Global trends in ozone concentration and attributable mortality for urban, peri-urban, and rural areas between 2000 and 2019: a modelling study

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Summary

Background Data on long-term trends of ozone exposure and attributable mortality across urban–rural catchment areas worldwide are scarce, especially for low-income and middle-income countries. This study aims to estimate trends in ozone concentrations and attributable mortality for urban–rural catchment areas worldwide.

Methods In this modelling study, we used a health impact function to estimate ozone concentrations and ozone-attributable chronic respiratory disease mortality for urban areas worldwide, and their surrounding peri-urban, peri-rural, and rural areas. We estimated ozone-attributable respiratory health outcomes using a modified Global Burden of Diseases, Injuries, and Risk Factors 2019 Study approach. We evaluate long-term trends with linear regressions of annual ozone concentrations and ozone-attributable mortality against time in years, and examined the influence of each health impact function input parameter to temporal changes in ozone-attributable disease burden estimates for 12 946 cities worldwide by region, from 2000 to 2019.

Findings Ozone-attributable mortality worldwide increased by 46% from 2000 (290 400 deaths [95% CI 151 800–457 600]) to 2019 (423 100 deaths [95% CI 223 200–659 400]). The fraction of global ozone-attributable mortality occurring in peri-urban areas remained unchanged from 2000 to 2019 (56%), whereas urban areas gained in their share of global ozone-attributable burden (from 35% to 37%; 54 000 more deaths). Across all cities studied, average population-weighted mean ozone concentration increased by 11% (46 parts per billion [ppb] to 51 ppb). The number of cities with concentrations above the WHO peak season ozone standard (60 μg/m³) increased from 11 568 (89%) of 12 946 cities in 2000 to 12 433 (96%) cities in 2019. Percent change in ozone-attributable mortality averaged across 11 032 cities within each region from 2000 to 2019 ranged from –62% in eastern Europe to 350% in tropical Latin America. The contribution of ozone concentrations, population size, and baseline chronic respiratory disease rates to the change in ozone-attributable mortality differed regionally.

Interpretation Ozone exposure is increasing worldwide, contributing to disproportionate ozone mortality in peri-urban areas and increasing ozone exposure and attributable mortality in urban areas worldwide. Reducing ozone precursor emissions in areas affecting urban and peri-urban exposure can yield substantial public health benefits.

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Introduction

Decades of scientific literature have shown an association between exposure to tropospheric ozone, a harmful air pollutant, and short-term and long-term respiratory and cardiovascular diseases.[1–5] The recent availability of fine resolution ozone surface estimates[6,7] has enabled the estimation of ozone concentrations and ozone-attributable mortality burdens at global, regional, and national scales, along with their temporal trends.[3,7] A study published in 2021 by DeLang and colleagues[7] reported the fine (0·1°) resolution estimates of global ozone season daily maximum 8 h mixing ratio (OSDMA8) concentrations for 1990 to 2017. The study applied M3Fusion[6] and Bayesian Maximum Entropy Data Fusion (BME)[7–9] in sequence to fuse ozone ground measurement data from the Tropospheric Ozone Assessment Report[10,11] and the Chinese National Environmental Monitoring Center Network, representing 8834 monitoring sites globally, with nine chemical transport model estimates.[7] Authors subsequently examined temporal and spatial trends globally and found that ozone exposure is increasing worldwide. A positive trend in global population-weighted OSDMA8 concentration over the period of 1990 to 2017 was attributed, in part, to strong positive trends in highly populated and polluted regions of Asia and Africa.

Estimates of OSDMA8 concentrations from the study by DeLang and colleagues were included in the Global Burden of Disease (GBD) 2019 study and were used to estimate ozone-attributable chronic obstructive pulmonary disease (COPD) burdens worldwide (365 000 deaths),

Research in context

Evidence before this study
We searched PubMed and Google Scholar for publications between Jan 1, 2019, and June 15, 2022, for studies assessing temporal trends in ozone exposure and attributable health risks in urban areas worldwide, limiting our search to articles published in English. Previous studies have estimated ozone concentrations and ozone-attributable mortality at national and regional scales, as well as subnationally for urban, peri-urban, peri-rural, and rural areas worldwide. However, the availability of information on temporal trends in ozone exposure and its associated mortality burden across cities is scarce, only available for subsets of urban areas, and only for short time periods.

