Quantitative and distributive measurement of ambient air pollution for global burden of disease

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Abstract

Air quality impacts human health from multiple perspectives. Ambient air pollution (AAP) exposure poses a great contribution to the global burden of disease (BoD). The United Nations launched the Sustainable Development Goals (SDGs) to evaluate sustainability levels and improve human living environments. In particular, the two indicators 3.9.1 and 11.6.2, i.e. fine particulate matters (PM2.5 and PM10) and relative disease mortality are listed to illustrate the development goals for the air environment. At present, countries around the world have adopted measures to mitigate AAP, and a quantitative evaluation of the effectiveness is necessary. Thus, statistics for AAP and BoD across the global 183 countries were analyzed to help assess the gap between the status quo and SDGs in this study. We offer a new perspective on BoD estimation research - proportional data (AAP-caused disease burden / total environment-caused disease burden) in grouped global countries (according to their geographical and economic conditions) were adopted to substitute the absolute value in this study, which is more reasonable for comparative analysis. The overlap of economic and geographic distribution shows that the heaviest BoD is concentrated in high-income and Middle Eastern regions. Concerning the type of disease burden, acute lower respiratory infections (ALRI) and ischemic heart disease (IHD) are two major contributors to BoD, and the worldwide deaths and Disability Adjusted Life Years (DALYs) caused by them need to be taken seriously. Generally, this study provides novel evidence for the formulation of air pollution control and management measures to reduce the related disease burden in global regions. To reduce the future BoD, different strategies should be designed depending on the order of driving factors in regions. Even the triggers of BoD are quite different across the globe, the correlation analysis results inform that reducing emissions along with CO_2 from social operations at the source is the most direct and effective path in areas with a high density of susceptible populations.

Keywords: Ambient air pollution; Particulate matters; Global burden of disease; Sustainable Development Goals.

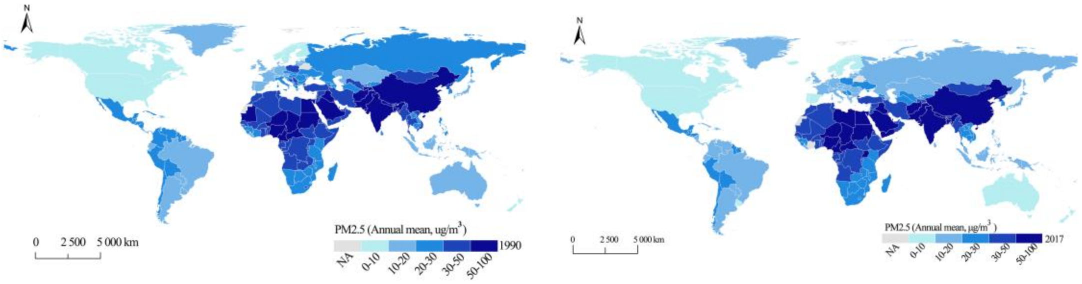
1．Introduction

Environmental pollution poses a great threat to human health since the industrial revolution.[1] According to the estimation of the World Health Organization (WHO), environment attributable deaths reached 12.6 million in 2012 across the world.[2] In contrast to many other environmental problems, exposure to ambient air pollution (AAP) occurs during the whole lifespan and is currently an intractable global problem,[3] especially in emerging countries with dense populations and rapid industrial development.[4] Exposure to a polluted climatic environment for a long time is the trigger for a series of respiratory and cardiovascular diseases. Currently, the AAP is considered to be one of the major contributors to the global burden of disease (BoD), i.e. lung cancer, stroke, etc.[5]

Nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), particulate matter with a median aerodynamic diameter <10 μm (PM10), and fine particulate matter <2.5 μm (PM2.5) are typical air pollutants that can cause significant negative influences on our ambient air quality.[6] Multiple research evidence from global regions has shown that these air pollution factors are closely related to the incidence of diseases. In Iran, PM10 and SO_2 with concentrations exceeding 10 μg/m^3 increased the hospitalization rate for respiratory disease by 0.44%.[7] In China, Liu et al. (2014) studied atmospheric pollution in seven Northeastern Chinese cities and asthma-related symptoms in more than 23,000 Chinese children and found that each 10 μg/m^3 increase in NO_2 concentration link to an adjusted prevalence of 1.25% for diagnosed asthma in 3 to 6 year-old children. Similar linkages also occur in developed regions.[8] The AAP leads to an annual mortality rate of 133 per 100,000 people and a 2.2-year reduction of the mean life expectancy in EU-28 countries.[9]

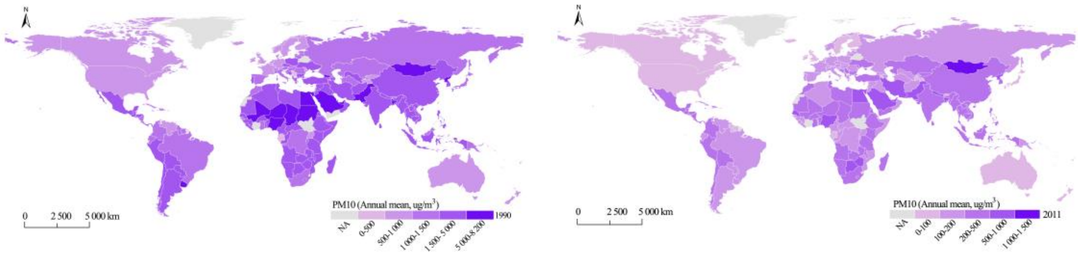
To reduce the concentration of pollutants in the air environment, most global countries have taken the necessary steps to limit and replace human activities that produce serious pollution.[10] For instance, the policy evidence in a Tasmanian city shows that replacing burning wood as the main heater with electricity in winter can significantly reduce PM2.5 by about 39%.[11] In the UK, the introduction of the *UK Clean Air Act* has resulted in great mitigation in SO_2 from coal-fired power plants.[12] At a global scale, Jacobson (2017) has drawn roadmaps to show that by 2050, a transition to 100% clean, renewable, and sustainable power for all energy uses in 139 countries to reduce the excess emission is a feasible schedule.[13] However, there is a gap in a few developing countries to reach this ambitious global project due to their unsatisfactory air pollution control policies.[14] For instance, Sub-Saharan Africa is a typical region with poor air environment protection policies, city authorities take little management of vehicle emissions, municipal solid waste (MSW), and solid fuel use into their policy decisions, which are major contributors to worsening air pollution.[15,16] Beyond the impact on health, economic development can also be affected by AAP. It is estimated that by 2060, the costs of AAP control gradually increase to 1% of global GDP, with the highest GDP losses in some developing regions, e.g. China, the Caspian region, and Eastern Europe.[17]

Against the background of global urban expansion and industrial development, the outdoor air environment has undergone a great deterioration. The main contributors of the global AAP are PM2.5 and PM10, and their concentrations showed a trend of increase or decrease in different countries during the last two decades, which implicitly affects the dynamic of BoD. As shown in Fig.1, PM10 concentrations have decreased broadly across the world. Whilst, significant reductions in PM2.5 concentrations were only shown in Australia, Russia, and some European and Southeast Asian countries. Coincidentally, by comparing the research of Richards and Belcher (2020) on vegetation coverage in 4,256 cities around the world, we superficially found that the dynamics in particulate matter and the changes in global urban vegetation coverage are roughly consistent in geographic space.[18] Overall, the particulate matter problem may have improved by sustainable human activities, but the current situation is still far from reaching the goal of risk-free to human health.



