The North-South divide in global air pollution: drivers and impacts

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Abstract

We used an Earth System Model to assess global air pollution changes and their impacts over the 1970-2010 period. We found emergence of a strong North-South divide driven by anthropogenic air pollutant emissions, with a secondary contribution from greenhouse gas increases. Increased concentrations of $\text{PM}_{2.5}$ and O_3 have respectively led to an additional 2.4 (95% confidence interval: 2.0-2.6) million and 0.8 (0.6-0.9) million premature deaths. Increases in O_3 have also led to an extra 173 ± 8 million tonnes annual staple crop losses at a cost of ~ 55 billion $\text{US\$}_{2010}$. Increased energy use dominates the worsening air pollution in global south regions, while technologies lowering emissions and mitigating impacts have been important in Europe, and to a lesser extent in North America. Reductions in energy-intensive sectors, not technologies alone, are required worldwide to protect global air quality, human health, and food security.

1. Introduction

Global air pollution has increased significantly since the Industrial Revolution¹, mainly due to emissions increases from three sectors: industry, power generation and transportation^{2,3}. These sectors are strongly influenced by policy-driven decisions, and particularly the competition between economic growth and emissions control measures². The former mainly reflects growth in energy use, while the latter has been mostly determined by technology advances in high-income countries in recent decades. Future global air quality will be strongly controlled by emissions changes associated with these two drivers. For example, the transition from coal and oil to renewable and clean energy, as well as changes in behaviours and technologies to mitigate climate change, may take very different courses in different countries, and these may be largely policy-driven.

Previous studies⁴⁻⁹ have demonstrated clear links between exposure to $\text{PM}_{2.5}$ and O_3 and premature mortality. Currently, around 3-9 million premature deaths annually are attributable to $\text{PM}_{2.5}$ exposure¹⁰⁻¹², and 0.2-1.2 million to O_3 exposure^{5,8,13}. O_3 also damages vegetation because of its phytotoxicity. Globally, exposure to O_3 pollution is estimated to result in yield losses of 4–15% for wheat, 5–15% for soybean, 3–4% for rice, and 2–5% for maize¹⁴⁻¹⁶. Continued and uncertain changes in air pollution pose considerable risks to both human health and food security worldwide in the future. Quantification of the drivers and impacts of past changes in air pollution will better inform future air quality and agriculture strategies.

Here we provide a global assessment of the 1970-2010 changes in air pollution and their impacts on premature mortality, crop production and economic losses, separating the contribution of changes in anthropogenic air pollutant emissions (APE) from those related to long-lived greenhouse gases (GHG). Note that GHG-related changes include physical (e.g., global warming) and chemical (e.g. anthropogenic emissions of methane) climate changes. For example, methane contributes via multiple pathways, impacting physical climate as a radiatively-active gas but also affecting air quality as a precursor of CO

and O₃. The period 1970-2010 was selected as it encompasses a large fraction of the preindustrial to present-day global warming^{17,18}, and features dramatic and distinct changes in regional atmospheric composition.

To the best of our knowledge, our study is the first of its kind to provide a holistic global apportionment of the key anthropogenic drivers of human health, crop and economic impacts from air pollution using a state-of-the-art Earth System model. Our work documents the origins and spatial structure of the global North-South divide in the drivers and impacts of significant air pollution changes that have emerged since 1970. We show that the changes in air pollution are predominantly driven by APE with a secondary impact from GHG increases. The impacts due to APE reflect a “tug-of-war” between growth in energy use and advances in technologies for controlling emissions at the global scale, emphasizing a key role of policymaking for the future state of the global environment. The North-South divide has grown as a result of new technologies tending to improve air quality in high-income countries, while energy use growth without parallel deployment of strong emission controls has resulted in worsening air quality and huge impacts in developing regions.

2. Main

To quantify changes in global air pollution and its impacts, we carried out several equilibrium model simulations^{18,19} for 1970 and 2010 conditions (see Methods and Supplementary Table S1 and Fig. S1) using the fully-coupled Community Earth System Model (CESM1²⁰). We first integrated CESM1 with its standard Community Atmosphere Model (CAM5) into quasi-equilibrium climate states under 1970 and 2010 forcings¹⁸. From these we branched off a number of sensitivity experiments with CESM1 using the full-chemistry module CAM5-Chem²¹. We compare 2010 model results to the Copernicus Atmosphere Monitoring Service (CAMS²²) reanalysis to demonstrate that CESM1 (CAM5-Chem) is a useful tool for this study. For more details, please refer to Note S1 and Fig. S2.