Added value of this study
Our results advanced on previous studies by extending the global coverage of ozone exposure and attributable burden estimates to urban areas, including thousands of cities, as opposed to hundreds of cities, as well as for peri-urban and rural areas worldwide, and provide a longer temporal record of city-level trends (2000–19) than previously reported. Over this period, exposure to ozone disproportionately burdened populations residing in peri-urban areas worldwide.

Implications of all the available evidence
Global ozone concentrations are increasing and substantially burdening the health of populations residing in urban and peri-urban areas worldwide. Mitigating ozone precursor emissions in areas affecting urban and peri-urban exposure can yield substantial public health benefits.

as well as at regional, national, and subnational scales for selected countries. To advance the understanding of how ozone exposure and attributable disease burdens vary within countries, we previously used OSDMA8 estimates from the GBD 2019 study to estimate ozone concentrations and ozone-attributable chronic respiratory disease mortality for urban, peri-urban, and rural areas worldwide in 2019.[12] We estimated that ozone was responsible for 423 100 (95% CI 223 200–659 400) chronic respiratory disease deaths worldwide in 2019. We found disproportionate ozone burdens in peri-urban areas worldwide (238 100 [56%] of 423 100 deaths), where nearly half (3·6 billion [47%]) of the 7·6 billion global population lives. In urban areas, where 3·1 billion (40%) of the 7·6 billion global inhabitants reside, we estimated that 157 000 (37%) deaths were attributed to ozone exposure.

See Online for appendix

Availability of information on spatial and temporal trends in ozone exposure and attributable mortality burden remains scarce, but has the potential to inform national and city governments, international organisations, and global sustainability networks for the purposes of planning, standard and policy setting, and public education. Here we investigate long-term trends of OSDMA8 exposure and ozone-attributable mortality across urban, peri-urban, and rural areas worldwide from 2000 to 2019, as well as trends for 12 946 cities and densely-populated towns worldwide. This study advances beyond previous studies of ozone concentration and attributable mortality trends by extending the global coverage to thousands of cities, as opposed to hundreds of cities, and provides a longer temporal record of city-level trends from 2000 to 2019.

Methods

Overview

In this modelling study, we used methods described by a previous study estimating ozone concentration and associated mortality in 2019,[12] which applied a health impact function[3,13–15] to estimate ozone concentrations and ozone-attributable chronic respiratory disease mortality for urban areas worldwide, and their surrounding peri-urban, peri-rural, and rural areas (appendix p 2). We follow a modified GBD 2019 approach for estimating ozone-attributable health burdens, which include respiratory health outcomes only, and do not include other acute and short-term health effects associated with ozone exposure.

Population-weighted ozone concentrations

We used estimates of OSDMA8 from 2000 to 2019 from the GBD 2019 study, based on findings from DeLang and colleagues.[8] OSDMA8 is calculated as the annual maximum of the six-month running mean of the monthly average daily maximum 8 h mixing ratio, including up to March of the following year to contain the Southern Hemisphere summer. By scaling relative to fine resolution global model output, DeLang and colleagues downscaled M3Fusion-BME model output to create fine (0·1°) resolution estimates of OSDMA8. For the GBD 2019 study, the Institute for Health Metrics and Evaluation extrapolated the available estimates to 2019 using log-linear trends based on 2008–17 estimates. Yearly global population estimates at 1 km (about 0·0083°) resolution were from WorldPop.[16] We regridded OSDMA8 data to match the resolution of the WorldPop dataset. Despite the availability of previous year OSDMA8 concentrations from DeLang and colleagues,[7] WorldPop estimates begin with the year 2000, and thus our analysis was constrained to 2000–19.