(a) 1990 annual average of PM2.5 concentrations (μg/m³)

(b) 2017 annual average of PM2.5 concentrations (μg/m³)



(c) 1990 annual average of PM10 concentrations (μg/m³)

(d) 2011annual average of PM10 concentrations (μg/m³)

Figure 1. Global annual mean levels of particulate matter population-weighted concentrations

2 . Literature review

Air environment control and management has become a serious issue and a research hotspot, as it poses challenges regarding human health and sustainable development. An increasing number of studies have paid attention to the relations between human disease burden and AAP, only in the 20 years from 1998 to 2017, 2,179 related researches could be retrieved from the Web of Science Core Collection (Dhital and Rupakheti, 2019)[19].

The previous research on association between ambient particulate matter and the disease burden provides a reliable basis for the further analysis of this study. Their starting point includes two perspectives - environment management and epidemiology. Their findings explained the links between the diffusion mechanisms of air particulate matter and the incidence of diseases caused by it. In detail, Kim et al. (2015)[20] summarized the typical law of the particulate matter impact on health through historical literature - as particles decrease in size, it is hypothesized to increase their ability to penetrate the lower airways and burden of respiratory and cardiovascular health. Hamanaka and Mutlu (2018)[21] also conducted a systematic review and meta-analyze to link the particulate pollution exposure to the morbidity and mortality in the human cardiovascular system from an endocrinological perspective. Their general evidence suggests that there is no “safe” level of particulate pollution exposure unless we put efforts to manage the climatic environment and reduce particulate pollution production and exposure. Miri et al. (2016)[22] built AirQ models to investigate the health effects of multiple air pollutants at a city level. The quantitative results showed that suspended particles of PM2.5 and PM10 have the greatest adverse effect on people’s health (in terms of respiratory and cardiovascular diseases) between NO_2, SO_2, O_3, and particulate pollution.

Besides, case studies from countries around the world also proving a strong link between the two. The U.S. cohort study of Bowe et al. (2019)[23] illustrated that the PM2.5 exposure is associated with the excess burden of death owning to multiple chronic diseases, and racial and socioeconomic disparities in the burden are evident. The sources of PM2.5 are almost cigarette smoking, industrial emissions, or the burning of wood and dung for fuel (Arnold, 2014)[24]. Evidence from Brazil and China suggested together that PM10 exposure increases respiratory and cardiovascular morbidity, with years of life lost (YLL) being more sensitive than mortality in the assessment (Chen et al., 2017; Zeng et al., 2017; Abe et al., 2018)[252627].

The literature has highlighted high-risk disease burdens caused by AAP in specific geographic regions or countries but without a comprehensive focus on the comparative Global Burden of Disease (BoD) (Kim and Johnston, 2011)[28]. In 2015, the United Nations Sustainable Development Goals (SDGs) were developed to address challenges related to poverty, inequality, climate change, environmental degradation, prosperity, and peace and justice on the United Nations Sustainable Development Summit (Schmidt-Traub et al., 2017; Haines et al., 2017)[2930]. The combination concern of air environment quality and human health are included in both goals of "3.9.1 Mortality rate attributed to household and ambient air pollution" and "11.6.2 Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population-weighted)" (UNSD, 2017)[31]. SDGs put forward strict requirements for air quality. To quantitatively evaluate the status quo of AAP based on the standards proposed by SDGs and offer optimal management measures on the air environment, here we aim to conduct an updated analysis on spatial differences and connections between BoD and AAP on a global scale.

3．Methods

As shown in Fig.2, it illustrates the system flow from the generation of emissions to effects on human health.[32] Simply, air pollution derives from the spread of various emissions, and human exposure to ambient pollution further causes health effects. This study gathered AAP data from different emissions and BoD data from various diseases to help clarify their relations.

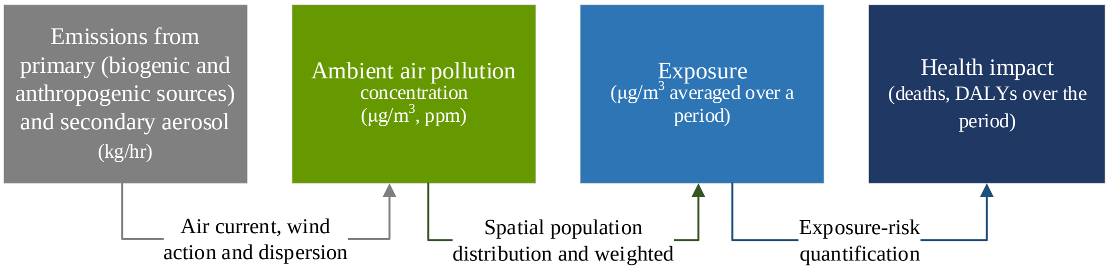


Figure 2. The linkage from emissions to the burden of disease

2.1 The study scope and data source

In this study, spatial and temporal analysis is carried out from AAP and BoD perspectives. The detailed research area is as follows:

(1) Global AAP analysis. The outdoor air pollution data from a total of 193 countries and regions across the world were included in this section. Specifically, follow the definition of WHO, to provide an accurate figure of BoD attributed to AAP, the measured AAP here is ambient air particulate pollution, and the impacts of health from other air pollutants such as nitrogen oxides and ozone are excluded.[33] The air particulate pollution data refers to the population-weighted exposure to ambient PM2.5 and PM10, which is calculated by weighting annual concentrations by the populations of urban and rural areas. The World Bank Open Database (WBOD) and WHO Database (see Tables S.3-S.4 in Supporting Information (SI)) offer the statistics of global PM10 and PM2.5 exposure data with the time ranges from 1990 to 2017 and 1990 to 2011, respectively (see Table 1). Primary data of WHO and WB are derived from official reporting from member countries. The Data Integration Model for Air Quality (DIMAQ) data from over two decades can help depict global dynamics in air particulate pollution (already shown in Fig.1).

(2) AAP attributable BoD. The assessment of environment- and AAP-associated BoD is available for 183 countries and regions (see Table 1). Geographically including 47 Asian countries, 39 European countries, 54 African countries, 21 North American countries, 12 South American countries, and 10 Oceanian countries. According to the income classification of WB, including 30 low-income countries, 52 lower-middle-income countries, 51 upper-middle-income countries, and 50 high-income countries.

When comparing and analyzing the BoD results, we follow the classification method proposed by the WHO, which is death and Disability Adjusted Life Year (DALY). Compared with the death that can directly assess the health impact caused by AAP, DALY is an indicator that reflects the long-term impact of AAP on human health. As for the type of BoD, based on the statistical approach of WHO provided by epidemiologists, ALRI (acute lower respiratory infections), lung cancer, COPD (chronic obstructive pulmonary disease), stroke, and IHD (ischemic heart disease) are chosen as the BoD assessment indicators with enough epidemiological evidence.

