find that the global total excess mortality rate is 8.79 million per year, with a 95% confidence interval of 7.11–10.41 million per year. The associated number of YLL is 233(95%CI 185–278) million per year. Consequently, the mean life expectancy decrease per affected individual is about 26.5 y (233/8.79), while the global mean loss of life expectancy is 2.9 (95%CI 2.3–3.5) y. Main causes of death are ischemic heart disease, chronic obstructive pulmonary disease, cerebrovascular disease, lung cancer, other noncommunicable diseases, and lower respiratory tract infections. Fig. 1 and Table 1 present the avoidable deaths by removing the fossil-fuel-related emissions in our model, i.e., from traffic, power generation, and industry. Further, we show the impact of removing all anthropogenic sources, which also includes agriculture, residential energy use, and nonfossil industrial emissions. We assumed that desert dust emissions cannot be controlled (even though a fraction of about 25% may be human-induced; see ref. 13) and that 90% of biomass burning emissions can be avoided (14).

By removing the fossil-fuel-related emissions in our model, we find that 3.61(95%CI 2.96–4.21) × 10^6/y of the attributable deaths can be avoided (Table 1). The avoidable mortality from all anthropogenic pollution is 5.55(95%CI 4.52–6.52) × 10^6/y. Considering that this is a factor of 3 higher than the mortality rate from other avoidable environmental risks such as unsafe water, sanitation, and hygiene (3), reducing air pollution is clearly an effective and urgent health intervention. The fact that a substantial mortality fraction is nevertheless difficult to prevent is largely related to natural sources, including desert dust to which a growing number of people are exposed. Furthermore, the hazard ratio functions are nonlinear, so that especially at relatively low $PM_{2.5}$ concentrations, below about 10–20 μg/m^3 (annual average), large health benefits can be achieved. We find that in some regions, for example in Africa where aeolian dust and biomass burning aerosols are abundant, it will be difficult to reduce $PM_{2.5}$ to very low levels, e.g., to the WHO air-quality guideline concentration of 10 μg/m^3 or the minimum risk exposure level of 2.4–5.9 μg/m^3 (10). Fig. 1 and Table 1 demonstrate how public health outcomes from emission controls can differ greatly among countries worldwide. For example, the phaseout of fossil energy emissions has relatively larger health gains in North America than in South Asia and Africa. The latter regions can benefit greatly from controlling residential energy use and biomass burning, and in Europe and East Asia agricultural emissions are important. On the other hand, the peoples of Egypt and Sudan are strongly impacted by desert dust emissions, which are difficult to control.

Reducing air pollution also has major implications for climate change, water, and food security, the latter in part through negative impacts of O_3 on crop yields (15). By decreasing aerosol concentrations, tropical precipitation tends to increase, because the particles shield the oceans from solar radiation, which inhibits evaporation and decelerates the hydrologic cycle (16–18). Aerosol radiative forcing at the Earth's surface is relatively strong as the particles both scatter and absorb sunlight, the latter, e.g., by black carbon (*SI Appendix*, Fig. S3). On a regional scale the surface cooling of aerosols can strongly exceed the greenhouse gas warming. By removing aerosol pollution, we find substantial regional invigoration of the hydrologic cycle, with 10–70% increases in precipitation over the densely populated Indo-Gangetic plains (IGP), 10–30% over northern China including the capital Beijing, 10–40% over West Africa and the Sahel, and 10–40% over Central America (Fig. 2 and *SI Appendix*, Fig. S7). Restoring the hydrologic cycle and the monsoonal flow in these regions could promote the wet deposition of aerosols, including the natural ones, which may create a positive feedback by removing the particles. Observations corroborate that these four

Table 1. Excess mortality rate attributed to air pollution in the top 15 ranking countries