To evaluate ozone trends, we calculate population-weighted ozone concentrations to incorporate spatial distributions of population in our estimation of ozone exposure (equation 1):

$$PWC_{k,g} = \sum(Pop_{k,g} \times Conc_{k,g}) \div \sum Pop_{k,g} \quad (1)$$

Pop is the population, and *Conc* is the concentration of ozone, at the grid cell (*g*) within a geographical extent (*k*), such as the spatial boundary of a city.

Ozone-attributable risk estimation

We calculated attributable fraction at the grid-cell level (equation 2), which represents the proportion of disease burden that would be eliminated if the risk factor were reduced to the counterfactual pollutant concentration or theoretical minimum risk exposure level:[15]

$$AF_g=(1-e^{-\beta(Xg-Xc)}) \quad (2)$$

β is the model-parameterised slope of the log-linear relationship between concentration and health endpoint from epidemiological studies, *X* represents the spatially and temporally resolved grid-cell level (*g*) ozone concentration estimates, and *Xc* represents the theoretical minimum risk exposure level.

We then calculate ozone-attributable mortality (equation 3) within each 1 km grid cell:

$$\Delta M_g=AF_g\times Pop_g\times y_{0c} \quad (3)$$

ΔM is the disease burden (ozone-attributable deaths), *Pop* is the population exposed at grid cell (*g*), and y_{0c} is the baseline mortality or disease rate within country c. Subsequently, ozone-attributable deaths in each grid cell are summed according to geographical extents.

We use a three-year mean of the ozone concentration centred on the year of interest to smooth out year-to-year variability.[3] For the counterfactual concentration, below which health effects are not calculated for ozone, we use the median (32·4 parts per billion [ppb]) of the theoretical minimum risk exposure distribution of ozone used by the GBD 2019 study (29·1 to 35·7 ppb), based on a uniform distribution around the minimum (29·1 ppb) and fifth 35·7 ppb) percentile values observed in a previous study.[4] We use national and subnational baseline disease rates for chronic respiratory disease mortality for all ages from the GBD 2019 study.[3]

We apply a relative risk (RR) for chronic respiratory disease mortality of 1·06 per 10 ppb ozone (95% CI 1·03–1·10) derived by GBD 2019 from a meta-regression of five cohorts from Canada, the UK, and the USA.[2–4,17] GBD 2019 applied these RR estimates for COPD only. However, studies have shown that additional respiratory outcomes are associated with ozone exposure beyond COPD,[1] and the American Cancer Society Cancer Prevention Study II, one of the largest ozone epidemiology studies used to generate the GBD RR estimates, reported RR for total respiratory disease.[4] Therefore, we apply these RR estimates with baseline disease rates for chronic respiratory disease mortality.

To derive estimates for urban, peri-urban, and rural areas worldwide we use a dataset of urban–rural catchment areas (URCA) at 1 km[12] that was modified from a previous dataset[18] (appendix p 2). Urban areas in the URCA dataset are comprised of boundaries for 13 189 cities from the 2015 Global Human Settlement (GHS) Grid Settlement Model (GHS-SMOD)[19] and densely populated towns from the GHS population grid model.[20] Cities are defined as having a minimum population of 0·05 million and at least 1500 inhabitants per km² or a built-up area of at least 50%, and towns as having populations between 20 000 and 50 000. We summarise ozone-attributable chronic respiratory disease mortality estimates according to urban, peri-urban, peri-rural, and rural areas worldwide and by region, and further stratify estimates for urban areas by cities and towns. For 243 (1·8%) cities, data on ozone, population, or baseline chronic respiratory disease mortality were not available. Consequently, our analysis includes the remaining 12 946 (98·2%) cities for which these data were available.