Table 1 Detailed study scope and data categories

Data type	Data sub-type		Time frame	Classification	Sub-classification
(1) AAP data*	PM2.5		1990-2017	Geographical**	Asia, Europe, Africa, North America, South America, Oceania
	PM10		1990-2011		
(2) BoD data*	Death	Lung cancer, Cataract, IHD, Stroke, COPD, ALRI	2016	Income** (based on world bank regions)	Low income, Lower middle income, Upper middle income, High income
	DALY				

** Data sources: AAP data gathered from World Bank Open Database and WHO Database (see Tables S.3-S.4 in SI), BoD 2016 data collected from WHO Database.*

*** The detailed country list can be found in Tables S.1-S.2 in SI.*

2.2 Data analysis

Based on the ground measurement data for PM2.5 and PM10, derived from monitors in global 2972 cities or towns, therefore, the ambient air quality measurements can cover almost all major regions and countries of the world. Similar to BoD exposure estimation in previous years, the mean of gridded values is also used in order to provide estimates at a high spatial resolution - 0.1° × 0.1° resolution globally.

According to the description in Table 1, the linkage between disease burden and AAP is assessed via AAP attributable BoD, and its spatial dynamics are discussed in terms of disease type, geographical regions, and income distributions.

In the temporal analysis of exposure AAP, Eq.1 shows the dynamic of AAP value over time in a specific area.

$$V_{i-x-mn} = \frac{A_{i-x-n}}{A_{i-x-m}} - 1 \quad (1)$$

where V refers to the dynamic of population-weighted concentration of type i AAP in region x between two statistical years (year m and n, $n > m$). A is the population-weighted concentration of type i AAP (namely PM2.5 or PM10 in this study) in region x in year m and n.

In the spatial analysis of BoD, Eq.2 shows the contribution of AAP to the BoD in a single year as a percentage of the BoD caused by the total environment. As the total population of different countries and regions varies greatly, this study uses the proportion of BoD caused by AAP in the BoD caused by the total environmental impact instead of the absolute number, which can produce a more reasonable comparison.

$$R_{ho-x-m} = \frac{B_{AAP-ho-x-m}}{B_{Envi-ho-x-m}} \quad (2)$$

where R refers to the ratio of AAP attributable different health impacts to environment attribution. Similarly, subscripts of disease burden (B) mean the attribution factors of the burden of disease (APP or environment) and their health impact (ho, death or DALY) in region x in year m.

After the calculation in different regions, the linkage between BoD and AAP can be shown in comparisons.

2.3 Correlation analysis

The AAP from complex sources indirectly leads to BoD. After a general understanding of BoD distribution, the identification of possible drivers for BoD is the purpose of correlation analysis. The analysis is to test whether there is some dependency relation between the driving factor variables (X_1–X_7) and the burden of disease (Y_1-Y_2) and to determine the degree of the dependency relation.[34] As the BoD analysis in this study adopts calculated proportion, the potential factors are also selected using ratio data rather than absolute data. We compiled data on population density (X_1),[35] Human Development Index (HDI, X_2),[36] Gini coefficient (X_3),[37] urbanization rate (by urban population rate) (X_4),[38] forest coverage rate (X_5),[39] and fossil CO_2 emissions (t CO_2 emissions per km^2 land area and t CO_2 emissions per capita, X_6 and X_7) from global countries to cover socioeconomic and natural factors.[40] Subsequently, the correlations between these factors and AAP attributable death rate and DALY rate are calculated respectively.

3 Results

According to the spatio-temporal dynamics of AAP attributable BoD, the spread of results among regions and economies highlights the impacts of AAP on human health.

3.1 AAP-caused BoD distribution

As the description in the previous section (*Materials and methods*), the BoD analysis is divided into death and DALY. The two types of AAP-caused BoD distributions are displayed in Figs.3-4. As shown in Fig.3, AAP poses a greater threat to human health than other environmental factors. The highest mortality is over 50% in 2016 (AAP caused / total environment caused), and it generally concentrates on the Middle East (part of West Asia and Northern Africa) and some Eastern Europe and South America (Peru, Chile, and Suriname) regions, in Lebanon even reaches 79%. While the lowest is under 20%, mainly in the Central and East Africa region. The potential attribution of high AAP-caused mortality burden in partial areas mainly to the following reasons: (1) As shown in Fig.1, Southeast Asia and the Middle East are the worst regions affected by PM2.5 as well as PM10 pollution, and fine particulate matters have been identified is one of the major threats to the atmospheric environment and sources of human premature mortality.[41,42] (2) Most countries in South America and the Middle East region are under accelerated industrial development or intensive construction, which leads to the expansion of cities and the increase of population density in urban areas, and urban metabolism and industrial production are the main sources of particulate matter emissions.[43] (3) The age structure of the population is also a driving factor,[44] evidence has shown that AAP exposure caused premature mortality of adults is higher than children.[45] (4) Other factors e.g. lower government expenditure on public health and air environment protection, serious desertification in the Middle

East, and relatively less-developed health system in some South America and Eastern Europe regions such as Peru and Ukraine.[46,47]

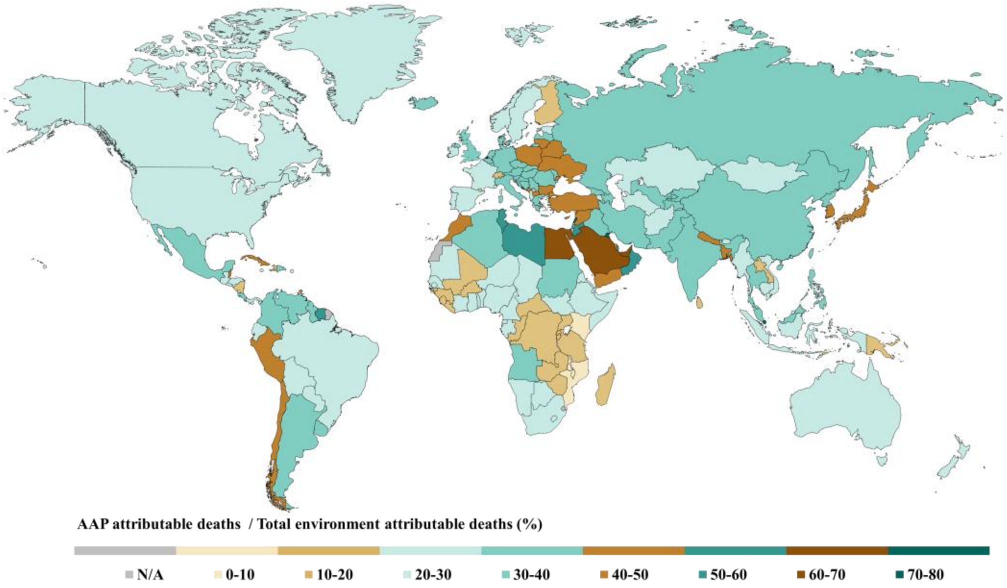


Figure 3. The proportion of AAP attributable deaths in the total environment attributable deaths

In Fig.4, compared to the mortality burden, the situation of AAP-caused DALY at a more acceptable level. The distribution shows that the highest DALY loss rate of over 30% (AAP caused / total environment caused) still occurs in the Middle East area, it even reached 55% in Kuwait. Whilst the lowest is under 10% in Canada, Nordic, and the Southern Africa region. As one of the reasons mentioned earlier, the urban environment of these Middle Eastern countries is characterized by desertification and aridity, and these geographical characteristics can easily lead to a series of dust events.[48] There is no doubt that high concentrations of particulate matter owing to dust events cause health impacts, for instance, the high particulate matter concentration brought by the Middle East Dust event in Ahvaz, Iran (from April to September 2010), resulted in total estimated mortality of 1,131 cases and morbidity of 8,157 cases.[49,50] The main result of AAP-caused DALYs is the incidence of chronic disease (e.g. COPD and asthma), and early diagnosis of chronic diseases often place higher requirements on the local medical and health conditions, which are all objective causes in this region.[51,52,69]