	All sources		Fossil-fuel-related		Total anthropogenic	
Countries	Excess deaths, ×10^3/y	YLL, ×10^6/y	Avoidable deaths, ×10^3/y	Unavoidable warming, °C	Avoidable deaths, ×10^3/y	Unavoidable warming, °C
China	2,799	61.9	1,554	0.92	2,204	1.21
India	1,853	55.0	692	0.38	1,140	0.42
USA	283	5.7	194	0.88	230	1.17
Pakistan	233	7.9	29	0.44	73	0.52
Japan	203	3.1	84	1.03	117	1.28
Russian Federation	186	4.3	114	1.07	152	1.23
Nigeria	181	9.1	6	0.10	33	0.09
Bangladesh	175	5.1	73	0.80	130	1.00
Indonesia	174	5.3	35	0.19	88	0.05
Sudan + South Sudan	126	5.5	6	0.45	11	0.36
Germany	124	2.1	76	0.91	115	1.14
Egypt	120	3.4	19	1.03	21	0.90
Brazil	102	2.7	16	0.35	65	0.36
Vietnam	88	2.2	35	0.35	61	0.52
Italy	81	1.2	41	0.84	50	1.10
World	8,793	233	3,608	0.35	5,554	0.36

Avoidable deaths and unavoidable net warming consider sources of air pollution and greenhouse gases. *SI Appendix*, Tables S1 and S2 present results for the different disease categories and all countries, plus 95% confidence intervals.

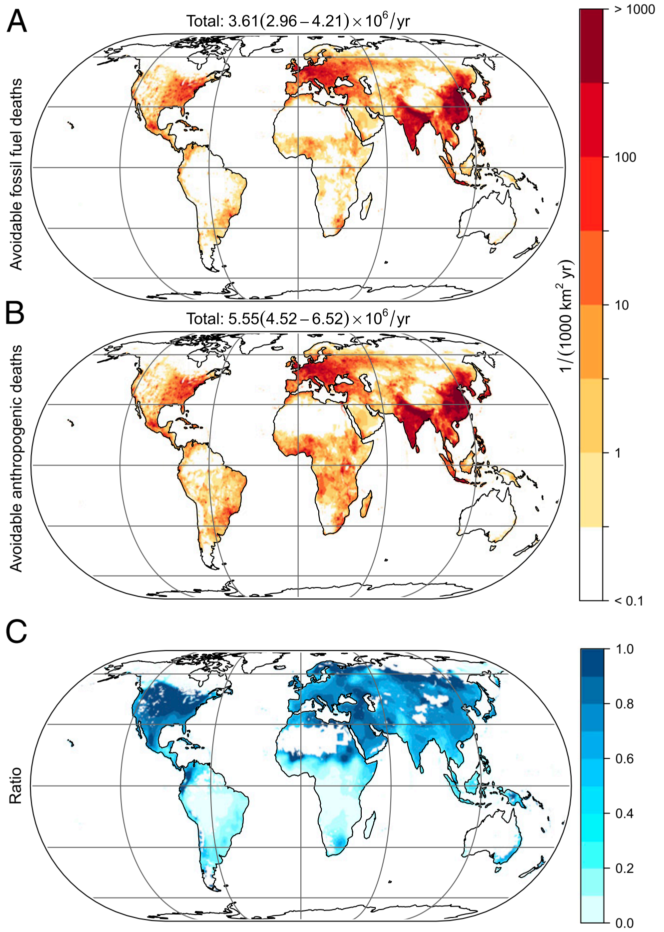

Fig. 1. Avoidable excess mortality rate from air pollution. Units: deaths per 1,000 km^2/y. (*A*) Excess deaths that may be avoided by the phasing out of fossil fuels, and (*B*) by all anthropogenic emissions. (*C*) Relative contribution to excess deaths from fossil fuel use compared with all anthropogenic emissions. The dark-blue regions would profit more from removing fossil-fuel-related emissions, while the light-blue ones profit more from removing other pollution sources.

regions experienced major decreases in rainfall, such as the devastating Sahelian drought that began in the late 1960s and continued until about 2010, the decrease in monsoon rainfall over the IGP, and dryness in northern China and Mexico. This substantiates previous studies that have linked aerosol pollution to drying conditions (16–18). Our results indicate that aerosols from fossil fuel use explain roughly half of these effects globally, while other anthropogenic sources, including biomass burning, contribute the other half. The aerosol weakening of the hydrologic cycle could be rapidly reversed after the phaseout of pollution emissions.