Trend analyses and drivers of change

We did linear regressions of annual ozone concentrations and ozone-attributable mortality against time in years to evaluate long-term trends. We evaluated the influence of each health effect function input parameter, including population, baseline chronic respiratory disease rates, and ozone concentrations, on temporal changes in ozone-attributable disease burden estimates for cities worldwide by region.[21] Using parameters held fixed at 2019 values as a control, we did three simulations, in which we reverted each parameter to 2000 estimates. The proportional effect of each parameter was quantified as the log-transform of the ratio of ozone-attributable chronic respiratory disease mortality obtained from each of these simulations to the net estimated change in ozone-attributable chronic respiratory disease mortality between the years 2000 and 2019.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

We first compared population-weighted ozone and ozone-attributable mortality in URCAs worldwide between 2000 and 2019. We observed clear increasing trends in population-weighted ozone concentration in all URCAs worldwide (figure 1A; appendix p 5). Compared with all other URCAs, peri-urban areas had the greatest annual increase in population-weighted ozone concentration, which increased at an annual rate of 0·25 ppb (SE 0·03 ppb) from 47 ppb in 2000 to 52 ppb in 2019, and the greatest percent change (11%) in population-weighted ozone from 2000 to 2019 (table 1; appendix p 6). In terms of simple average ozone concentration, only hinterland areas had a decrease over the 20-year period (appendix p 23). The areas with the greatest percent change in simple average ozone concentration compared

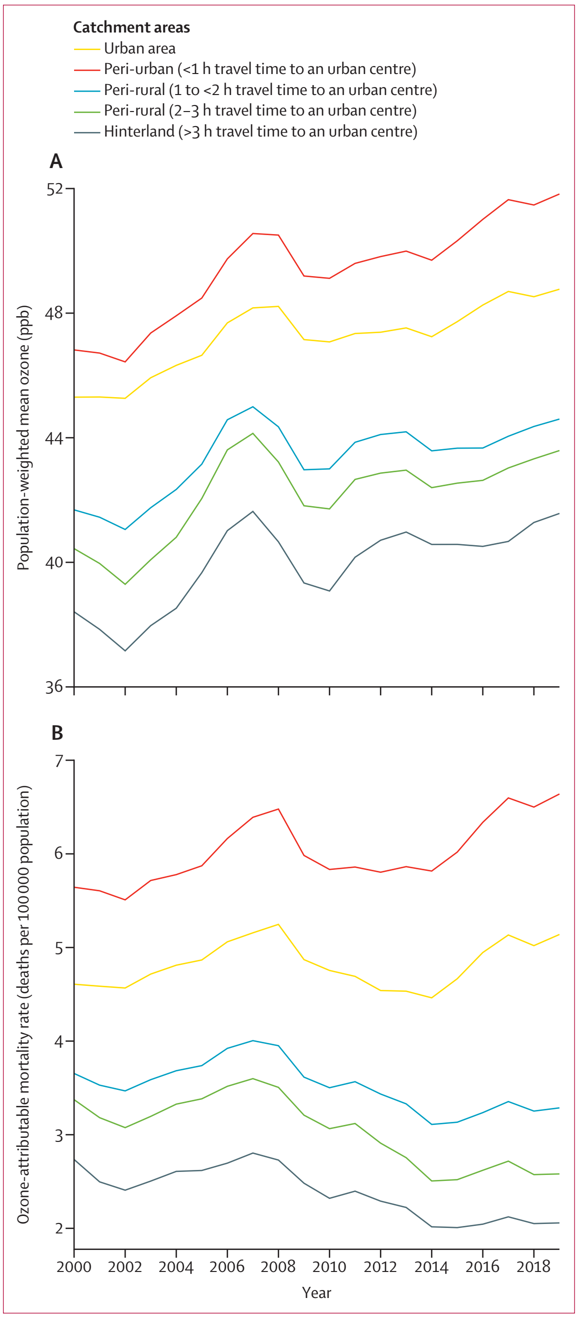

Figure 1: **Population-weighted mean ozone season daily maximum 8 h mixing ratio concentration (A) and ozone-attributable mortality rate (B) by urban–rural catchment area, 2000–19**
ppb=parts per billion.

with all other URCAs from 2000 to 2019 were urban areas (5%) and hinterland areas (–5%).

