Age-dependent health risk from ambient air pollution: a modelling and data analysis of childhood mortality in middle-income and low-income countries

Jos Lelieveld, Andy Haines, Andrea Pozzer

Summary

Background WHO estimates that, in 2015, nearly 1 million children younger than 5 years died from lower respiratory tract infections (LRIs). Ambient air pollution has a major impact on mortality from LRIs, especially in combination with undernutrition and inadequate health care. We aimed to estimate mortality due to ambient air pollution in 2015, particularly in children younger than 5 years, to investigate to what extent exposure to this risk factor affects life expectancy in different parts of the world.

Methods Applying results from a recent atmospheric chemistry-general circulation model and health statistics from the WHO Global Health Observatory, combined in integrated exposure-response functions, we updated our estimates of mortality from ambient (outdoor) air pollution. We estimated excess deaths attributable to air pollution by disease category and age group, particularly those due to ambient air pollution-induced LRIs (AAP-LRIs) in childhood. Estimates are presented as excess mortality attributable to ambient air pollution and years of life lost (YLLs). To study recent developments, we calculated our estimates for the years 2010 and 2015.

Findings Overall, 4·55 million deaths (95% CI 3·41 million to 5·56 million) were attributable to air pollution in 2015, of which 727 000 deaths (573 000–865 000) were due to AAP-LRIs. We estimated that AAP-LRIs caused about 237 000 (192 000–277 000) excess child deaths in 2015. Although childhood AAP-LRIs contributed about 5% of air pollution-attributable deaths worldwide, they accounted for 18% of losses in life expectancy, equivalent to 21·5 million (17 million to 25 million) of the total 122 million YLLs due to ambient air pollution in 2015. The mortality rate from ambient air pollution was highest in Asia, whereas the per capita YLLs were highest in Africa. We estimated that in sub-Saharan Africa, ambient air pollution reduces the average life expectancy of children by 4–5 years. In Asia, all-age mortality increased by about 10% between 2010 and 2015, whereas childhood mortality from AAP-LRIs declined by nearly 30% in the same period.

Interpretation Most child deaths due to AAP-LRIs occur in low-income countries in Africa and Asia. A three-pronged strategy is needed to reduce the health effects of ambient air pollution in children: aggressive reduction of air pollution levels, improvements in nutrition, and enhanced treatment of air pollution-related health outcomes.

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Atmospheric Chemistry Department, Max Planck Institute for Chemistry, Mainz, Germany (Prof J Lelieveld PhD, A Pozzer PhD)**; Energy, Environment and Water Research Centre, The Cyprus Institute, Nicosia, Cyprus** (Prof J Lelieveld)**; and Department of Public Health, Environments and Society, London School of Hygiene & Tropical Medicine, London, UK** (Prof A Haines F Med Sci)

Correspondence to: Prof Jos Lelieveld, Atmospheric Chemistry Department, Max Planck Institute for Chemistry, Mainz 55128, Germany **jos.lelieveld@mpic.de**

Introduction

The *Lancet* Commission on pollution and health concluded that diseases caused by environmental pollution were responsible for about 9 million excess deaths worldwide in 2015, 15 times more than from all wars and other forms of violence combined.[1] About half of these deaths are due to ambient (outdoor) air pollution, which is responsible for about 8% of all deaths globally, exceeding the combined effects of malaria and HIV/AIDS by a factor of three.[2–5] The *Lancet* Commission[1] emphasises the high risk posed to children by exposure to environmental pollution, even at low levels, especially during in-utero development and early infancy. Poor air quality is the predominant environmental health risk. Morbidity and mortality from air pollution are mainly attributed to $PM_{2·5}$, particles with a diameter smaller than 2·5 µm, which are small enough to deeply penetrate into the airways, and to ozone (O_3), a strong gaseous oxidant.[6–8] The principal sources of air pollution are fossil fuel and biofuel combustion, agriculture, biomass burning, and aeolian (atmospheric) dust.[9] Exposure to air pollution increases the risk of ischaemic heart disease, cerebrovascular disease, lower respiratory tract infections (LRIs) such as pneumonia, chronic obstructive pulmonary disease (COPD), and lung cancer.

Although global mortality from tobacco smoking is 6·4 million per year,[2] which is 1·9 million more than that from ambient air pollution, the numbers of disability-adjusted life-years (DALYs) lost compare more closely, both being in excess of 120 million per year.[2,10] The reason is that air pollution increases the risk of mortality through LRIs in children who consequently

Research in context

Evidence before this study

According to the Global Burden of Disease (GBD) studies, ambient (outdoor) air pollution is the predominant environmental health risk worldwide. Furthermore, the GBD team concluded that lower respiratory tract infections (LRIs) are the leading infectious cause of death and the fifth-leading cause of mortality overall and that they are potentially preventable with available means. In 2015, nearly one million children younger than 5 years died from LRIs.

Added value of this study

Our results call attention to excess deaths in childhood from LRIs, such as pneumonia, that are attributable to ambient air pollution. We adopted GBD methods, combined with recent air quality, health, and demographic data, to estimate mortality attributable to air pollution in the year 2015. We found that atmospheric fine particulate matter significantly reduces the life expectancy of children in low-income countries.