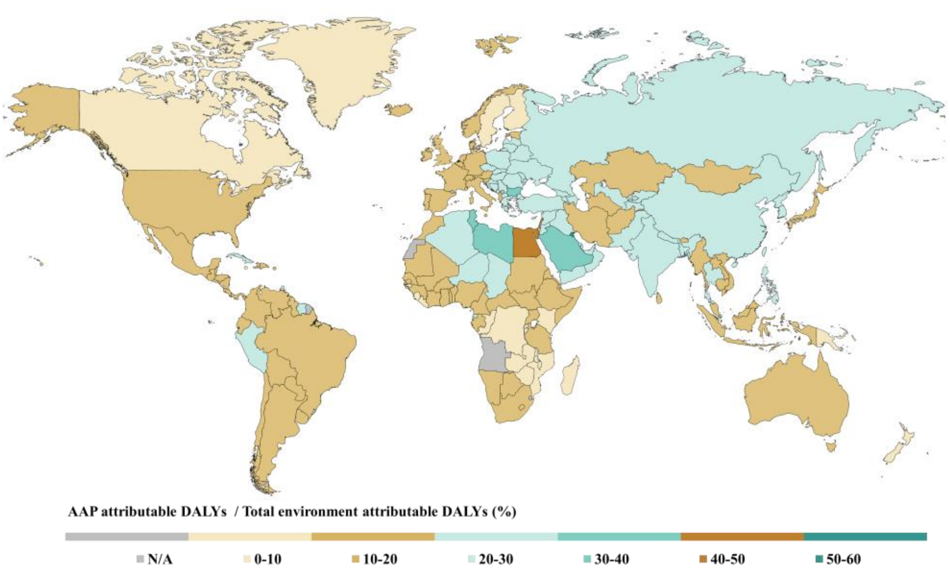


Figure 4. The proportion of AAP attributable DALYs in the total environment attributable DALYs

3.2 BoD 2016 analysis

In the previous section, the general outline of AAP-caused BoD is introduced. In fact, the multiple diseases caused by BoD are also closely related to the geographical, political, economic, and other factors in different regions of the world.

3.2.1 Geographic-based analysis

As illustrated in Fig.5, the overall distribution of death and DALY is analogous. Nevertheless, the situation of death owing to AAP exposure is more serious than DALY across the world, and the gap between these two proportions is even over 16% in Europe (16.1%) and South America (16.5%). Even if high mortality and DALY loss rates have been noted in some regions, AAP poses a higher human health risk in Europe and Asia in terms of overall geographic distribution. Similar results also appeared in the research of other scholars, the calculation of Lelieveld et al. (2015) showed that outdoor air pollution (mostly by PM2.5) leads to 3.3 million premature deaths per year worldwide, predominantly in Asia.[41] PM2.5 pollution is the most elementary environmental threat factor for deaths and DALYs from respiratory and cardiovascular diseases, which tend to occur a high incidence of these two types of disease in densely populated areas such as Asia and aging population areas such as Europe.[53,54] As the research of Rajagopalan et al. (2018) estimates, short-term elevations in PM2.5 concentration increase the cardiovascular diseases risk by 1% to 3% within several days.[55] Whilst the region with the highest disease burden includes North Africa, the situation in Africa as a whole is more optimistic due to the neutralization of the low burden value of the vast African regions below North Africa (see Figs.3-4).

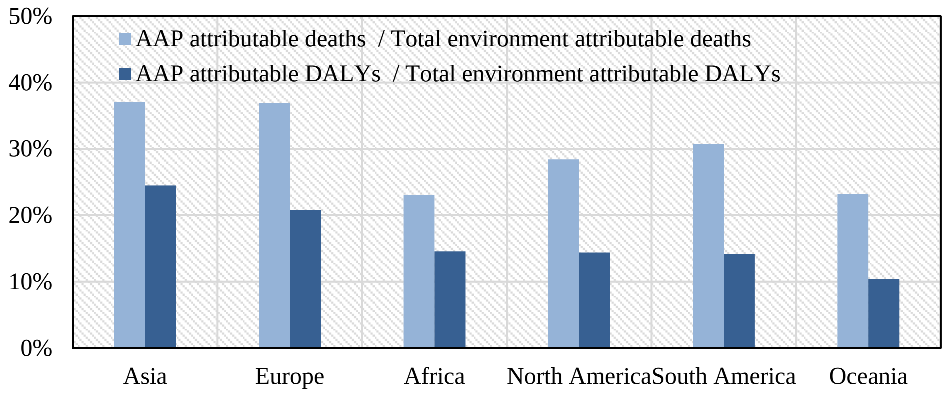
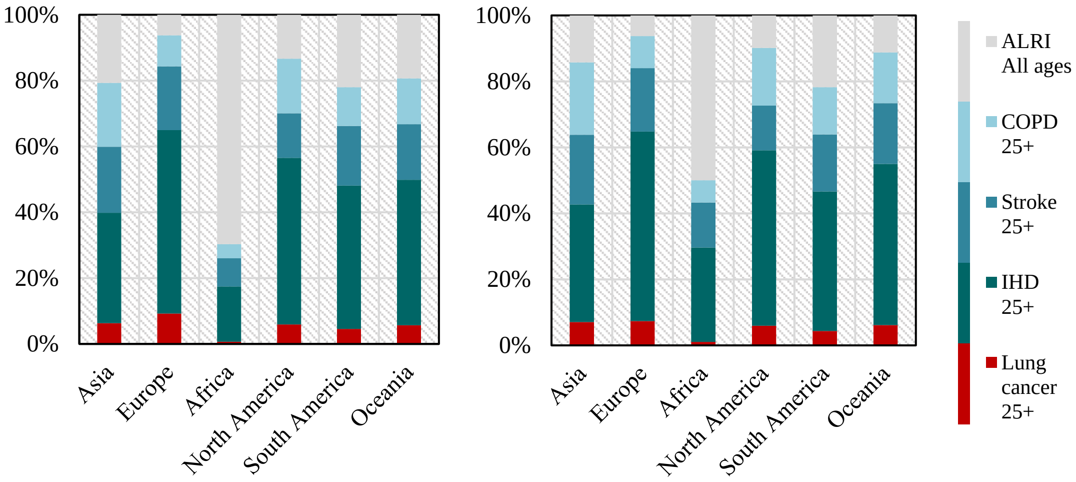


Figure 5. AAP attributable burden of disease by geographical distribution

Specifically, the incidence of the diseases triggered by particulate pollution varies among regions, but mainly cardiovascular and respiratory diseases (see Fig.6). ALRI and IHD are the two leading AAP-caused BoD that pose the greatest threat to human health, regardless of the region. It is worth noting that in Africa, the ALRI has a huge contribution to DALY and mortality burden, which are approximately 70% and 50% respectively. One of the underlying reasons may be that frequent desert dust events in Africa have contributed to the increase of ambient particulate matter concentration and thus affected human respiratory health.[56] As for the other diseases, IHD poses the highest health risk in all continents except Africa, and epidemiological statistics have proved that both long-term and short-term ambient particulate matter exposure will increase the risk for IHD.[57,58] Lung cancer is a serious disease, equipped with complex pathogenesis and is often caused by the accumulation and deterioration of other relative diseases, its contribution to BoD is only the most insignificant proportion.[59,60]