In 2019, there were 46% more ozone-attributable deaths worldwide than in 2000 (290 400 deaths [95% CI of the central risk estimate 151 800–457 600] in 2000 and 423 100 deaths [223 200–659 400] in 2019; appendix p 6). In 2019, as in 2000, the greatest burden of ozone-attributable deaths was found in peri-urban areas, where nearly half of the world's population resides (table). The share of the total global burden of ozone-attributable mortality by URCA remained roughly consistent from 2000 to 2019, except for urban areas, in which it increased from 35% to 37%, and in peri-rural areas (1–2 h from an urban area), in which it decreased from 7% to 5% (appendix p 6). From 2000 to 2019, ozone-attributable mortality rates increased by 0·04 deaths per 100 000 population (SE 0·01) in peri-urban areas per year and by 0·01 deaths per 100 000 (SE 0·01) in urban areas per year, and decreased by between 0·03 and 0·05 deaths per 100 000 population per year in other URCAs worldwide (figure 1B; appendix p 5). Peri-urban areas had the greatest percent increase (18%), and hinterland areas the greatest percent decrease (25%) in ozone-attributable mortality rate from 2000 to 2019.

Regionally, percent change in population-weighted ozone concentrations by URCA from 2000 to 2019 varied considerably (appendix p 26). 11 (55%) of 20 GBD world regions had decreasing ozone trends across the majority of URCAs within their region, including central Asia, central Europe, and high-income North America. Several high-income regions showed decreasing population-weighted ozone across all URCAs except for urban areas. In high-income Asia Pacific, urban ozone concentrations increased by 8% and hinterland concentrations decreased by 77%, and in western Europe, urban ozone concentrations increased by 1% and in hinterland areas decreased by 21%. South Asia and east Asia, the regions with the greatest share of the global population and ozone-attributable mortality in 2019, showed opposing ozone trends; population-weighted ozone concentration increased across all URCAs in south Asia and decreased across all URCAs in east Asia. In south Asia, the greatest increases from 2000 occurred in urban and peri-urban areas (both 20%). In east Asia, peri-rural and hinterland areas had the greatest percent decreases in population-weighted ozone (ranging from –6% to –9%). Population-weighted ozone concentration increased across all URCAs of sub-Saharan African regions.

For most world regions, percent change in ozone-attributable mortality rates from 2000 to 2019 across URCAs (appendix pp 27–28) followed a similar pattern to that of population-weighted ozone concentration (appendix p 26). For example, both population-weighted ozone concentrations and ozone mortality rate increased across south Asian UCRAs and were greatest in urban and peri-urban areas. Additionally, similar increases in both population-weighted ozone concentrations and ozone mortality rate were observed for all regions of sub-Saharan Africa. Patterns in percent change in population (appendix p 29) and baseline chronic respiratory disease rates (appendix p 30) by URCA also varied substantially by region but did not appear to have similar trends as observed for ozone-attributable mortality rates.

	Average ozone concentration (ppb)			Population-weighted mean ozone concentration (ppb)			Population (millions)			Average baseline chronic respiratory disease mortality rate (per 100 000)			Ozone-attributable chronic respiratory mortality rate (per 100 000)		
	2000	2019	Percentage change	2000	2019	Percentage change	2000	2019	Percentage change	2000	2019	Percentage change	2000	2019	Percentage change
Hinterland (≥3 h*)	39	37	–5%	38	42	8%	105	151	44%	38	37	–3%	2·8	2·1	–25%
Peri-rural (2 to <3 h*)	41	41	2%	40	44	8%	94	123	30%	40	38	–5%	3·4	2·6	–24%
Peri-rural (1 to <2 h*)	41	42	2%	42	45	7%	541	657	21%	42	41	–2%	3·7	3·3	–11%
Peri-urban (<1 h*)	44	45	4%	47	52	11%	2859	3586	25%	47	47	0%	5·6	6·6	18%
Urban	46	48	5%	45	49	8%	2236	3055	37%	54	53	–2%	4·6	5·1	11%
Towns (20 000–50 000 population)	46	48	5%	45	48	7%	145	214	48%	53	51	–4%	4·4	4·9	11%
Cities† (>50 000 population)	46	48	5%	45	49	8%	2092	2842	36%	54	53	–2%	4·6	5·2	13%
Worldwide	41	39	–3%	45	50	11%	5839	7572	30%	41	39	–5%	5	5·6	12%