Finally, our model simulations show that fossil-fuel-related aerosols have masked about 0.51(±0.03) °C of the global warming from increasing greenhouse gases (Fig. 3). The largest temperature impacts are found over North America and Northeast Asia, being up to 2 °C. By removing all anthropogenic emissions, a mean global temperature increase of 0.73(±0.03) °C could even warm some regions up to 3 °C. Since the temperature increase from past CO_2 emissions is irreversible on human timescales, the aerosol warming will be unleashed during the phaseout (11, 19–22). Some near-term mitigation can be achieved from the simultaneous reduction of short-lived greenhouse gases such as methane (CH_4), O_3, and hydrofluorocarbons (HFCs) (15, 23–25). Fossil-fuel-related CH_4 emissions constitute nearly 20% of the total source, and removing all anthropogenic CH_4 (nearly 60% of the source), in addition to anthropogenic O_3, would limit the near-term warming to 0.36(±0.06) °C. While the current climate forcing of HFCs is still small, it will be critical to prevent increases in the future, as they are potent greenhouse gases (26). Table 1 presents the unavoidable net warming from emission control measures that simultaneously affect aerosols and greenhouse gases, which have many sources in common. *SI Appendix*, Table S1 lists these results for all countries, including the uncertainty intervals.

Discussion

While we have consistently addressed air pollution and greenhouse gas effects on public health, climate, and the hydrologic cycle in context, and distinguished fossil-fuel-related emissions from other pollution sources, some aspects have been addressed by other groups. Next, we discuss our results in view of recent studies that complement and corroborate the robustness of our calculations.

Health Risks. Possible future impacts of air pollution on mortality have been estimated previously by using the output from chemistry–climate and chemical transport models that applied Representative Concentration Pathway scenarios (RCPs) (27). Apart from the fact that the new GEMM was not available at the time, it differed from our approach by estimating increased and avoided mortality from different RCPs, assuming that economic development drives air pollution control. Here we estimate the attributable effects of both fossil fuel and all anthropogenic air pollution plus greenhouse gases by removing emissions in the model, rather than applying time-dependent scenarios that rely on assumptions about socioeconomic futures. While this may seem a daring assumption, these source categories will need to be phased out to reach the 2 °C target of the Paris Agreement (7). We realize, however, that especially agricultural emissions cannot be fully avoided in a world with growing food demand, although a large fraction (e.g., of ammonia and methane sources) could be effectively controlled. A limitation of our approach is that it refers to emission and demographic data for 2015, while population growth is expected up to about 9 billion by the middle of the century, especially in developing countries where air pollution levels can be very high. Therefore, we performed sensitivity simulations that account for the projected population in 2050, indicating that the total excess mortality may be about 10% higher globally. Most of the increase is due to population growth in South and West Asia, and especially in Africa, while in East Asia the population is expected to decline. In Europe and the Americas (notably South America) projected population changes are comparatively small. Interestingly, the avoidable excess mortality in 2015 and 2050 are practically the same (within 1–2%). Furthermore, we did not take into account that the introduction of clean household energy in low-income countries could substantially reduce excess deaths from household air pollution, estimated at about 2.9–4.3 million per year (3). The phaseout of anthropogenic emissions is expected to be paralleled by a reduction of household air pollution from the introduction of clean "zero carbon" domestic energy sources.