(a) AAP attributable DALYs, geographical

(b) AAP attributable deaths, geographical

Figure 6. Distribution of disease by geographical distribution

3.2.2 Income-based analysis

In terms of BoD's distribution from the economic perspective, Figs.7-8 indicate the details. It can be seen in Fig.7, the death rate due to AAP-caused disease is proportional to income globally, and the peak of DALY is concentrated in developing regions. One of the reasons for the significant differences in the burden of disease among income groups is that environmental threats in low-income countries are complex compared with high-income countries. Overall environmental health impacts are higher in low-income countries, but multi-source environmental factors diluted shares of AAP. For instance, the degree of water pollution in an area is generally considered to be inversely proportional to the development of the area.[61] Another non-negligible driving factor is booming industrial development in middle-income countries, cheap conventional energy structures are used in industrial production, which has caused the air pollution emission plight of these countries.[62] London used to be a proper example, in the early twentieth century, a type of air pollution called the London Fog due to the extensive use of coal in the field of daily life and industrial production, and Hanlon (2018) counted that high-pollution air exposure accounted for at least one out of every 200 deaths in London during that period.[63] Besides, it is noteworthy that the gap between AAP-caused mortality and DALY burden is inversely proportional to the national economy. The mainstays of chronic disease treatment are standard and low-cost medications that are sadly insufficiently used in patients who live in low- and middle-income regions. The fiscal revenue of these countries to support the establishment of a complete health system is obstructive, and followed citizens cannot enjoy regular public medical services for their chronic diseases.[64]

Also, we consider that some interfering and co-existing factors in alliance with AAP cause chronic diseases and affect the results of the disease burden, such as COPD and smoking, IHD, and obesity, which may contribute to the higher burden in high-income countries.[65]

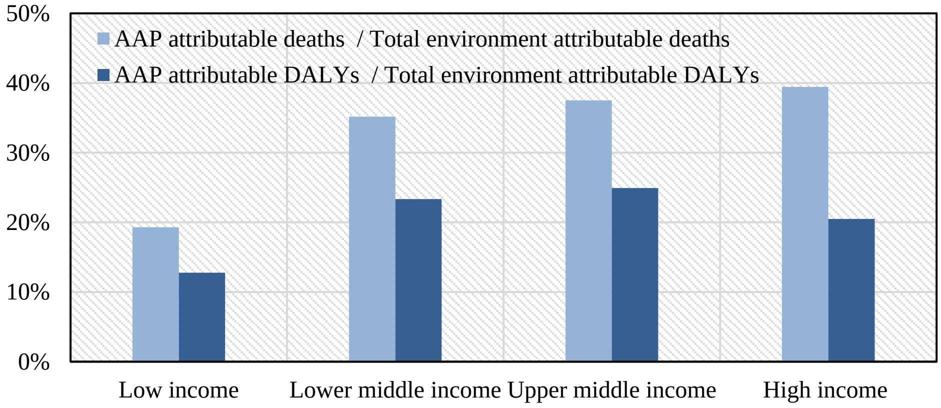
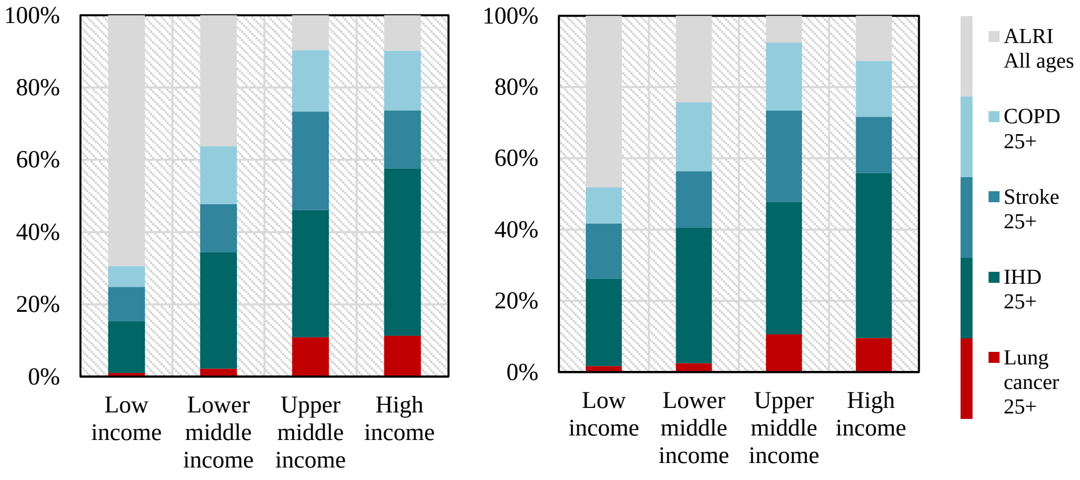


Figure 7. AAP attributable burden of disease by income distribution

Combined with the results in Fig.8, it can be seen that the mortality and DALY loss rate of serious diseases caused by AAP (such as lung cancer) are both proportional to income, which is one of the reasons for the results of high mortality in high-income regions (see Fig.7). In the analysis of DALYs and deaths, it can be seen that their distribution is roughly similar except for the slight difference in proportion. Obviously, the distribution of disease burden is closely related to income (see Fig.8).

The distribution of the major AAP-caused disease burdens has shown regularity across world economies. The burden of IHD & lung cancer, COPD & stroke, and ALRI are prevalent in high-income, middle-income, and low-income, respectively. The death and DALY burden of AAP-caused IHD both have reached 46% in high-income regions, and ALRI is the contributor for half of the burden in low-income regions (70% and 48% to DALY and death burden respectively). In 2018, the WHO estimated the global health situation and IHD ranked first among the top 20 causes. However, when subdivided into different economies, the impact of IHD on health is not significant in low-income countries, which is similar to the BoD caused by AAP.[66] According to the findings of Shi et al. (2017), ALRI tends to occur in people with weakened immune systems.[67] In low-income regions, exposure to AAP and a certain percentage of the undernourished population allows ALRI to infect. Due to the lack of a well-developed health care system, many patients who cannot be treated in time could pose a significant impact on BoD in low-income regions. Besides, previous research told that low socioeconomic status is also associated with BoD, compared with higher socioeconomic status, the mortality of ALRI significantly increased by 62% odds among young patients.[68]



(a) AAP attributable DALYs, income

(b) AAP attributable deaths, income

Figure 8. Distribution of disease by income distribution

3.3 Correlations

Combining the display of Fig.9 and Figs.3-4, a consistent result can be found that that high-income region of Asia, particularly the Middle East (including Egypt, UAE, Saudi Arabia, and Lebanon), is still the "worst-hit" region in terms of disease burden. Fig.9(a) and (b) also confirm the changes in Fig.5 and Fig.7, they suggest that AAP-caused two types of disease burden (death and DALY) are well correlated in all regions. In other words, changes in mortality and DALY loss rates generally follow the same trend. In the previous part, the underlying causes of the death and DALY burden are analyzed in combination with the disease type and distribution area. A more detailed driver correlation analysis is shown in Figs.10-11.