OSDMA8=ozone season daily maximum 8 h mixing ratio. ppb=parts per billion. GHS=Global Human Settlement. *Travel time to an urban centre. †Cities represent 12 946 GHS Settlement Model grid cities.[19]

***Table:* Percent change in simple average and population-weighted mean OSDMA8, all-age population, average baseline chronic respiratory disease rate, and ozone-attributable chronic respiratory disease mortality, from 2000 to 2019 by urban–rural catchment area.**

To understand how ozone concentrations and attributable mortality vary between urban areas, we evaluated estimates at the city level (excluding towns) for 12 946 cities. Population-weighted mean ozone concentration, averaged across all 12 946 cities worldwide, increased by 11%, from 46 ppb in 2000 to 51 ppb in 2019 (appendix p 7). The percentage of cities worldwide with OSDMA8 concentrations greater than the 2021 WHO ozone peak season standard of 60 μg/m³ (~30 ppb) increased from 11 568 (89%) of 12 946 in 2000 to 12 433 (96%) of 12 946 in 2019. Trends in annual average population-weighted mean ozone concentration for cities worldwide over this time varied substantially by region (figure 2A; appendix pp 8, 31–37). Annual average population-weighted mean ozone concentrations increased most in south Asia (from 55 ppb in 2000 to 66 ppb in 2019; an annual rate of increase of 0·61 ppb [SE<0·001; appendix 8, 11]) and sub-Saharan Africa (from 35 ppb in 2000 to 46 ppb in 2019; an annual rate of increase of 0·6 ppb [SE=0·01]; appendix pp 8, 11). Urban ozone in regions of central Europe, eastern Europe, high-income North America, western Europe, the Caribbean, central Latin America, and east Asia had decreasing trends. A decreasing trend in population-weighted mean ozone for high-income regions was largely driven by decreases in high-income North America, which had an annual decrease of 0·33 ppb (SE=0·01), from 49 ppb in 2000 to 43 ppb in 2019.

Ozone-attributable deaths in cities increased by 53%: from 95 600 deaths (95% CI 49 900–150 900) in 2000 to 146 400 deaths (77 100–228 700) in 2019 (appendix p 7). The fraction of global ozone-attributable mortality occurring in cities increased from 33% in 2000 to 35% in 2019 and the fraction of total global population increased from 36% in 2000 to 38% in 2019 (appendix p 6). Cities in east Asia and south Asia had the greatest share of city-level ozone-attributable mortality worldwide in 2000 and 2019. Cities of east Asia had the greatest number of ozone-attributable deaths in 2000 (46 400 deaths). Ozone-attributable deaths in east Asian cities decreased between 2008 and 2014, and so by 2019 the greatest number of ozone-attributable deaths were in south Asian cities, where they had increased dramatically from 28 900 deaths in 2000 to 69 500 deaths in 2019.

Percent change in ozone-attributable mortality averaged across 11 032 cities within each region from 2000 to 2019 (appendix p 9) ranged from –62% in eastern Europe to 350% in tropical Latin America. Percent changes in ozone-attributable mortality appeared to correspond to similar changes in population-weighted mean ozone concentrations. Ozone-attributable mortality increases from zero (ie, increases in ozone concentration more than the theoretical minimum risk exposure level) were seen in a total of 1666 cities worldwide from 2000 to 2019; ozone-attributable mortality decreases to zero (ie, decreases in ozone concentrations to below the theoretical minimum risk exposure level; appendix p 10) were seen in 248 cities worldwide. Cities with increases in ozone-attributable mortality from zero in 2000 were predominately in south Asia (n=484), sub-Saharan Africa (n=422), and southeast Asia (n=311). Roughly half (n=134 [54%]) of the 248 cities experiencing decreases in ozone-attributable mortality to zero occurred in central Europe, eastern Europe, and central Asia, primarily driven by decreases in central European cities (n=98).