We used the Emissions Database for Global Atmospheric Research (EDGAR) retrospective emission scenarios², which were designed to separate emissions changes from energy use growth (ENE) and technology advances (TEC) in addition to a best estimate of the overall 1970-2010 changes in APE¹. These retrospective scenarios shed light on the contributions from various high-level drivers of global air pollution change over the 1970-2010 period. Note that the emission changes due to ENE and TEC in these scenarios do not perfectly add to yield the overall changes. Rather, our results provide an indicative quantitative measure of these components, which are useful from the perspective of informing policymakers, rather than a full and rigorous attribution.

2.1 Air pollution changes

Surface concentrations of PM_{2.5}, O₃, NO_x and CO show statistically significant changes worldwide between 1970 and 2010 (Fig. 1a-d). However, whilst for PM_{2.5} (Fig. 1a) and CO (Fig. 1d) there are

distinctly opposite trends between Europe and North America (grouped as high-income countries for clarity) and developing regions, for O_3 (Fig. 1b) and NO_x (Fig. 1c) there are increases worldwide, albeit with much larger increases over Asia. Global (population-weighted) mean concentrations for each of the four air pollutants show relatively small trends compared to their significant regional increases in Asia (Fig. 1i-l). This is due to the opposing effects of worsening air quality in Asia and improved air quality in Europe and North America. The trade-off is clearly seen in the 1970-2010 changes to the probability distributions of grid-cell values (Fig. 1e-h), and regional means (Fig. 1i-l), and particularly the contrast between Europe and Asia. The strong air pollution increases over Asia come mainly from East and South Asia (Fig. S3), while changes in Central Asia are relatively moderate. This is particularly important for CO which shows a compensation between declines in Central Asia and extremely large increases in East and South Asia (compare Fig. 1h to Figs. S3t-v).

Overall, we conclude that statistically significant changes in global air pollution emerged during the 1970-2010 period, which display a pronounced gradient between high- and low-income regions. This gradient implies huge global inequality in air pollution exposure, given that these less developed regions contain over 80% of the global population. This inequality is likely to deepen as these regions are forecast to experience the greatest population growth in the next few decades.

2.2 Drivers of air pollution changes

Figure 2 shows population-weighted global and regional mean changes in surface air pollution, as well as with the contribution of each individual driver. The equivalent figure for area-weighted regional mean changes is shown in Fig. S4, whilst the spatial distributions in air pollution changes associated with each driver are shown in Figs. S5-S8. Both the area-weighted and population-weighted mean changes highlight the dominant role of Asia in worsening global air quality, with some trade-offs from high-income countries.

Air pollution changes are primarily driven by APE at both global and regional scales. The effects of GHG are secondary and show large uncertainties (Fig. 2). Note however that within the GHG effects, increases in CH_4 , which is a precursor of CO, lead to an increase in global area-weighted mean CO (Fig. S4) 2.3 times (8.4 ppb) larger than the 1970-2010 net change (3.6 ppb). Nevertheless, we conclude that APE is the dominant driver of changes in the surface concentrations of major surface air pollutants. There is a clear competition between TEC and ENE. For example, the increase in $PM_{2.5}$ in Asia (a population-weighted annual mean of $11.3 \pm 3.2 \mu\text{g m}^{-3}$), as well as in other developing regions, is dominated by APE ($10.1 \pm 3.7 \mu\text{g m}^{-3}$). This is primarily driven by ENE, while TEC has a counteracting effect almost globally.

The global annual mean surface O_3 concentration shows a statistically significant increase of $16.9 \pm 0.4 \text{ ppb}$ over the 1970-2010 period. The change is driven by APE worldwide ($+15.9 \pm 0.4 \text{ ppb}$), which is most prominent over Asia ($+22.4 \pm 0.6 \text{ ppb}$). While the competition between ENE and TEC in O_3 changes is also clear. Changes in NO_x (Fig. 2c) resembles that of O_3 , showing a worldwide increase driven by APE which is dominated by ENE and partially counteracted by TEC. Notably, there is a large benefit from TEC in

Europe that reduces NO_x by up to 3.3 ± 0.2 ppb. Surface CO concentration shows a strong reduction in Europe (-64.2 ± 4.5 ppb) and North America (-53.3 ± 2.2 ppb), both primarily driven by TEC (Fig. 2d). Overall, we show that the North-South divide in air pollution changes has resulted from very different regional trends in APE, with the two major emission drivers of ENE and TEC having opposing impacts. We note again that changes due to ENE and TEC do not perfectly add to yield the overall changes seen in APE.