Implications of all the available evidence

Each year, about 237 000 excess child deaths due to LRIs result from exposure to fine particulate matter. Worldwide, these deaths account for 18% of the overall life expectancy decrease attributable to poor air quality. Although the per capita mortality rate from ambient air pollution is highest in Asia, the per capita loss of life-years is highest in Africa due to LRIs in childhood. Virtually all of the deaths from LRIs attributable to air pollution under the age of 5 years occur in low-income countries in Africa and Asia. We conclude that a three-pronged strategy is needed, consisting of aggressive reduction of air pollution, improved nutrition, and enhanced treatment of air pollution-related health outcomes.

experience a relatively large decrease in life expectancy. Air pollution-induced LRIs have been shown to be a common cause of both short-term and long-term health impacts that lead to the death of children younger than 5 years.[11–13] The triggering mechanism might involve incitement of oxidative stress due to respiratory deposition of $PM_{2·5}$ and increased susceptibility to infections.[11,14] The assessment of morbidity and mortality by the Global Burden of Disease (GBD) LRI Collaborators concludes that LRIs are the leading infectious cause of death worldwide and the fifth-leading cause of mortality overall, and have the potential of being prevented with available means.[3] Here, we use recently updated global model results and health statistics for the year 2015 to estimate mortality from ambient air pollution, particularly through LRIs in childhood, to investigate to what extent this risk factor affects life expectancy in different parts of the world.

Methods

Integrated exposure response functions

While it is not feasible to identify individuals who die from environmental hazards, we can estimate the increment in the number of deaths due to air pollution over a defined period, referred to as excess deaths, or attributable mortality, and determine statistically the number of years of life lost (YLLs)—ie, life expectancy reduction.[15] We adopted the GBD method, described by Cohen and colleagues,[4] which applies the following expression:

$$M(\text{age, lat, lon, year}) = y_0 \times \text{AF} \times \text{Pop}$$

The attributable mortality, M, is a function of age, geographical latitude and longitude, and the year for which air pollution concentrations and population distributions are being considered. Our baseline calculations are for the year 2015, as presented in the tables and figures; however, we also did them for the year 2010 to gain some insight into temporal developments. The baseline mortality rate, y_0, is available on a country level for the different disease categories (ischaemic heart disease, COPD, LRI, cerebrovascular disease, lung cancer) from the WHO's Global Health Estimates database,[5] from which we also obtained the population (Pop) data. The YLLs and the years of life lived with disability (YLDs), which together make up DALYs, are calculated with the same expression, in which y_0 is replaced by the baseline ratios of the YLL and YLD from the WHO database. The attributable fraction (AF) is calculated as:

$$\text{AF} = \frac{R(t) - 1}{R(t)}$$

where $R(t)$ is the relative risk at age t, calculated with the GBD method.[2,4,16,17] $R(t)$ is a function of ambient $PM_{2·5}$ and O_3 concentrations, and is computed for the different disease categories and seven age classes: 0–4, 5–14, 15–29, 30–49, 50–59, 60–69, and 70 years or older. For the disease categories ischaemic heart disease and cerebrovascular disease, we need to consider that AFs for morbidity and mortality are different, which is accounted for with the methods of Cohen and colleagues.[4] The relative risk, $R(t)$, from exposure to $PM_{2·5}$ was estimated with the formulation of Burnett and colleagues,[17] which is referred to as integrated exposure-response (IER) function:

$$R(t) = 1 + \alpha[1 - \exp[-\gamma(PM_{2·5} - X_0)\delta]]$$

$R(t)$ is calculated for concentration bins of 1 μg/m³ of $PM_{2·5}$, for each disease and age class. We adopted the most recently updated parameter values—ie, of α, γ and δ that describe the shape of the IERs—based on the compilation of Cohen and colleagues.[4] X_o is the minimum risk exposure level, for which a range of 2·4–5·9 μg/m³ has been determined.[4] The relative risk, $R(t)$ related to O_3, which only contributes to COPD and not to the other disease categories, has been calculated following the IER of Jerrett and colleagues,[6] with the updated coefficients (β) of Cohen and colleagues:[4]

$$R(t)=[\frac{O_3}{X_0}]^{\beta}$$

where X_o is the minimum risk exposure level for O_3, which was 37·3 ppbv.[4,6] 95% CIs were computed through 1000 realisations of the IER functions over the ambient concentration ranges, for all five disease categories, based on distributions of the above parameters described.[4,17] The results of the mortality and YLL calculations for all countries are provided in the appendix. Intermediate results of our calculations, such as concentrations of $PM_{2·5}$, O_3, $R(t)$, and M(age, lat, lon, year), including YLLs, YLDs, and uncertainty ranges are available in NetCDF format on request. The statistical uncertainty is specified through that of the described parameters, including the time and geographical location-dependent concentration enhancements of $PM_{2·5}$ and O_3 relative to the minimum-risk exposure levels.