Climate Forcing. *SI Appendix*, Fig. S4 presents model results of the direct and total aerosol radiative forcing at the top of the atmosphere (TOA). The direct aerosol forcing is −0.46 ± 0.009 W/m^2, which closely agrees with the best estimate of −0.45 W/m^2 of the IPCC (11). Our total direct plus indirect radiative forcing is −0.9 W/m^2, which also agrees with IPCC (11). However, by also accounting for the chemical aging of aeolian dust by air pollution we obtain a −0.3-W/m^2 larger effect, about −1.2 ± 0.06 W/m^2 (28, 29). The dust aging has multiple consequences, such as increased solar radiation scattering from hygroscopic particle growth and decreased lifetime from more efficient rainout, while the climate effect is dominated by the enhanced CCN activity. Since dust particles are globally abundant and relatively large in size, their increased hygroscopicity effectively enhances cloud

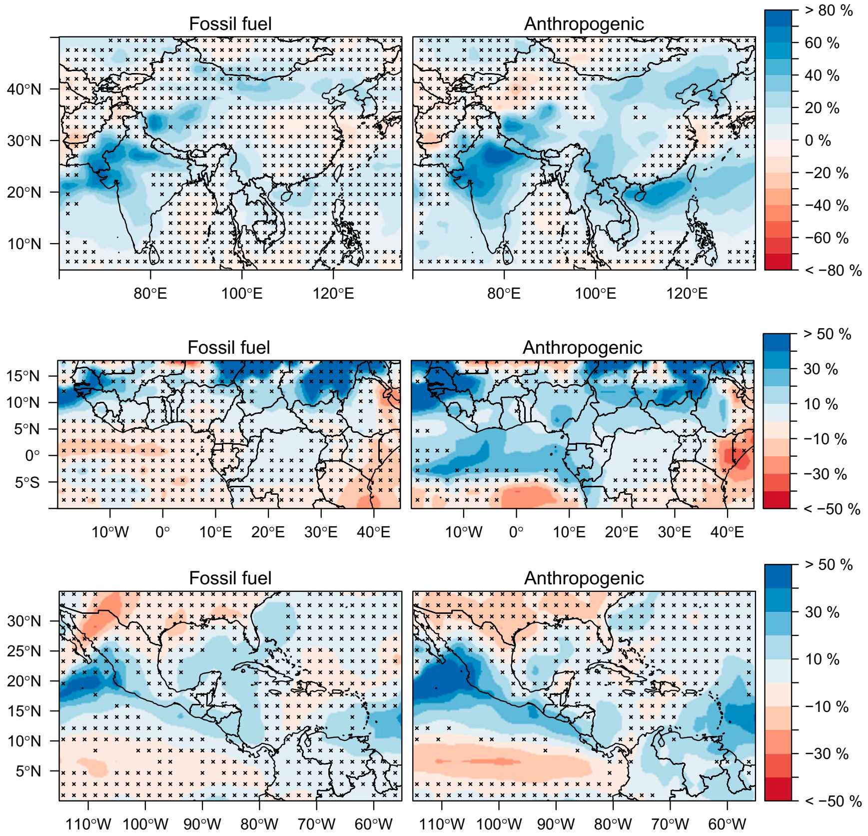

Fig. 2. Fractional precipitation changes at the surface. Effects from the removal of fossil-fuel-related and all anthropogenic pollution emissions in Asia, Africa, and Central America. Crosses denote areas where precipitation changes are not significant at the 95% confidence level.

droplet formation (29). To account for these effects, it is needed to simulate the particle chemistry and thermodynamics of crustal ions, dependent on the composition of aeolian dust from different deserts, which was not included in the IPCC climate models. *SI Appendix*, Figs. S3 and S4 show the global, multiannual mean geographic distribution of the aerosol direct and total radiative forcing, both at the TOA and the bottom of the atmosphere (BOA), making the distinction between fossil fuel generated and all anthropogenic aerosols. The differences between the TOA and BOA forcings represent heating of the atmosphere through the absorption of sunlight, mostly by black carbon. We find that the negative (cooling) BOA forcings from aerosols are generally largest over South and East Asia, partly in excess of –20 W/m^2 (annual average), which can regionally dwarf the positive (warming) radiative forcing from greenhouse gases. The strong surface cooling downwind over the ocean can significantly reduce evaporation and precipitation on a regional scale (16).