2.3 Premature mortality

We estimate premature mortality associated with $\text{PM}_{2.5}$ (all-causes) and O_3 (respiratory diseases), which together account for more than 90% of global air pollution-related premature mortality²³. Fig. 3 shows the spatial distribution of 1970-2010 changes in the attributable fraction of premature mortality due to long-term exposure to $\text{PM}_{2.5}$ and O_3 , as well as changes in air pollution ($\text{PM}_{2.5} + \text{O}_3$) attributable mortality calculated using the assigned relative risk (RR; see Methods). The contribution of each individual driver is shown in Fig. S9, while the estimates associated with the 5th -95th confidence intervals of the RR are included in Fig. S10.

Due to the divide in air pollution between high- and low-income regions, the attributable fraction shows a strong North-South gradient for both $\text{PM}_{2.5}$ (Fig. 3a) and O_3 (Fig. 3b). This divide is also clear in the total air pollution attributable premature mortality changes (Fig. 3c). The 1970-2010 air pollution changes cause the global total premature mortality to increase by 3.2 (95% confidence level: 2.6-3.5) million yr^{-1} (referenced to 2010 global population and underlying mortality rates), with around 2.4 (2.0-2.6) million yr^{-1} from $\text{PM}_{2.5}$, and 0.8 (0.6-0.9) million yr^{-1} from O_3 pollution (Table 1; equivalent data for each region is in Table S2). These estimates are consistent with a recent study showing around 2.8 million yr^{-1} premature mortality increases during the period 1970-2014²⁴ (see their Fig. 1c). The additional premature deaths are primarily attributable to APE, and ~6% to GHG effects. It is noteworthy that APE accounts for well over 95% of the increases in the premature mortality over developing regions (Asia, Africa, and South America; Fig. 3d and S10).

Table 1

Impacts of 1970-2010 air pollution changes on changes in global annual premature mortality, crop yield and economic loss. Changes in premature mortality (10^3 persons yr^{-1}) are calculated for long-term exposure to $\text{PM}_{2.5}$ (all-causes) and O_3 (respiratory diseases). The associated uncertainties (in brackets) are based on the 5th -95th confidence intervals of the relative risks used in the concentration-response functions. Uncertainties related to changes in crop production and economic losses are estimated using one standard deviation of model simulated annual mean AOT40.

		Total net (TOT)	Greenhouse gas increases (GHG)	Anthropogenic air pollutant emissions (APE)	Energy Consumption growth (ENE)	Technology advances (TEC)
Premature mortality (10^3)	$\text{PM}_{2.5}$	2432 (1979, 2628)	197 (165, 210)	2234 (1813, 2417)	1807 (1454, 1965)	-1141 (-1231, -934)
	O_3	760 (567, 911)	48 (35, 58)	713 (533, 853)	185 (141, 216)	-87 $\pm$ (-67, -100)
Crop yield loss (10^6 tonnes)	Maize	-34 $\pm$ 1	-5 $\pm$ 1	-29 $\pm$ 1	-18 $\pm$ 1	8 $\pm$ 1
	Rice	-39 $\pm$ 1	-2 $\pm$ 1	-37 $\pm$ 1	-15 $\pm$ 1	6 $\pm$ 1
	Soybean	-23 $\pm$ 1	-3 $\pm$ 1	-20 $\pm$ 1	-12 $\pm$ 1	4 $\pm$ 1
	Wheat	-77 $\pm$ 2	-8 $\pm$ 2	-69 $\pm$ 2	-32 $\pm$ 1	18 $\pm$ 3
	Gross total	173 $\pm$ 3	-18 $\pm$ 3	-155 $\pm$ 4	-77 $\pm$ 3	36 $\pm$ 4
Economic loss ^b (10^9 US\$ ₂₀₁₀)		-55 $\pm$ 1	-5 $\pm$ 1	-50 $\pm$ 2	-23 $\pm$ 1	10 $\pm$ 2

ENE leads to a global $\text{PM}_{2.5}$ increase that results in 2.2 (1.8-2.4) million yr^{-1} additional premature deaths. Regionally, ENE has driven increases in $\text{PM}_{2.5}$ - and O_3 -related mortality of 1.0 (0.8-1.1) million yr^{-1} in East Asia, 0.8 (0.6-0.8) million yr^{-1} in South Asia, 76 (59-86) thousand yr^{-1} in North America and 57 (45-65) thousand yr^{-1} in Europe (Fig. 3d). Due to avoided emissions from TEC, there are 1.2 (1.0-1.3) million yr^{-1} less premature deaths globally from reduced $\text{PM}_{2.5}$ exposure, and 92 (71-106) thousand yr^{-1} from reduced O_3 exposure. The reductions in premature deaths due to improved air quality from TEC in Europe and North America are greater than the corresponding premature mortality increases associated with ENE in these regions (green hatches in Fig. 3c). This picture is, however, reversed over the rest of the world (black hatches in Fig. 3c). Overall, Fig. 3 shows a strong North-South gradient in the dominant drivers of mortality changes due to air pollution: ENE is the primary driver of increased premature mortality from air pollution in developing regions, while TEC has reduced air pollution-related premature mortality in high-income countries.