Global model

The $PM_{2·5}$ and O_3 concentrations for each location (grid cell) were computed with the global atmospheric-chemistry general circulation model EMAC, which has been extensively tested against ground-based in-situ and remote sensing measurements, as well as satellite data.[9,18–20] We used a spatial model resolution of about 100 km, which is coarser than of the demographic data (5 km), and typically finer than the country-level health statistics from the WHO database.[5] To study recent developments in mortality related to ambient air pollution-induced LRIs (AAP-LRIs), we performed the calculations for the years 2010 and 2015. For the global concentration distributions, which were applied in the IER functions, our model results have similar accuracy to satellite data in comparison to ground-based measurements, although they have full spatial and temporal (eg, diurnal) coverage, are not affected by data gaps due to clouds and darkness, and are not sensitive to resolution.[9,14] For example, we tested a grid size of 20 km for Europe, and compared with 10 km resolution satellite data, and obtained results within a few percent of those from our 100 km grid calculations, indicating that the uncertainty is dominated by that of IER functions rather than the spatial resolution of calculations.

Uncertainty evaluation

It should be noted that the 95% CIs, which were generally within 30% of the mean values, do not account for epistemic (scientific) uncertainty. This type of error can be associated with unaccounted confounding factors, misclassification of health data, or limitations in the representativeness of the IER functions for the diverse countries to which they are applied. The confounder problem can work in two directions, either by over-attributing air pollution deaths to the five disease categories, or by neglecting other effects of $PM_{2·5}$—eg, on birthweight and neonatal deaths—and diseases such as diabetes and high blood pressure, which might be aggravated by air pollution. It has been suggested that long-term exposure to elevated O_3 causes circulatory mortality, in addition to respiratory mortality.[21] Another example is the emerging evidence about the effects of air pollution exposure on cognitive function in children.[22] Following the conservative practice established by the GBD,[1] the estimates presented here are likely to be lower limits. If epidemiological information is not available for a particular country, it is not known whether the composition of $PM_{2·5}$ in that country will have the same health consequences as in the country where the data have been collected, typically in the USA, Europe, or China. For example, in the USA, about 58% of the estimated excess deaths are due to fossil fuel use (ie, traffic, power production, industry). In India, where solid biofuel use for residential energy production (ie, heating and cooking) is the major source of ambient air pollution, this fraction is 26% (figure 1). Nevertheless, the state of the science in epidemiology and toxicology is such that no specific source types or compounds within $PM_{2·5}$ can be identified that contribute more or less to mortality than others.[4]

See Online for appendix

The mortality calculations have highest uncertainty for developing countries, especially sub-Saharan Africa, where LRIs are a major burden of disease and atmospheric composition measurements, as well as autopsy data, are sparse. Although the health impacts and mortality from household and ambient air pollution are computed independently,[2] there is overlap between the sources,

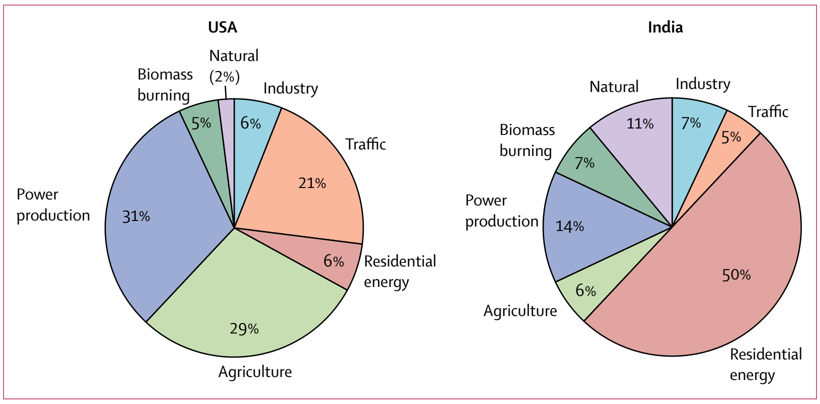

Figure 1: **Sources of mortality from air pollution**
Percentages are the proportions of the deaths attributable to ambient air pollution. Excess deaths attributable to air pollution in 2015 were estimated at 120 000 (95% CI 81 000–156 000) in the USA and 967 000 (753 000–1 150 000) in India. Natural refers to natural sources of air pollution, predominantly aeolian dust.

	Population, millions	Excess deaths		Deaths by disease category, thousands						YLLs, millions	
		Total, thousands	Deaths per 1000 person–years	LRIs		COPD†	Cerebrovascular disease‡	Ischaemic heart disease	Lung cancer	All-age	Under-5§
				All-age	Under-5*						
Africa	1184	523	0·44	270	127·9, 102·1–150·8 (47%)	37	87	125	4	25	11·6, 9·3–13·7 (47%)
Asia	4516	3414	0·76	407	106·8, 88·6–123·0 (26%)	943	736	1074	254	85	9·7, 8·1–11·2 (11%)
East Asia	1692	1609	0·95	118	9·3, 7·7–10·7 (8%)	473	425	389	204	33	0·8, 0·7–1·0 (3%)
South Asia	2246	1383	0·62	247	85·5, 70·8–98·4 (35%)	432	218	456	31	42	7·8, 7·1–9·0 (20%)
West Asia	414	198	0·48	28	11·4, 9·6–13·1 (40%)	21	37	103	8	5	1·0, 0·9–1·2 (21%)
North and central Asia	164	224	1·37	14	0·6, 0·5–0·7 (4%)	17	56	126	11	5	0·05, 0·04–0·06 (1%)
Europe	597	373	0·62	23	0·2, 0·1–0·3 (1%)	50	66	203	31	7	0·03, 0·02–0·03 (4%)
Australia	31	3	0·10	0·1	0	1	0·4	1·5	0·2	0·5	0
North America	486	148	0·25	10	0·3, 0·1–0·5 (0%)	44	14	68	12	3	0·03, 0·02–0·04 (1%)
South America	498	94	0·19	17	1·4, 0·5–2·1 (1%)	15	17	42	3	2	0·12, 0·05–0·2 (6%)
World	7312	4555	0·62	727	237, 192–277 (33%)	1090	920	1514	304	122	22, 17–25 (18%)