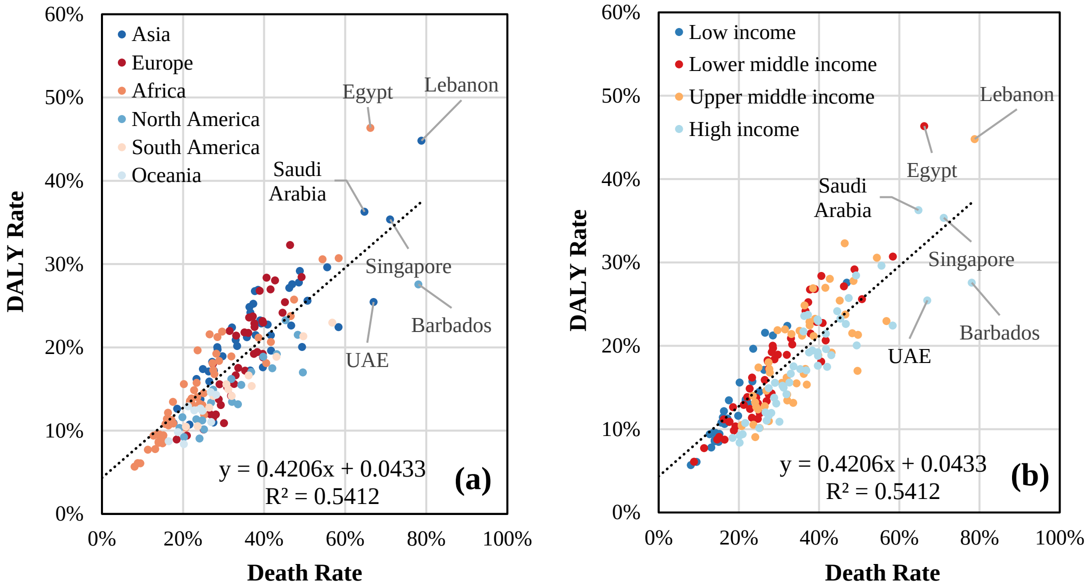


Figure 9. Correlation between AAP attributable death rate and DALY rate by geographical and income distribution (countries without available data for correlations are not shown in this Figure)

The correlations between the BoD and various factors are shown in Figs.10-11, and they may help further mathematically verify the speculation of BoD causes in previous sections. The Y_1 and Y_2 are death rate and DALY rate, respectively. Among these correlation analyses, the correlation coefficients vary in different country groups. As shown in Fig.9, among the considered socioeconomic and natural possible drivers, the highest correlated factors with disease burden in Asia, Europe, Africa, North America, South America, and Oceania are urbanization rate (X_4), HDI (X_2, negative correlation), per capita fossil CO_2 emissions (X_7), per km^2 land area fossil CO_2 emissions (X_6), per capita fossil CO_2 emissions (X_7), and population density (X_1), respectively. The per capita fossil CO_2 emissions (X_7) show the strongest comprehensive correlation with the burden of disease (the sum of the absolute values of the correlations) in contrast to the other columns, which may potentially because the emissions of CO_2 and particulate matter from social operations are mixed and accompanied. In addition, the total correlations of various factors are most significant in terms of mortality in Asia and DALY rates in North America from the horizontal perspective.

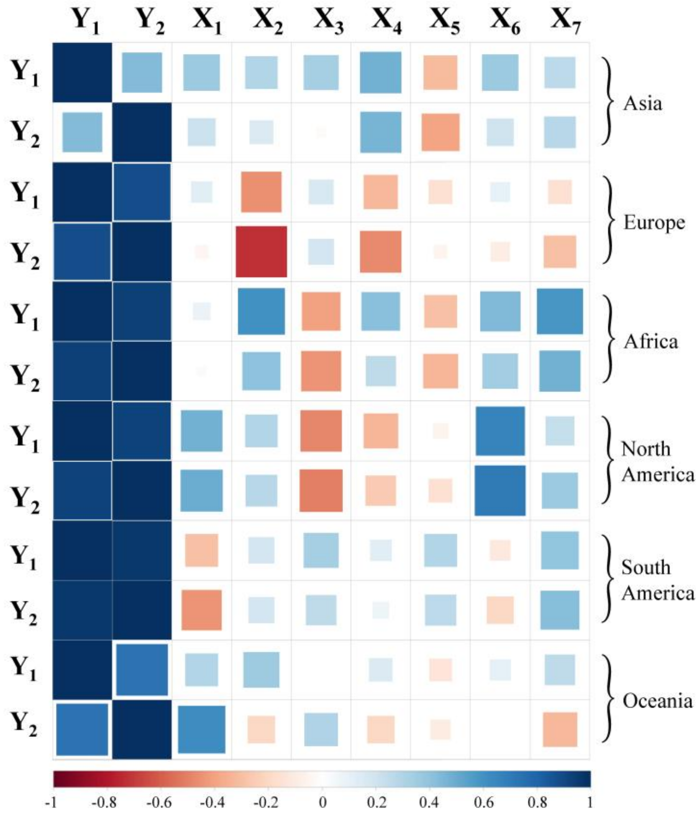


Figure 10. Detailed correlations between AAP-caused BoD and socioeconomic and natural factors by geographical distribution

Since the country groups by income are more compact than those by geography, the correlation analysis results are more obvious. In Fig.11, urbanization rate (X_4) correlate very weakly with BoD longitudinally, in contrast to the strong correlation between per capita fossil CO_2 emissions (X_7) and BoD. Besides, the Gini coefficient (X_3) and forest coverage rate (X_5) present the negative correlations with disease burden. In terms of row order, the negative relation is striking, with the Gini coefficient (X_3), forest coverage rate (X_5), Gini coefficient (X_3), and HDI (X_2) contributing the greatest correlation with disease burden in low-, lower-middle-, upper-middle-, and high-income countries, respectively. The combined results of Figs.10-11 may reflect that the BoD of the income-based group is more sensitive to socioeconomic factors, whilst the geographical group is to natural factors.

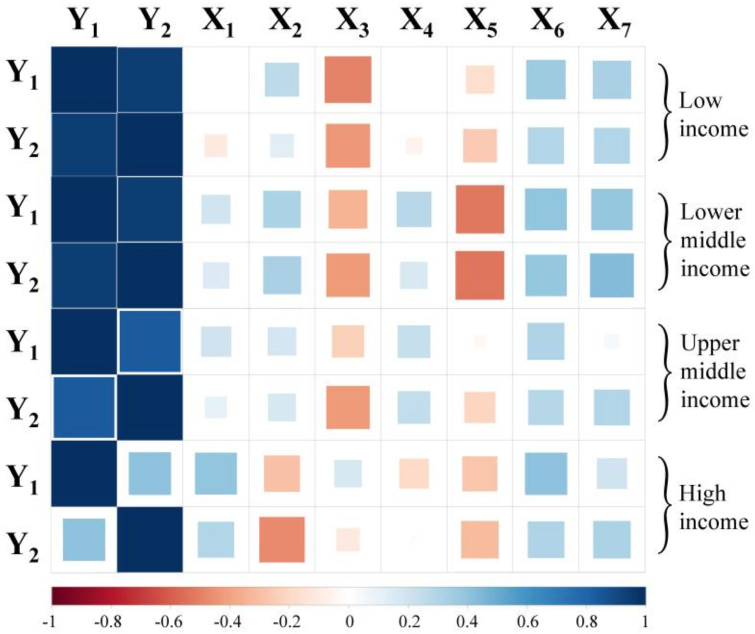


Figure 11. Detailed correlations between AAP-caused BoD and socioeconomic and natural factors by income distribution

4 Discussion

In recent decades, there is a great improvement in our air environment. It can be seen in Table 2, PM10 and PM2.5 pollution have changed towards a positive direction in most areas. The PM10 pollution has mitigated dramatically, whilst the PM2.5 concentrations in low-income, lower-middle-income, and African regions are no sign of improvement. Compared with the target value of the WHO, PM2.5 and PM10 are both substandard, although PM2.5 concentrations in most regions (income distribution) are well above the WHO's proposed minimum requirement (IT-1, 35 μg/m^3), and according to the target proposed by SDG 11.6.2, there is still a long way to reach the goal of air environment sustainability.