2.4 Crop production and economy

The O_3 exposure metric relevant for crops (AOT40) increases significantly over the Northern Hemisphere (Fig. 4a). Most noticeably, AOT40 exceeds 30 ppm*hr over a large portion of East Asia during the growing seasons of all five staple crops (Fig. S11). The spatial distribution of crop yield changes associated with each individual driver (Fig. S12) is translated into changes in crop production (Fig. S13) and economic impacts (Fig. S14). The spatial distribution of the gross total impact (integration of all five crops) on crop production, economy, as well as their dominant drivers are shown in Fig. 4b-d. It is emphasised that these figures report the changes and not the absolute losses at a given time point.

The 1970-2010 increase in AOT40 leads to an increase in total global crop production loss of 173 ± 8 million tonnes yr^{-1} (maize: 34 ± 1 (2.0% loss); rice: 39 ± 1 (5.2% loss); soybean: 23 ± 1 (5.3% loss), and wheat: 77 ± 2 (8.9% loss); see Table 1). We note that the relative crop production losses are consistent in general with previous estimates^{16,25,26}. The economic valuation of the total crop production loss is ~ 55 billion $US\$_{2010} yr^{-1}$, which is equivalent to $\sim 2.2\%$ of 2010 gross world product from the sum of agriculture, forestry, and fishing (2,557 billion $US\$_{2010}$ ²⁷). Regionally, the 1970-2010 net total crop production loss is greatest over East Asia (Fig. 4b, d) for all the staple crops, with a relative loss of up to 30% for wheat. Of the 55 billion $US\$_{2010} yr^{-1}$ total economic loss, the GHG effects account for $\sim 9\%$ (~ 5 billion $US\$_{2010} yr^{-1}$), while 91% (50 billion $US\$ yr^{-1}$) is due to APE (Table 1).

The 1970-2010 ENE changes lead to a total crop production loss of 77 ± 3 million tonnes yr^{-1} that is worth ~ 23 billion $US\$_{2010} yr^{-1}$, explaining around half of the APE impact. In contrast, TEC leads to a total crop production gain of 36 ± 6 million tonnes yr^{-1} , which is equivalent to an economic gain of ~ 10 billion $US\$_{2010} yr^{-1}$. The spatial distribution of the dominant drivers of O_3 related economic impacts (Fig. 4c), can be compared with that of pollution-related premature mortality impacts (Fig. 3c). Clearly, there is also a strong North-South divide in the drivers of O_3 pollution and related crop impacts, with TEC playing an important role in Europe but ENE predominantly accounting for the economic losses worldwide (Fig. 4d). More interestingly, the role of TEC in controlling air pollution differs between Europe and North America (comparing Fig. 4d with 3d). Europe seems to have adopted more rigorous pollution abatement measures that significantly reduced both $PM_{2.5}$ and O_3 pollution and their associated impacts. That is, along with reductions to NO_x emissions, anthropogenic non-methane volatile organic compound emissions have also been significantly reduced, leading to further reductions to O_3 ². By contrast, emission control technologies in North America have mainly reduced $PM_{2.5}$ but do not have much influence on O_3 pollution and related impacts. Nevertheless, it is possible that North America is more impacted than Europe by long-range transport of O_3 , from Asia, which outweighs the effects of pollution abatement measures²⁸.

3. Implications For Tackling Global Air Pollution

We show significant increases in global air pollution over the period 1970-2010, which has had enormous impacts on human health worldwide (an extra 3.2 (2.6-3.5) million premature deaths annually), as well as on food security and economy (an additional annual loss of 173±8 million tonnes of staple crops worth 55 billion US\$₂₀₁₀). These impacts have been primarily driven by anthropogenic air pollutant emission changes, and show a strong North-South divide in their driving factors. Technology advances have generally improved air quality over Europe and North America with considerable health and economic benefits, while energy use growth without parallel emissions abatement technology has resulted in worsening air quality and associated impacts in low-income regions.

Our results imply that global air pollution changes and their impacts are largely under policy control. That is, the different balances in regional trajectories of economic growth and emission control measures and technologies reflect different strengths of the influence of policy interventions. This provides useful information for assessing and interpreting the possible outcomes of future emission pathways, and also for coordinating climate, air quality, agriculture, and economic strategies. However, it is important to note that air pollution mitigation measures to reduce emissions of aerosols and their precursor gases may disproportionately exacerbate changes in climate extremes²⁹, whose impacts on human health and crops are not included here. This reinforces the urgency of reducing greenhouse gas emissions simultaneously with air pollutants.