Statistical uncertainty is typically within ±30% of the mean, whereas total uncertainty can be larger. LRI=lower respiratory tract infections. COPD=chronic obstructive pulmonary disease. YLLs=years of life lost. *Data in parentheses are the percentage of LRI deaths in children <5 years relative to all–age LRI mortality. †Sum of COPD attributed to $PM_{2·5}$ and to O_3. ‡Sum of mortality from ischaemic and haemorrhagic stroke. §Data in parentheses are the percentage of YLLs in children <5 years relative to all–age YLLs (LRIs in the defined regions).

Table: **Mortality attributable to air pollution in 2015 by disease categories**

which contributes to uncertainty. Hammitt and colleagues (Hammitt JK, Harvard TH Chan School of Public Health, personal communication) showed that, in the theoretical limits of $R(t)$ approaching either one or infinity, mortality from the exposure to air pollution could lie between 1/e (about 37%) of the AF and 100% of all deaths by LRIs, and the same holds true for the other diseases listed in the table. It is not possible to unambiguously determine the actual limits from epidemiological data, but assuming that the very low as well as the very high percentages are implausible, we estimate the overall uncertainty range of our mortality calculations to be within 50% of the calculated mean excess mortality. Throughout the text, we follow the GBD convention by reporting the 95% CI.

Role of the funding source
There was no funding source for this study.

Results

Between 2000 and 2015, the global population increased from 6·1 billion to 7·3 billion people, while life expectancy increased by 5 years, up to an average of 71·4 years.[5] In this period, the total all-age mortality from LRIs decreased from 3·41 million to 3·19 million per year, and mortality from LRIs in children younger than 5 years dropped from about 1·72 million to 917 000 per year; the fraction of neonatal (≤4 weeks) deaths remained close to 20%.[5] At the same time, the global annual mean exposure of the population to ambient $PM_{2·5}$ increased from 40·5 μg/m³ to 44·0 μg/m³, exceeding the WHO guideline concentration (10 μg/m³) by more than four times and the minimum-risk exposure level, or so-called safe-threshold (2·4 μg/m³), by a factor of 18. The table shows the numbers of excess deaths attributed to ambient air pollution and YLLs.

Figure 2 and the table show total mortality attributable to air pollution in 2015 (all ages), which amounted to 4·55 million deaths (95% CI 3·41 million to 5·56 million) per year, an update of our previous result obtained with the same method with IER functions and WHO data for the year 2010.[9] Our new result agrees with the revised GBD estimate for 2015,[2] which was 4·5 million deaths (3·80–5·20) per year.

Of the total global mortality attributable to air pollution, we estimated that 270 000 deaths per year (6%) were from O_3 and 4·28 million (94%) were from $PM_{2·5}$. Notably, the contribution of O_3 in India was about 10% (96 000 deaths per year), nearly as high as the 12% contribution in the USA (14 000 deaths per year), whereas in sub-Saharan Africa the contribution was less than 2% (7500 deaths per year).

The table shows air pollution-related impacts on mortality by continent. Asia is the largest and most populous continent, with 4·5 billion inhabitants and 3·4 million excess deaths (95% CI 2·6 million to 4·1 million) per year, representing 75% of the 4·5 million deaths attributed to air pollution worldwide. The prominent position of Asia depends not only on population density, but also on the large mortality rate of 0·76 per 1000 person-years attributable to exposure to poor air quality, with residential energy use for cooking and heating being the largest source of ambient air pollution.[9] In India, air pollution emissions are growing rapidly—eg, due to intensifying coal use—whereas in China, the strong growth of emissions typical of the 1990s