Climate Response. We performed equilibrium climate response computations, following the example of Shindell et al. (15), with the difference that they computed atmospheric composition changes offline with different models, whereas we calculate the processes online with a coupled atmosphere–ocean model. The equilibrium assumption is justified for short-lived climate forcers since most of the climate response that follows phaseout of fossil fuels and other pollution sources happens within a few decades. Although the equilibrium assumption does not apply to CO_2, this is not relevant here because the phaseout of CO_2 emissions does not translate in a near-term temperature decrease (11, 19–22). In the period during which CO_2 concentrations still increase, the warming is tempered by heat transport into the deep oceans. When CO_2 emissions are phased out, the atmospheric concentrations can decrease, but with a delay due to the slow uptake of anthropogenic CO_2 by the oceans (30). These physical climate and carbon cycle effects are of opposite sign and of similar magnitude. Consequently, even if fossil CO_2 emissions stop abruptly, global temperatures remain constant for several centuries, which means that past CO_2 emissions commit the planet to persistent warming on the human timescale (for a discussion, see ref. 11). While the timing of air pollution and greenhouse gas emission phaseout is the subject of scenario studies, here we focus on the climate response magnitude. For example, global warming from increasing CO_2 scales approximately linearly with cumulative emissions (11). It implies that the phaseout may occur over 5 or 50 y, but the integral climate response over these periods is the same. In fact, the key factor is "societal inertia" from the slow phaseout of polluting infrastructure, often constructed to last for many decades (30, 31).

The warming and precipitation pattern changes that result from removing aerosols in our climate simulations (Fig. 3 and *SI Appendix*, Fig. S7) are comparable to those presented by Samset et al. (32), who analyzed the ensemble results from four climate models. They reported that the removal of anthropogenic aerosols causes a global mean surface warming of 0.5–1.1° and a precipitation increase of 2.0–4.6%, where we find 0.73 ± 0.03 °C and 3.2 ± 0.2%, respectively. Consistent with our results, they showed how the aerosol-related climate response patterns differ markedly from those of greenhouse gases. However, they studied anthropogenic emissions of SO_2 and fossil fuel black and organic carbon, without the distinction between fossil fuel use and other anthropogenic sources, and did not consider pollution impacts on dust. Further, they did not account for the greenhouse gases O_3 and CH_4, and calculated CO_2 and aerosol reductions separately to contrast the cooling and warming patterns. While greenhouse gases act globally, the radiative forcing and consequent net warming from

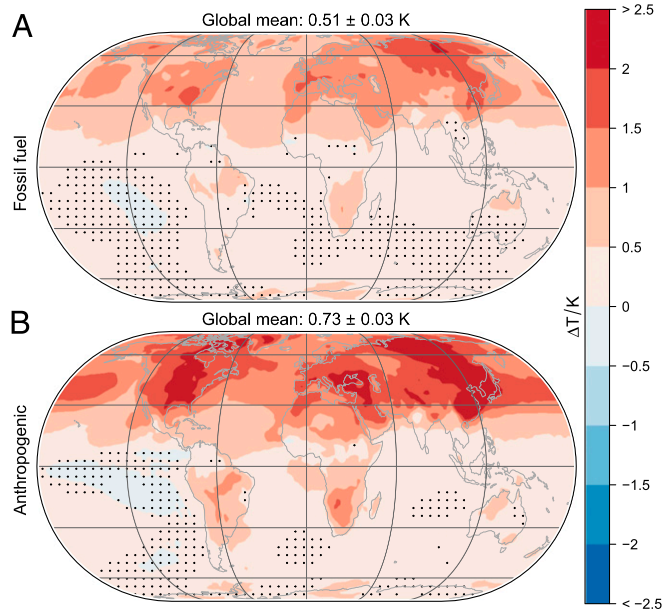

Fig. 3. Temperature changes at the surface from removing particulate air pollution. (*A*) Due to fossil-fuel-related and (*B*) due to all anthropogenic emissions. Pollution includes scattering and absorbing (e.g., black carbon) aerosols. Stippling denotes areas where the temperature changes are not significant at the 95% confidence level. Table 1 presents the unavoidable net warming from removing air pollution as well as greenhouse gases.