Huge inequality exists between low- and high-income regions in air pollution, which is further exacerbated when considering population density as well as social and economic factors. The inequality is partly attributable to consumption in high-income countries which is responsible for more than half of the health impacts over the world's production-and-emission regions³⁰. The North-South divide also has important implications for the potential evolution of emissions in developing regions. For example, since around 2013 China has issued a series of measures to mitigate PM_{2.5}, which have achieved substantial health benefits^{31,32}. While other countries such as India have also issued clean-air policies, the enforcement of these policies remain challenging and have caused huge impacts³³. Currently, there are enormous challenges in transitioning to clean and renewable energy along with strong resistance to phase out fossil fuel as concluded by the latest United Nations Climate Change Conference 2021 (COP26³⁴). Therefore, we anticipate that the world, and particularly developing countries, will continue relying on fossil fuel for economic growth over the next couple of decades. This will further exacerbate the North-South divide shown here. Moreover, some nations may overfocus on technology development for mitigating global climate change. While technology is a great part of the solution, we show that the benefits from technology advances in mitigating air pollution over the past few decades are limited. Additionally, most of the currently available technological solutions are too expensive for most developing regions to afford. Given all the above, we recommend that a range of behavioural actions are needed to mitigate air pollution worldwide, whilst internationally coordinated efforts together with cost-effective technological support are urgently needed for developing regions.

Future growth in population and economy requires growth in energy use and food demand. The global renewable energy transition and technology-breakthroughs can be pivotal in meeting such demands whilst, importantly, also saving lives and securing food production. However, it is more crucial to control air pollutant emissions from energy-intensive sectors which, as we report here, drives most of the impacts.

4. Methods

4.1 The EDGAR retrospective emission scenarios

Trace gas emissions from the Emissions Database for Global Atmospheric Research (EDGAR) v4.3.1 were used for 1970 (REF1970) and 2010 (REF2010). Crippa et al.² constructed retrospective emissions scenarios for the period 1970-2010 based on these emissions, estimating the changing contributions from several factors including energy consumption, energy efficiency, technology progress and end-of-pipe emission reduction measures. These retrospective emission scenarios focus on the three most important and regulated sectors (power generation, industry, and road transport), while emissions from all other sectors are the same as those in REF2010. The retrospective scenario with the highest emissions (STAG_TECH) assumes no further improvements in technologies and abatement measures after 1970, but assumes energy consumption and fuel mix as in REF2010. The retrospective scenario with lower emissions (STAG_ENE) assumes stagnation of energy consumption at 1970 levels, while fuel mix, energy efficiency, emission factors and abatements are the same as in REF2010. Therefore, the difference between REF2010 and STAG_TECH reveals the avoided emissions associated with technology advances (TEC). Similarly, the difference between REF2010 and STAG_ENE reflects increased emissions due to energy consumption (ENE). Note that emission changes from these two driving factors were deliberately not designed to add up to the total net 1970-2010 changes. Consequently, these scenarios need to be viewed as broad indicators of the roles of energy consumption and technology change since 1970, rather than full attribution of each individual factor.

4.2 Model and simulations

We employ the CESM1 fully-coupled (including atmosphere, ocean, land and vegetation, and sea ice) at the nominal 1° resolution. The standard atmospheric component of CESM1 is the Community Atmosphere Model (CAM5³⁵), which has 30 vertical levels between the surface and 4 hPa (≈ 40 km). CAM5 is capable of including atmospheric chemistry of various complexities^{21,35,20}. For example, the full-chemistry version (CAM5-Chem²¹) used here has extensive tropospheric and stratospheric chemistry schemes. In CAM5-Chem, the surface concentrations of long-lived species (CO₂, CH₄, H₂, etc.) are prescribed with latitude gradients using historical constructions. CAM5-Chem uses the modal aerosol model with three modes (MAM3³⁶), and predicts aerosol number concentration as well as mass in each lognormal mode. In this study, long-lived species and natural aerosols are obtained from the Coupled

Model Intercomparison Project Phase 5 (CMIP5) project for 1970³⁷ and 2010³⁸. Global gridded monthly mean emissions of anthropogenic aerosols and their precursors (SO₂, BC, OC and NMVOCs, as well as other gases (NO_x, CO and NH₃) are from the EDGAR retrospective scenarios as described in Sect. 4.1. Emissions from sectors including industry, power and aviation are emitted at various injection altitudes, while those from all other sectors are lumped together and emitted at the surface. Also, NMVOC emissions are aggregated to match the VOC categories in CAM5-Chem.