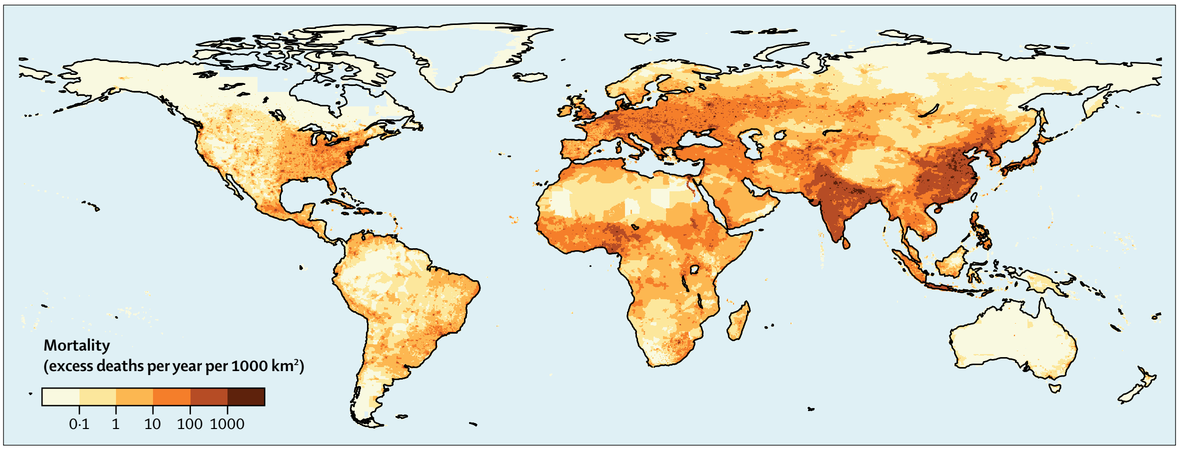

Figure 2: Mortality from ambient air pollution in 2015

and 2000s has halted.[23–25] By contrast, air pollution-related mortality in Australia is not only lowest because of the relatively small population size, but also because the air is least polluted, with mortality attributable to air pollution of 0·10 per 1000 person-years.

Attributable mortality was second highest in Europe (0·62 per 1000 person-years) and third highest in Africa (0·44 per 1000 person-years; table). Excess deaths from air pollution in North America amounted to about 148 000 deaths per year (with 120 000 per year in the USA alone), whereas in Europe, which has a population that is about 20% larger than North America, the estimated number of excess deaths was 372 000 per year, higher by a factor of 2·5 (274 000 per year in the 28 member states of the European Union). Our findings underscore that the average level of air pollution in Europe is considerably higher than in the USA. The air quality standard for annual mean $PM_{2.5}$ in the USA is 12 µg/m³ (since 2013), whereas in the EU, it is 25 µg/m³ (since 2015), which exceeds the safe threshold by more than a factor of ten.

WHO estimates that more than one in four deaths of children younger than 5 years of age are attributable to unhealthy environments.[26] Our results show that, from the global population of children younger than 5 years, which was 669 million in 2015, about 246 000 (95% CI 196 000–288 000) died from the health impacts of ambient air pollution. Thus the mortality rate was 0·37 deaths per 1000 children-years—ie, 37 (29–41) per 100 000 children younger than 5 years in 2015. Figure 3 shows the countries with the highest mortality rate in childhood. Globally, about 96% of excess childhood mortality attributable to air pollution was due to LRIs (AAP-LRIs), amounting to 237 000 deaths (192 000–277 000) per year, out of an all-age total of 727 000 deaths (573 000–865 000) due to AAP-LRIs. This child mortality value compares to about 87 000 deaths from HIV/AIDS, 525 000 from diarrhoeal diseases, and 312 000 from malaria in 2015.[5] Although the proportion of excess deaths in children younger than 5 years constituted about 5% of the total (ie, all ages) mortality attributable to ambient air pollution in 2015, the consequences in terms of life expectancy reduction, and hence YLLs, are much larger among children. The estimated global number of YLLs due to air pollution for all ages in 2015 was 122 million (95% CI 92 million to 148 million) and the number of DALYs was 127 million (96 million to 154 million) per year. Our DALY estimate is higher than that of the GBD team,[2] who reported 107 million (92 million to 122 million) DALYs due to ambient air pollution; the difference is largely associated with updated age-dependent health data from WHO.[5]

We calculated that, among children younger than 5 years globally, air pollution was related to 22·4 million YLLs (95% CI 18 million to 26 million) and 22·5 million DALYs (18 million to 26 million) in 2015. These values represent 18% of the all-age YLLs (and DALYs) attributable to air pollution, mainly as a result of AAP-LRIs, which were responsible for 21·5 million YLLs (17–25) in 2015 (figure 4). About 95% of the all-age mortality due to AAP-LRIs and associated YLLs occurred in Africa and Asia, distributed roughly equally between the two continents, despite the Asian population being nearly four times that of Africa. YLLs due to air pollution in children accounted for 47% of all-age YLLs in Africa and 11% in Asia, where the highest values were in south Asia (20%) and west Asia (21%). It was previously estimated that the highest rate of childhood mortality due to LRIs was in sub-Saharan Africa (eg, in Chad),[3] which is consistent with the high number of AAP-LRI deaths estimated for sub-Saharan Africa in our results (figure 3). In Africa, AAP-LRIs were responsible for about half (270 000 [52%] of 523 000) of all excess deaths from ambient air pollution (at all ages); in sub-Saharan Africa this fraction was 58% (258 000 of 444 000 total mortality per year). In South America AAP-LRIs were responsible for 17 000 (18%) of 94 000 excess deaths, whereas the value was 407 000 (12%) of 3 414 000 in Asia, 23 000 (6%) of 373 000 in Europe, 10 000 (7%) of 148 000 in North America, and 140