aerosol removal is regional and most pronounced over the continental northern hemisphere (Fig. 3). In agreement with the results of Samset et al., we find that the removal of aerosols creates south–north shifts of precipitation over the Pacific and Atlantic Oceans and relatively strong rainfall increases over Africa, South and Northeast Asia (Fig. 2 and *SI Appendix*, Fig. S7). Westervelt et al. (33) studied precipitation changes from the removal of SO_2 emissions in the United States. The computed reductions of aerosol sulfate and cloud droplet number concentrations were found to cause increasing precipitation over the United States, and downwind over the Atlantic Ocean, qualitatively consistent with our results. *SI Appendix*, Figs. S3 and S4 illustrate that the direct radiative effect of aerosols at the BOA typically exceeds that at the TOA by a factor of 2–3, e.g., due to solar radiation absorption within the atmosphere by black carbon, and that the radiative forcing can regionally exceed the global average by a factor of 5–10. This results in strong, although localized influence on surface temperature, evaporation and associated precipitation.

Regional Hydrologic Cycle Changes. Numerous studies have addressed the causes of observed decreases in precipitation over tropical regions, and analyzed the influence of pollution aerosols on the monsoon circulation over South and East Asia, and to a lesser extent over Africa. An exhaustive review of the South and East Asian studies can be found in Li et al. (34). The basic inference has been that the radiative forcing from increasing greenhouse gases is unlikely to account for the sign and magnitude of negative precipitation trends, associated with a weakening of the monsoon. Dominant factors are trends in sea-surface temperature (SST), particularly the asymmetric warming of the southern tropical oceans relative to the northern oceans. Two principal forcing mechanisms have been proposed. Interdecadal variability of SSTs; and the negative aerosol forcing (from direct and indirect effects) of the ocean surface, which is larger in the northern than the southern hemisphere. Further, the solar dimming from pollution aerosols reduces the land–ocean heating contrast (since pollution levels are highest over land areas), so that winds at the surface weaken and evaporation decreases, hence affecting the dominant drivers of the monsoon. There is compelling evidence that anthropogenic aerosol forcing explains most of the drying tendency in South Asia, also simulated by our model, and supported by observations (35–38). Our results support those of Chen et al. (39), who modeled pollution-induced precipitation reductions over Southeast and Northeast Asia, triggered by aerosol cooling of the midlatitude sea surface. Likewise, in East Asia aerosol cooling over land reduces the thermal contrast with the ocean, and weakens the monsoon circulation (40). Further, it was found that the weakening monsoon contributes to the pollution haze in the Beijing area (41). Negative rainfall trends have been observed over Northeast China, enhanced by the aerosol forcing, which was not captured well by climate models in the past (34, 42), which underscores the need for a comprehensive account of these processes.

For the Sahel, drying during the latter part of the 20th century has been largely attributed to changes in SST patterns, influenced by external greenhouse gas and aerosol forcings as well as internal climate variability (43–45). By comparing climate model simulations with increasing greenhouse gases to those that also account for pollution aerosols it was shown that the latter cause a meridional SST gradient, associated with a reduced West African monsoon flow (46). Hence, the reduction or removal of anthropogenic aerosol forcing can be expected to increase the North Atlantic SST, leading to a moistening of the Sahel (47, 48). In addition, warming of the Mediterranean, through a decrease in solar dimming from European pollution, contributes to evaporation and moisture transport into the eastern Sahel (49, 50). Our results demonstrate that the asymmetric aerosol radiative forcing creates interhemispheric heating gradients and meridional rainfall shifts over all tropical oceans, including the Pacific (Fig. 2), which could be restored by removing the particulate pollutants. While Central America has been affected by droughts throughout its history, including El Niño influence on summer precipitation, our model simulations suggest that recent dryness, e.g., in Mexico, has been aggravated by air pollution. More work will be needed to substantiate these findings. Generally, it is a major challenge to attribute the contributions of greenhouse gas and aerosol forcings to decadal precipitation trends, and distinguish them from natural variability of the atmosphere–ocean system.