To compromise between computational costs and the representation of atmospheric chemistry, we first run the fully-coupled CESM1-CAM5 branching off from one (ensemble member No 34) of the transient simulations at either 1970 or 2010 derived from the CESM1 large ensemble experiments²⁰. The two baseline runs were integrated to quasi-equilibrium (after around 150 years) under the 1970 (B70) and 2010 (B10) all forcings/emissions (baseline climate runs; Fig. S1). Next, we switch the atmosphere component from CAM5 to CAM5-Chem to use the full-chemistry scheme, and also to include all air pollutant emissions. Thereafter, the two baseline runs (i.e., B70 and B10) were continued for an additional 40 years. For clarity, we refer to the last 40 years of the CAM5-Chem runs as B_1970 and B_2010, respectively. Additionally, branching off from B10, we performed three other 40-year sensitivity simulations with CAM5-Chem. In these simulations, emissions of anthropogenic aerosols and their precursors and other active gases are set, respectively, to REF1970, STAG_ENE and STAG_TECH while all other parameters are kept the same as those in the B_2010 (Table S1 and Fig. S1). We refer to the three sensitivity runs as P_1970A, P_ENE and P_TECH respectively.

The difference between B_2010 and B_1970 reflects the total effects of 1970-2010 anthropogenic air pollutant emission changes (APE) plus those associated with 1970-2010 changes in long-lived GHGs and land cover (grouped as GHG effects). The GHG effects are estimated by the difference P_1970A–B_1970 which includes both physical (e.g., global warming) and chemical (notably increase in prescribed CH₄) climate change. Also, each of the other three simulations is subtracted from B_2010 to deconvolute the impacts of anthropogenic emission changes due to each individual factor. They are: APE (B_2010–P_1970A), ENE (B_2010–P_ENE), and TEC (B_2010–P_TECH).

4.3 Model evaluation

We compare the model-simulated 2010 annual mean surface concentrations of major air pollutants to those from the Copernicus Atmosphere Monitoring Service (CAMS²²). CAMS is the latest global reanalysis dataset of the atmospheric composition produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). It consists of 3-dimensional time-consistent atmospheric composition fields, including aerosols and chemical species. More details on CAMS can be found in Note S1 and Inness et al. (2019).

4.4 Surface PM_{2.5} concentration

As CAM5-Chem does not have diagnostics for total particulate matter (PM), we calculate PM_{2.5} using the sum of all PM_{2.5} species (SO₄²⁻, BC, POM, SOA, sea-salt and dust). Note that a constant factor of 13.6% is applied to coarse-mode sea-salt and dust aerosols to give the fraction that is within the PM_{2.5} size range; the factor was derived based on the lognormal size distribution of the coarse mode in MAM3³⁹.

4.5 Health impact assessment

We estimate premature mortality due to long-term exposure to PM_{2.5} and O₃ using the health impact function (Eq.(1)⁵) based on epidemiological relationships between ambient air pollution concentration and mortality in each model grid-cell^{4,7,13}:

$$\Delta M = \gamma_0(1 - e^{-\beta \Delta x})P \quad (1)$$

where ΔM is the change in premature mortality, γ_0 the baseline mortality rate and P the exposed population (adults aged 30+). β represents the concentration-response factor which is derived from relative risks (RR) estimated in long-term epidemiological studies¹³. That is, by assuming log-linear relationships, RR is estimated per 10 ppb of increase in MDA8 or per 10 $\mu\text{g m}^{-3}$ increase in PM_{2.5}, such that $\beta = \ln(\text{RR})/10$. ΔX represents changes in the annual mean MDA8 or annual mean PM_{2.5} concentration. For the MDA8 metric, we apply a cut-off threshold of 26.7 ppb and calculate premature mortality due to respiratory diseases using the RR value of 1.12 (5-95 CI: 1.08-1.16) following Turner et al. (2016)⁸. For PM_{2.5}, we use the RR for all-cause premature mortality from the recent global meta-analysis by Chen and Hoek¹⁰: RR = 1.08 (5-95 CI 1.06–1.09). The country-level baseline mortality rates (γ_0) for non-accidental and respiratory disease are obtained from the WHO 2000-2016 cause-specific mortality for the population aged 30+⁴⁰.

To maintain consistency with the design of the EDGAR emission scenarios, we use the 2010 exposed population (adults aged 30+; Fig. S15) for calculating premature mortality in all the experiments so that our estimates represent a range of ‘what-if’ conditions. To calculate the exposed population, we use the 2010 world population density from version 4 of the Gridded Population of the World collection developed by the Center for International Earth Science Information Network at Columbia University⁴¹. The country-level fraction of the population aged 30+ in 2010 was obtained from the United Nations Population Division (2017)⁴². When country-level data are unavailable, continental estimates are used as a replacement.