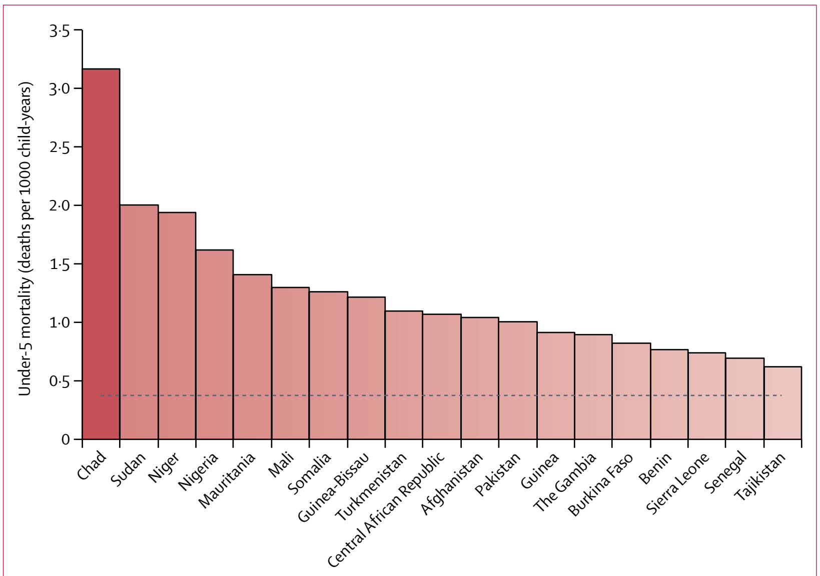

Figure 3: **Excess mortality attributable to ambient air pollution in children younger than 5 years**
The dashed line marks the global mean of 0·37 deaths (95% CI 0·29–0·41) per 1000 children-years in 2015.

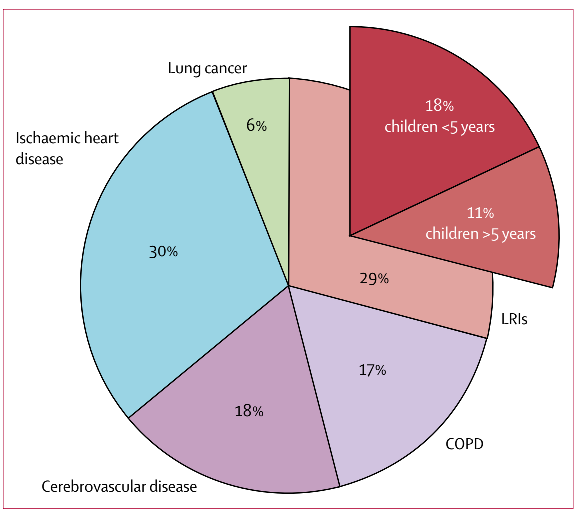

Figure 4: **YLLs from ambient air pollution by disease category**
Global YLLs in 2015 were estimated at 122 million. LRI=lower respiratory tract infections. COPD=chronic obstructive pulmonary disease. YLL=years of life lost.

(5%) of 3000 in Australia. Within Asia, the contribution of AAP-LRIs was relatively large in India, at 19%, compared with 6% in China, which is similar to that in North America, Europe, and Australia. Globally, the effects of AAP-LRIs become more prominent when considering YLLs instead of excess deaths, as they have a particularly large impact on children, who bear a large loss of life-years. The most affected regions include countries where undernutrition and health-care deficiencies are prevalent. Of the 122 million YLLs (95% CI 92 million to 148 million) due to all disease categories at all ages globally in 2015, AAP-LRIs were responsible for about 17·5 million (13 million to 21 million; 14%) in Africa and 16 million (13 million to 19 million; 13%) in Asia. Nigeria, Sudan, Chad, and Niger were the African countries with the most YLLs due to AAP-LRIs, which matches the high child mortality shown in figure 3. In Asia, the largest impacts of AAP-LRIs were in India (similar to Nigeria with about 7·5 million YLLs) and Pakistan (similar to Sudan with about 2 million YLLs).

Figure 5A shows the global distribution of YLLs attributable to ambient air pollution, integrated over the five disease categories combined. 70% of the global YLLs each year were in Asia (corresponding to 75% of the excess deaths). Although the per capita number of excess deaths was largest in Asia, which is associated with Asia having the highest mean exposure to air pollution, Africa leads in per capita YLLs (18 and 21 years per 1000 inhabitants per year, respectively). The countries in Asia with highest per capita YLLs are India and Pakistan (21 and 27 years per 1000 inhabitants per year, respectively), whereas countries in sub-Saharan Africa, such as Chad, Sudan, and Nigeria, have values that are two to three times higher (76, 56, and 49 years per 1000 inhabitants per year. respectively). Figure 5B shows YLLs in children younger than 5 years. Taking figure 5 as a whole, it is notable that in sub-Saharan Africa and south Asia, mortality in childhood, which is dominated by AAP-LRIs, contributes substantially to the global YLLs due to ambient air pollution. Our estimates showed that each child in sub-Saharan Africa loses an average of 4–5 years of life expectancy at birth due to ambient air pollution, which is caused by the exposure to $PM_{2·5}$. In Africa, $PM_{2·5}$ is typically composed of aeolian dust, mixed with pollution from anthropogenic sources, including vegetation fires, which satellite measurements show are growing rapidly.[24]