Table 2 Variations of PM10 and PM2.5 concentration (population-weighted) in different global regions

Region	PM10 (μg/m^3)				PM2.5 (μg/m^3)				
	1990	2000	2011	Change (%)	1990	2000	2010	2017	Change (%)
Low income	3734.0	2730.1	370.3	(90.1)	42.9	42.8	41.3	43.2	0.7
Lower middle income	3599.1	2884.1	451.3	(87.5)	60.4	61.7	67.3	64.4	6.6
Upper middle income	2166.3	1702.0	323.1	(85.1)	43.1	44.8	49.4	38.7	(10.1)
High income	1215.3	970.4	135.5	(88.9)	16.6	16.2	16.7	14.7	(11.7)
Asia	2911.1	2310.1	292.8	(89.9)	39.0	38.9	40.6	37.0	(5.3)
Europe	1220.1	862.8	157.5	(87.1)	19.0	17.3	17.2	14.2	(25.1)
Africa	2833.2	2104.5	265.7	(90.6)	38.5	37.8	34.8	38.5	0.0
North America	1433.4	1183.0	154.5	(89.2)	21.2	21.8	21.7	17.6	(16.7)
South America	2374.6	1830.4	207.1	(91.3)	20.7	21.5	22.2	17.5	(15.5)
Oceania	934.7	795.0	114.6	(87.7)	12.6	12.9	12.9	10.6	(16.4)
WHO interim target-1 (IT-1)			70					35	
WHO interim target-2 (IT-2)			50					25	
WHO interim target-3 (IT-3)			30					15	
WHO air quality guideline (AQG)			20					10	

For the indicator of SGD 3.9.1, the results in Fig.5 and Fig.7 show that AAP-caused death burden is still high and the high mortality caused by AAP-caused diseases such as IHD and ALRI should be taken seriously, and worse, Lelieveld et al. (2015) project the AAP-caused premature mortality could double by 2050 under a business-as-usual particulate matter emission scenario. Besides, the health risks for children caused by AAP should not be ignored either,[69] Lelieveld et al. (2018) estimated that AAP-caused children under-five mortality accounted for 5% of the total AAP-caused mortality.[70]

Some researchers have estimated the future PM concentrations will continue to increase in emerging regions.[71] Meanwhile, the threat to human health posed by the AAP-caused BoD is also unoptimistic in the future. There are multiple proven factors are driving the results, e.g. indiscriminate burning of waste outdoors in India,[72] massive dust carried by winds from the Sahara and lacking enough health interventions in Africa,[73] and the public health system and citizen income of low-income regions are not enough to support long-term treatment of AAP-caused chronic diseases.[74] Local authorities should put control policies for these obstacles forward immediately. The Massachusetts case shows a negative relation between PM2.5 concentration and the recycling rate of MSW. Governments should take responsibility for better management of waste to improve air quality.[75] Evidence from Africa and Iraq suggests that in reducing particulate matter policies should be making for controlling the further expansion of deserts and reduce the eco-hazardous human activity, e.g. over-burning of agricultural biomass.[76,77] With the more national and regional governments enqueue to reduce AAP and the associated BoD, higher requirements for industrial production and human activity will be put forward.

By summarizing the pollution process in Fig.2, it is found that reducing emissions and controlling human exposure risk are two options that should be two significant paths to reduce the APP-caused burden of disease. The control of land desertification to reduce the frequency of dust events and the use of clean energy can significantly reduce particulate matter at the source. But the growing global aging has provided increased susceptible populations for pollution.[78] The extension of the health-care coverage and provision of affordable diagnosis and treatment of related chronic diseases are the basic remedy to lighten BoD in the hard-to-change aging situation.

In addition to the above factors, this study also sorted out the spatial drivers of AAP-caused disease burden according to the correlation analysis. Reducing CO_2 emissions is feasible to access for countries around the world to ease the burden of disease. In particular, recently some great powers have put forward their ambitious plans to control CO_2 emissions, which are expected to provide a great opportunity to reduce the AAP-caused burden of disease. For instance, China has announced an aim to hit peak emissions before 2030 and for carbon neutrality by 2060.[79] When the statistical data are further refined, the correlation analysis including medical conditions, population age structure, and other factors can also be carried out systematically. But we should at least attach importance to the factors that have been tested so far that harm air quality, and work to reduce the burden of disease caused by air pollution.

In conclusion, the global air pollution statistics combined with the relative disease data have been used in this study to analyze the AAP and BoD situation and distribution. The results show that the BoD caused by AAP (including ALRI, lung cancer, COPD, stroke, and IHD) is related to geography and income distribution. ALRI and IHD are two main AAP-caused diseases that contribute to BoD around the world. Generally, the burden of the disease tends to increase in affluent areas, but the reason is complex, it might include the level of CO_2 emissions, forest coverage rate, population density government policies, etc. These negative circumstances show that there is still a distance to reach the SDGs and to fully protect human health from the adverse effects of air pollution, lots of further studies need to be developed in the near future.

Contributors

NZ conceptualized and wrote the original draft of this study, SC reviewed and edited the draft and improved the methodology of this study, HD directed the study and was responsible for field supervision. All the authors contributed to critically revised the manuscript.

Declaration of interests

The authors declare no competing interests.