4.6 Crop ozone exposure and production loss

We calculate the ozone exposure metric AOT40 (accumulated exposure over a threshold of 40 ppb during daylight hours^{25,15}, Eq. (2)) for five staple crops: maize, rice, soybean and spring and winter wheat. The AOT40 (ppm*hr) metric is derived using hourly surface ozone concentration during daylight hours from CAM5-Chem over the last 92 days of a growing season:

$$AOT40 = \sum_{t=08:00}^{t=19:59} 10^{-3} ([O_3]_t - 40) \quad (2)$$

where $[O_3]$ is the hourly surface ozone concentration in ppb, t the local time in summation. The growing season information for the above four crops is derived from the Crop Calendar Dataset determined by the Center for Sustainability and the Global Environment (SAGE) at the University of Wisconsin-Madison⁴¹. We use the mean harvest date (Fig. S16) from the 0.5° filled dataset to ensure input data for calculation over each model grid-box. Note that, at a given location, we assume mutual exclusivity for each crop (i.e., one crop being cultivated once within a growing season)¹⁶, in spite of double cropping over some (very few) regions. Therefore, the impacts on crop production and related statistics are possibly slightly underestimated.

Using AOT40, we calculate the relative yield loss (RYL) based on empirical relationships listed in Table S4. The crop yield loss (CYL) is then estimated using Eq. (3):

$$CYL = \frac{RYL}{1 - RYL} \times CY \quad (3)$$

where CY represents the base crop yield. The base crop yield comes from the Global Agro-Ecological Zones (GAEZ⁴³) assessment for 2000 developed by the Food and Agriculture Organization (FAO) of the United Nations along with the International Institute for Applied Systems Analysis (IIASA). The base crop yield for 2000 is scaled to 2010 (Fig. S17) using the 2000-2010 country-level trend determined by the FAO Statistics Division (FAOSTAT). Finally, to assess economic losses due to crop yield losses, we make use of the 2010 annual mean producer prices (Fig. S18) determined by FAOSTAT.

4.7 Uncertainties and statistical significance test

Through this study, we use differences, averaged over the last 30 years, between the baseline and each perturbation simulation. The statistical significance of the difference between each two (baseline and perturbed) sets of 30-year model runs is evaluated using the two-tailed student t-test at the 10% level (p -value<0.1). Uncertainties in global and regional mean air pollutant concentration changes are reported as one standard deviation of the 30-year annual mean differences. For premature mortality, we use the 30-year annual mean changes in air pollution, while reporting uncertainties associated with the 5th-95th

confidence intervals of the relative risks (RR) estimated in long-term epidemiological studies. For crop production and economic losses, we report uncertainties associated with one standard deviation of the 30-year annual mean differences in the ozone metric AOT40 for each of the five crops.

Declarations

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Author contributions: A.Z. conceived the study, performed all model experiments and data analysis, and wrote the initial draft of this paper. D.S. M.B. and M.H. contributed to the discussion and interpretation of the results, as well as to writing the final version of the paper.

Competing interests: The authors declare no conflict of interest.

Data availability: The global GHG mixing ratios in 1970 and 2010 are derived from the CESM1 large ensemble projects (<https://www.cesm.ucar.edu/projects/community-projects/LENS/data-sets.html>). Anthropogenic emissions are from the Emissions Database for Global Atmospheric Research (EDGARv4.3.1; <https://edgar.jrc.ec.europa.eu/overview.php?v=pegasos>). Air pollution-related baseline mortality rates are from the World Health Organization (WHO) 2000-2016 cause-specific mortality for the population aged 30+ (https://www.who.int/healthinfo/global_burden_disease/estimates/en/). The 2010 world population density is from the Gridded Population of the World collection (<https://aquaknow.jrc.ec.europa.eu/content/gridded-population-world-version-4-gpwv4>). The country-level fraction of population aged 30+ in 2010 is obtained from the United Nations Population Division 2017 revision (<https://population.un.org/wpp/Download/Standard/Population/>). The crop growing season information is derived from the Crop Calendar Dataset (<https://nelson.wisc.edu/sage/data-and-models/crop-calendar-dataset/netCDF0-5degree.php>). The base crop yield data is derived from the Global Agro-Ecological Zones assessment for 2000 (<http://www.fao.org/nr/gaez/en/>). The 2000-2010 country-level crop production trend (<http://www.fao.org/faostat/en/#data/QC>) and the 2010 annual mean producer prices (<http://www.fao.org/faostat/en/#data/PP>) are from the Food and Agriculture Organization of the United Nations (FAO). Model simulations and all calculated metrics are archived in the UK's Centre for Environmental Data Analysis (CEDA; <https://www.ceda.ac.uk/>) and are accessible through the UK's data analysis facility for environmental science (JASMIN; <https://www.jasmin.ac.uk/>).