The GBD 2015 LRI Collaborators uncovered a significant relationship between LRI mortality and sociodemographic development.[3] In some low-income countries in sub-Saharan Africa, the overall incidence of LRIs associated with childhood undernutrition seems to have dropped; however, the number of YLLs (and DALYs) has not decreased because of population growth. We found that between 2010 and 2015, global all-age mortality increased from about 4·28 to 4·55 million deaths per year, largely in parallel with the population increase, whereas mortality due to AAP-LRIs among children younger than 5 years has decreased from about 302 000 to 237 000 per year. The global number of all-age deaths attributable to AAP-LRIs decreased relatively less, from about 742 000 to 727 000, mostly due to growth in the population older than 60 years. During 2010–15, under-5 AAP-LRI mortality in Asia declined from about 150 000 to 107 000 deaths per year, and in Africa from about 150 000 to 128 000 deaths per year. The decrease in Asia was substantially affected by the decrease in India, from about 77 000 to 51 000 deaths per year, despite growing ambient air pollution. This finding suggests that improvements in health care and possibly nutrition have been driving factors, although notably, the under-5

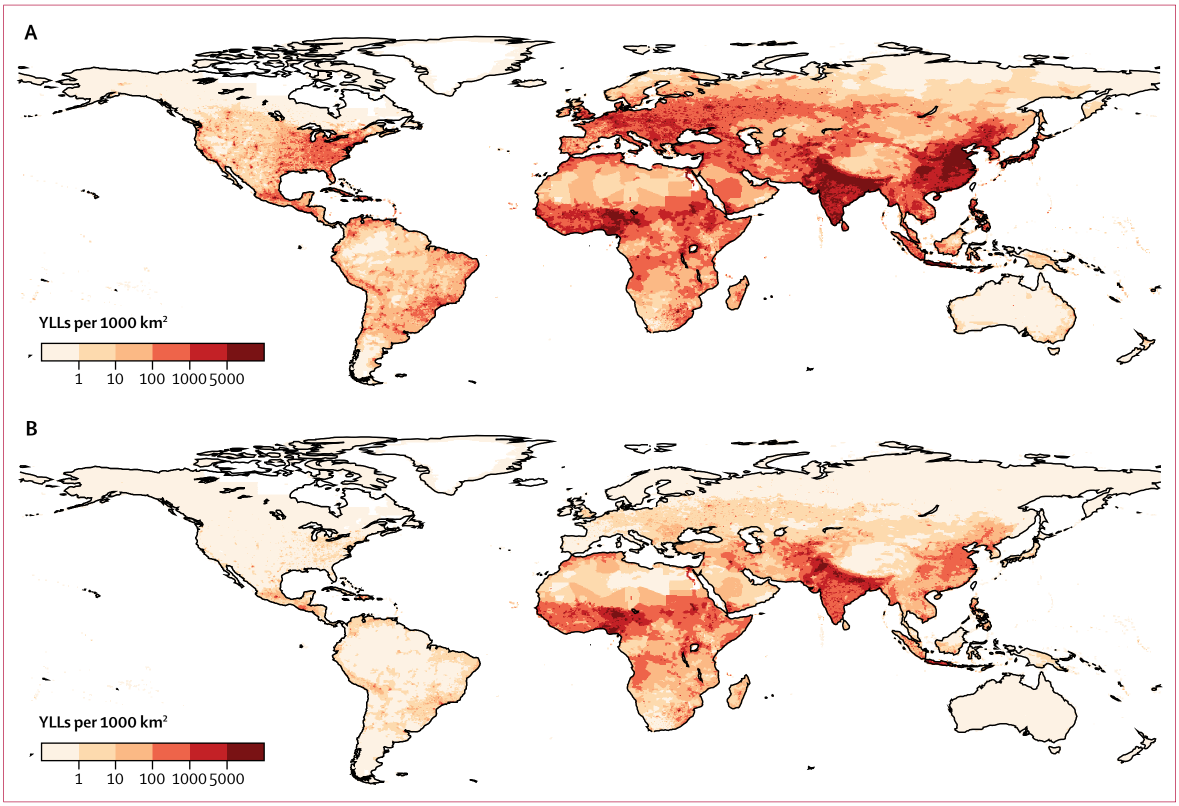

Figure 5: **YLLs attributable to ambient air pollution, 2015**
YLLs at (A) all ages and (B) in children younger than 5 years. YLLs=years of life lost.

population also decreased, by nearly 4%. In several countries in sub-Saharan Africa, under-5 mortality due to AAP-LRIs also decreased—eg, from about 59000 to 51000 deaths per year in Nigeria—which was largely related to a decrease in the under-5 population.

Discussion

To assess the public health impact of ambient air pollution, YLLs are particularly relevant for the interpretation of excess deaths in childhood, and therefore we discuss both metrics. We estimate that in 2015, diseases related to ambient air pollution caused 4·55 million excess deaths globally, of which about 727000 were from AAP-LRIs, including 237000 in children younger than 5 years. Around a third deaths due to AAP-LRIs and two-thirds of the associated YLLs were in children younger than 5 years. Under-5 mortality from AAP-LRIs occurs almost exclusively in low-income countries in Africa and Asia. In 2015, there were about 122 million YLLs due to air pollution globally, of which about 10% (11·6 million) were due to childhood AAP-LRIs in Africa and 8% (9·7 million) in Asia. Of the total all-age YLLs from air pollution in Africa, nearly half were due to AAP-LRIs. The mortality rate from ambient air pollution was largest in Asia, whereas the per capita YLLs were highest in Africa.