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Supplementary Material

Quantitative and distributive measurement of ambient air pollution for global burden of disease

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Table S.1 Global countries divided by income

Groups	**Countries / Regions**
Low income	Afghanistan, Democratic People's Republic of Korea, Nepal, Benin, Burkina Faso, Burundi, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Eritrea, Ethiopia, Gambia, Guinea-Bissau, Liberia, Madagascar, Malawi, Mali, Mozambique, Niger, Rwanda, Senegal, Sierra Leone, Somalia, South Sudan, Togo, Uganda, United Republic of Tanzania, Zimbabwe, Haiti
Lower middle income	Armenia, Bangladesh, Bhutan, Cambodia, Georgia, India, Indonesia, Jordan, Kyrgyzstan, Lao People's Democratic Republic, Mongolia, Myanmar, Pakistan, Philippines, Sri Lanka, Syrian Arab Republic, Tajikistan, Timor-Leste, Uzbekistan, Viet Nam, Yemen, Republic of Moldova, Ukraine, Angola, Cabo Verde, Cameroon, Congo, Côte d'Ivoire, Djibouti, Egypt, Ghana, Guinea, Kenya, Lesotho, Mauritania, Morocco, Nigeria, Sao Tome and Principe, Sudan, Swaziland, Tunisia, Zambia, El Salvador, Guatemala, Honduras, Nicaragua, Bolivia (Plurinational State of), Kiribati, Micronesia (Federated States of), Papua New Guinea, Solomon Islands, Vanuatu
Upper middle income	Azerbaijan, China, Iran (Islamic Republic of), Iraq, Kazakhstan, Lebanon, Malaysia, Maldives, Thailand, Turkey, Turkmenistan, Albania, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Montenegro, Romania, Russian Federation, Serbia, The former Yugoslav Republic of Macedonia, Algeria, Botswana, Equatorial Guinea, Gabon, Libya, Mauritius, Namibia, South Africa, Belize, Costa Rica, Cuba, Dominican Republic, Grenada, Jamaica, Mexico, Panama, Saint Lucia, Saint Vincent and the Grenadines, Argentina, Brazil, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Venezuela (Bolivarian Republic of), Fiji, Samoa, Tonga
High income	Bahrain, Brunei Darussalam, Cyprus, Israel, Japan, Kuwait, Oman, Qatar, Republic of Korea, Saudi Arabia, Singapore, United Arab Emirates, Austria, Belgium, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom, Seychelles, Antigua and Barbuda, Bahamas, Barbados, Canada, Trinidad and Tobago, United States of America, Chile, Uruguay, Australia, New Zealand

Table S.2 Global countries divided by geography

Groups	**Countries / Regions**
Asia	Afghanistan, Armenia, Azerbaijan, Bahrain, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China, Cyprus, Democratic People's Republic of Korea, Georgia, India, Indonesia, Iran (Islamic Republic of), Iraq, Israel, Japan, Jordan, Kazakhstan, Kuwait, Kyrgyzstan, Lao People's Democratic Republic, Lebanon, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Oman, Pakistan, Philippines, Qatar, Republic of Korea, Saudi Arabia, Singapore, Sri Lanka, Syrian Arab Republic, Tajikistan, Thailand, Timor-Leste, Turkey, Turkmenistan, United Arab Emirates, Uzbekistan, Viet Nam, Yemen
Europe	Albania, Austria, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Montenegro, Netherlands, Norway, Poland, Portugal, Republic of Moldova, Romania, Russian Federation, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, The former Yugoslav Republic of Macedonia, Ukraine, United Kingdom
Africa	Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Togo, Tunisia, Uganda, United Republic of Tanzania, Zambia, Zimbabwe
North America	Antigua and Barbuda, Bahamas, Barbados, Belize, Canada, Costa Rica, Cuba, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, United States of America
South America	Argentina, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela (Bolivarian Republic of)
Oceania	Australia, Fiji, Kiribati, Micronesia (Federated States of), New Zealand, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu

Table S.3 Global annual mean levels of PM10 population-weighted concentrations (μg/m^3)

	Low income	Lower middle income	Upper middle income	High income	Asia	Europe	Africa	North America	South America	Oceania
1990	3734.01	3599.14	2166.27	1215.32	2911.14	1220.12	2833.24	1433.37	2374.61	934.72
1991	3543.59	3599.57	2124.15	1180.87	2881.60	1172.55	2711.29	1407.28	2260.67	895.83
1992	3452.23	3579.90	2081.31	1141.82	3119.42	1121.41	2692.93	1448.76	2225.16	895.07
1993	3345.89	3504.43	2026.86	1119.19	2963.07	1092.81	2704.05	1388.32	2158.85	903.85
1994	3213.92	3301.82	1903.05	1093.37	2813.44	1043.45	2571.25	1355.52	2071.96	877.48
1995	3143.53	3206.88	1817.63	1061.89	2625.00	979.47	2436.55	1334.92	2032.68	858.89
1996	3004.41	3075.34	1772.13	1043.57	2534.03	945.96	2303.82	1315.80	2045.87	844.25
1997	2907.01	3030.17	1723.74	1027.53	2481.56	924.27	2186.77	1202.34	1947.75	839.84
1998	2780.18	2986.47	1705.07	1011.67	2440.33	902.64	2091.79	1210.42	1907.69	828.85
1999	2740.17	2967.37	1715.63	989.96	2377.24	881.44	2174.71	1206.33	1923.20	812.36
2000	2730.05	2884.06	1701.98	970.44	2310.10	862.80	2104.47	1182.99	1830.41	794.99
2001	2685.68	2776.90	1658.11	966.66	2254.87	859.23	2069.57	1166.48	1752.50	764.54
2002	2596.41	2708.22	1635.77	943.93	2207.11	835.24	2003.77	1153.18	1775.61	735.16
2003	2300.19	2447.68	1524.60	852.42	2002.43	742.30	1787.92	1006.27	1615.70	681.45
2004	2166.87	2359.32	1495.89	821.27	1905.81	708.85	1674.03	960.64	1625.09	663.00
2005	1941.66	2099.37	1358.41	747.69	1674.80	647.21	1511.09	857.87	1430.94	589.53
2006	1665.45	1795.76	1220.57	646.41	1414.46	562.88	1288.64	757.72	1238.34	503.05
2007	1265.19	1386.83	1014.49	500.22	1081.04	440.68	978.87	602.73	912.00	378.43
2008	1223.64	1352.87	987.21	481.82	1041.48	433.95	934.32	572.98	909.08	365.75
2009	933.38	1065.79	783.76	373.86	795.45	346.64	723.35	440.80	670.74	293.55
2010	593.53	677.76	510.94	227.89	485.95	230.40	439.71	265.68	376.51	182.56
2011	370.27	451.33	323.10	135.49	292.82	157.50	265.66	154.46	207.14	114.60

Table S.4 Global annual mean levels of PM2.5 population-weighted concentrations (μg/m^3)

	Low income	**Lower middle income**	**Upper middle income**	**High income**	**Asia**	**Europe**	**Africa**	**North America**	**South America**	**Oceania**
1990	42.91	60.45	43.12	16.63	39.02	18.99	38.48	21.19	20.72	12.62
1995	43.14	60.95	43.50	16.22	38.92	17.94	37.94	21.38	20.89	12.58
2000	42.80	61.67	44.77	16.20	38.90	17.33	37.79	21.85	21.47	12.93
2005	41.36	64.77	47.64	16.32	39.48	17.24	35.53	21.98	22.22	12.83
2010	41.34	67.29	49.42	16.67	40.62	17.18	34.80	21.71	22.18	12.94
2011	41.94	67.81	49.87	16.96	40.68	17.61	34.95	22.53	22.31	13.16
2012	42.05	63.32	45.98	16.08	39.87	16.26	35.48	21.18	21.27	12.30
2013	41.01	64.02	46.58	15.88	39.40	15.63	34.72	20.70	20.40	11.88
2014	40.05	62.66	42.98	14.99	37.49	15.03	34.40	19.11	19.14	11.27
2015	43.77	64.86	42.71	15.82	39.10	15.19	39.19	18.83	18.60	11.23
2016	42.89	63.91	38.58	14.52	36.73	14.23	38.25	17.72	17.59	10.57
2017	43.22	64.41	38.75	14.68	36.97	14.22	38.48	17.65	17.51	10.55