Code availability: This study used the Community Earth System Model Version 1.2 (CESM1; <https://www.cesm.ucar.edu/models/cesm1.2>) on the UK National Supercomputing Service ARCHER (retired and replaced by ARCHER2: <https://www.archer2.ac.uk/>). The model outputs were

processed using the NetCDF Operator (NCO) and Climate Data Operator (CDO). The analysis was carried out on the UK HPC JASMIN using Cf-python; the code for the analysis is available upon request to the corresponding author.

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Figures

Figure 1

1970-2010 changes in annual mean surface air pollution. The spatial distributions of changes in PM_{2.5} (a, $\mu\text{g m}^{-3}$), O₃ (b, ppb), NO_x (c, ppb) and CO (d, ppb). Green hatches denote statistically insignificant changes below the 10% level. Purple boxes in (a) define regions. The normalised probability distribution of grid-point air pollutant concentrations (e-h) within the Asia (red, encompassing East, South, and Central Asia boxes) and Europe (blue) domains in 1970 (dashed) and 2010 (solid). Shadings represent the 10th-90th percentile model uncertainties. Changes in other regions can be found in Fig. S3. Population-weighted regional mean changes (horizontal bars) and uncertainties (black error-bars) in air pollutant concentrations (i-l), with Europe and North America in blue and Asia, Africa, and South America in red. Vertical dashed lines denote the population-weighted global mean changes (as also shown by the numbers on top right of (a-d)). The area-weighted regional mean changes are included in Fig. S4.

Figure 2

Population-weighted 1970-2010 changes in annual mean surface air pollution and the changes associated with each individual driver. PM_{2.5} (a, $\mu\text{g m}^{-3}$), O₃ (b, ppb), NO_x (c, ppb) and CO (d, ppb) for Europe, North America, Asia (encompassing East, South and Central Asia boxes), Africa, and South America. Black for 1970 to 2010 total net change (TOT), orange for greenhouse gas effects (GHG) and red for anthropogenic air pollutant emission changes (APE). Also shown are the changes related to energy use growth (ENE, purple) and technology advances (TEC, pale blue). The black error-bars represent one standard deviation of the annual mean changes. The equivalent figure for area-weighted mean changes is shown in Fig. S4.

Figure 3

The impact of 1970-2010 air pollution changes on premature mortality. Changes in attributable fraction (%) of premature mortality due to changes in $\text{PM}_{2.5}$ (a, all-causes) and O_3 MDA8 (b, respiratory diseases) exposure, calculated using relative risks of 1.08 per $10 \mu\text{g m}^{-3}$ for annual mean $\text{PM}_{2.5}$ and 1.12 per 10 ppb for annual mean O_3 MDA8. Changes in total premature mortality (c, persons per thousand people per year) due to air pollution ($\text{PM}_{2.5} + \text{O}_3$). Black cross hatches signify locations where ENE dominates, green plus hatches where TEC dominates, and purple vertical line hatches where GHG dominates. Note that APE dominates over GHG over all places hatched by green pluses and black crosses. The equivalent maps associated with the 5th-95th confidence intervals of the relative risks are included in Fig. S9. The 1970-2010 net total, and those associated with each individual driver, integrations of premature mortality changes (d, million persons yr^{-1}) in Europe, North America, East Asia, South Asia, Africa, and South America. Colour conventions in (d) are the same as Fig. 2.

Figure 4

The impact of 1970-2010 O₃ changes on staple crop production and economy. The spatial distribution of the annual mean AOT40 (a, ppm*hr) changes weighted by the 2010 base yields shown in Fig. S17 of five staple crops (maize, rice, soybean, and spring and winter wheat). Net total gross loss/gain (b, tonnes ha⁻¹) from five staple crops losses/gains. The dominant drivers (c) of the changes in (a, b). The 1970-2010 gross net total, and those associated with each individual driver, integrations of economic loss/gain (d, billion US\$₂₀₁₀ yr⁻¹) from five staple crop production losses/gains in Europe, North America, East Asia,

South Asia, Africa, and South America. Colour conventions in **(c, d)** are the same as Fig. 2. NB the symmetric logarithm scale (with base 2) of the x -axis in **(d)** is used to make small values readable. Negative values mean economic losses and positive mean gains.

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