On the basis of growing epidemiological evidence, the minimum risk exposure level distribution for annual mean $PM_{2·5}$, which we applied in the IER functions, has been revised down to 2·4–5·9 μg/m³.[4] This is a significant reduction compared with the range of 5·8–8·8 μg/m³ that was applied in the previous assessment for 2010, whereas the minimum risk exposure level of O_3 remained unchanged.[4,9] However, it is long-term exposure to O_3 that is associated with COPD deaths, which is not relevant for children. The downward adjustment of the safe threshold for $PM_{2·5}$—ie, from 5·8 μg/m³ to 2·4 μg/m³, is the main reason for the higher mortality estimates presented here and by the GBD 2015 study compared with those for 2010[9,17] because a much larger fraction of the population is affected by air pollution levels that have impacts on health: about 7 billion people in 2015, representing about 95% of the global population. The calculated COPD mortality has been revised upward relatively sharply, making it the second largest cause of all air pollution-related deaths, after ischaemic heart disease (all ages).

So far, much of the focus on air quality-related LRIs in children has been on household exposure.[27] In 2008, Rudan and colleagues[28] emphasised the role of pneumonia as a leading cause of child mortality, with the highest incidence in south Asia, which now appears to have been overtaken by Africa. Among the leading risk factors identified were undernutrition, lack of breastfeeding, low birthweight, and household air pollution, while ambient air pollution was mentioned as a possible risk factor. Although the attention on household air pollution is appropriate, because children are disproportionally affected by indoor conditions, we emphasise that ambient air pollution is a substantial contributor. Cohen and colleagues[4] estimated that all-age excess mortality from household air pollution amounts to about 2·8 million deaths per year, and that the impact when combined with ambient air pollution is about 6·4 million (95% CI 5·7 million to 7·3 million) deaths per year. Their estimate of excess deaths per year from ambient air pollution was 4·5 million—consistent with our results—showing that there is overlap between these risk factors.

Uncertainties in these estimates remain large, especially for low-income countries where dedicated epidemiological studies and improved health surveillance are needed. For example, many studies have been done in the USA where the YLLs from air pollution are dominated by cardiovascular diseases (56%) and where AAP-LRIs contribute just 6%. By contrast, in Chad, cardiovascular diseases are estimated to contribute 11% of YLLs while AAP-LRIs contribute 87%. The statistical uncertainty is determined through the parameters of relative risk calculations, expressed as the 95% CI; however, other uncertainties might dominate. This includes the effect of unaccounted confounding factors due to overlapping causes of diseases. Since the calculations do not include diseases for which causal effects between air pollution and morbidity or mortality risks have not been unequivocally established, but that can nevertheless be aggravated by air pollution, we expect that our results represent conservative estimates.

There is a relationship between poverty, which is associated with deficient nutrition and health conditions, and under-5 LRIs,[3] and therefore also with under-5 AAP-LRIs. In Chad, for example, the per capita YLLs due to AAP-LRIs in children younger than 5 years are 1000 times higher than in the USA. It was previously reported that India is the country with the highest number under-5 deaths due to LRIs, which is related to the large population size, and that girls are affected 1·2 times more frequently than are boys (which was also reported for Pakistan), whereas the distribution between sexes is about equal in the rest of the world.[3] This difference could be related to nutrition and health care, given that the exposure of boys and girls to air pollution (both indoor and outdoor) is expected to be the same.

In India, the YLLs due to under-5 AAP-LRIs decreased by 30% between 2010 and 2015, despite increases in air pollution as the country overtakes China in worldwide anthropogenic sulphur dioxide emissions.[25] This finding suggests that improved nutrition and health care in India have helped to prevent childhood mortality from AAP-LRIs. In India, child and maternal undernutrition, together with ambient and household air pollution, are considered the leading health risk factors.[29] In Asia as a whole, all-age mortality attributable to air pollution increased by nearly 10% between 2010 and 2015, whereas among children younger than 5 years, it decreased by nearly 30%. In China, all-age mortality increased by 12% in this period, despite emission controls starting to take effect, which could indicate an enhanced attributable risk from air pollution as other risk factors decline. In India, all-age mortality increased by 8%, close to the population growth, while emissions from fossil fuel (ie, coal) use have grown markedly. It is possible that the increase in exposure to fossil fuel-related air pollution has been offset by a decrease in household air pollution through the replacement of solid biofuels by cleaner alternatives, particularly liquified petroleum gas, in households.[30]

In conclusion, a three-pronged strategy is needed to reduce the health effects of ambient air pollution in children: aggressive reduction of air pollution levels, improvements in nutrition, and enhanced treatment of air pollution-related health outcomes. Progress on nutrition and health care is crucial, but will not be enough, given the global shift that we found in AAP-LRI mortality from children younger than 5 years to adults older than 60 years, and the shift in air pollution-related mortality more generally from respiratory causes to cardiovascular diseases.

Contributors

JL planned the research and AP did the model calculations.
JL, AH, and AP analysed the results and wrote the paper.

Declaration of interests

We declare no competing interests.

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