Cocontrolling Air Pollution and Greenhouse Gases. Our model results show that the phaseout of air pollution emissions leads to substantial precipitation increases in these four regions. Recovery from aerosol-perturbed rainfall patterns could be relevant for countries with rapidly growing populations, e.g., in the Sahel, South Asia, and West Africa, which depend on monsoon rainfall for water availability and food production. While the surface temperature and hydrologic cycle respond rapidly to the radiative forcings of short-lived climate pollutants such as aerosols, the response to CO_2 emissions is irreversible for centuries (11, 19–22, 30). On the other hand, the simultaneous reduction of short-lived greenhouse gases, such as O_3, counteracts the warming from removing aerosols on short timescales. We find that the fossil-fuel-related and the total anthropogenic O_3 cooling could compensate about 0.12 and 0.19 °C of the aerosol warming, respectively (i.e., counteracting the 0.51 and 0.73 °C warming from fossil and total anthropogenic aerosols). The reduction of fossil methane, on the other hand, has limited impact, as it accounts for less than 20% of the total source, while an additional 40% of the emissions are related to other anthropogenic activities such as agriculture (rice paddies, domesticated animals), landfills, biomass burning, and biofuel use. Phasing out fossil as well as nonfossil CH_4 emissions additionally moderates the warming from removing aerosols by about 0.21 °C.

The importance of reducing methane emissions to mitigate climate change, in part through the impact on O_3, and together with black carbon, was emphasized by Shindell et al. (15), who calculated the cobenefits for human health and food security. They developed CH_4 and black carbon scenarios to optimally decrease the rate of climate warming (up to about 0.5 °C), and considered improved air quality and food security as cobenefits. Here we stress that a complete phaseout of fossil fuels, and accompanying reductions of other anthropogenic emissions, will be needed to reverse the major impacts on public health, regional climate, water supply, and food production. The prospect of preventing millions of excess deaths attributable to air pollution, and restoring perturbations of the hydrologic cycle that have contributed to regional drying, with the cobenefit of limiting climate warming to below 2 °C, is compelling and underscores the urgency of acting on global environmental change.

Conclusion

The mutual goals of clean air and a stable climate under the WHO guidelines and the Paris Agreement require a rapid phaseout of fossil fuels. Other pollution sources such as agriculture, biomass burning, and residential energy use should be controlled as well, to achieve a mortality reduction up to 5.55 million excess deaths annually (with additional mortality reduction from reduced household air pollution), limit the warming from aerosol removal, and restore the monsoon rainfall. Replacing fossil by clean, renewable energy sources could decrease the global attributable mortality by 65%, and up to 84% in the United States. If air pollution would be controlled by traditional end-of-pipe techniques alone to abate fine particulates, but leaving greenhouse gas emissions unchanged, global warming could be enhanced by 0.51(±0.03) °C, while removal of all anthropogenic aerosols can unleash 0.73(±0.03) °C (and >2 °C in the United States). However, if air pollution and greenhouse gases are removed concurrently by replacing the common sources, a reduced residual, but unavoidable near-term global warming of 0.36(±0.06) °C will be liberated. Since a temperature increase of 1.0(±0.2 likely range) °C has been realized already, and considering the observed warming rate of 0.2(±0.1) °C per decade (high confidence) (51), our results suggest that it is very unlikely that the 1.5 °C target is achieved this century without massive CO_2 extraction from the air. However, with a phaseout by midcentury the 2 °C goal may still be within reach.

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