Trends in annual average ozone-attributable mortality rates (deaths per 100 000) by region closely resembled annual trends for ozone concentrations (figure 2B; appendix p 8), with most super regions showing increasing trends apart from central Europe, eastern Europe, central Asia, and high-income GBD regions (appendix p 8). Southeast Asia, east Asia, and Oceania had increasing population-weighted ozone and decreasing

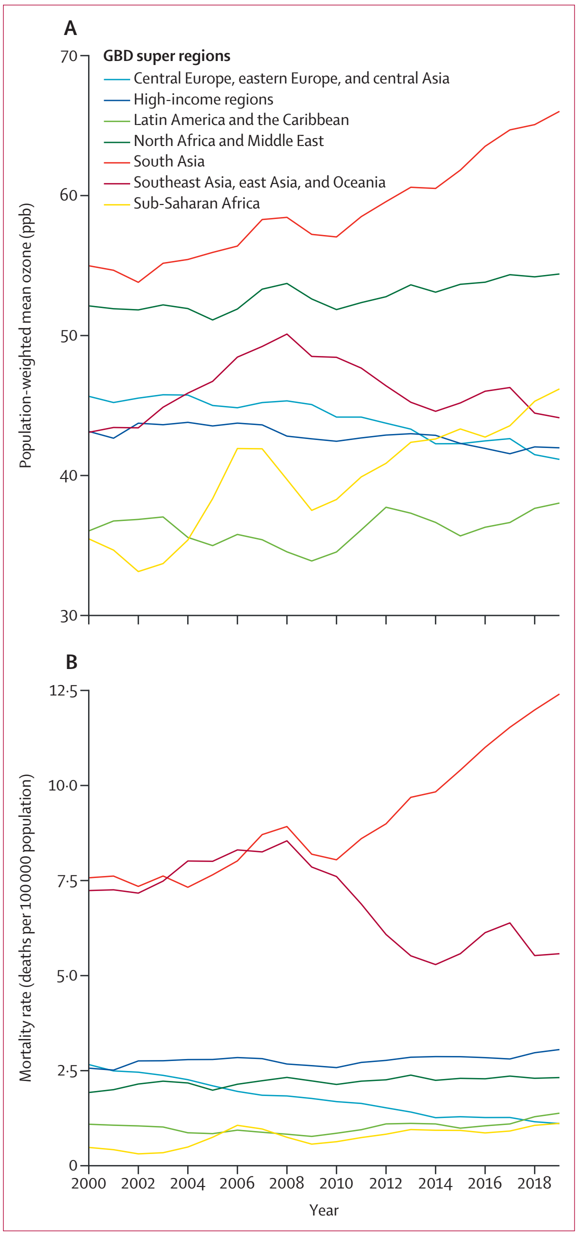

***Figure 2:* Annual average population-weighted mean ozone season daily maximum 8 h mixing ratio concentration (A) and ozone-attributable mortality rate (B) for 12 946 urban areas by GBD super region, 2000–19**
ppb=parts per billion. GBD=Global Burden of Diseases, Injuries, and Risk Factors Study.

ozone-attributable mortality rate trends. For south Asia and east Asia, patterns of population-weighted mean ozone and ozone-attributable mortality were closely matched. Cities of southeast Asia had the greatest percent increase (249%) in ozone-attributable mortality rate over 2000 to 2019 compared with all other regions (appendix p 9); the cities with the greatest decreasing percentage change were within eastern Europe (63%), the Caribbean (40%), and east Asia (27%).

Among the 250 most populous cities worldwide (appendix p 13), population-weighted mean ozone increased by an average of 10% from 2000 to 2019, ranging across cities from –36% to 92% (figure 3A; appendix p 22). Attributable mortality among these 250 cities comprised 37% of the total global ozone-attributable mortality in the year 2000 (36 300 deaths) and 43% of the total global ozone-attributable mortality in 2019 (63 400 deaths). Out of the 250 cities 152 (61%) showed an increase in ozone-attributable mortality rate. Cities with the largest percentage decrease in population-weighted mean ozone were in central Europe (14%), eastern Europe (15%), and the Caribbean (12%). Cities within Latin America, sub-Saharan Africa, south Asia, and southeast Asia showed the greatest increases in population-weighted mean ozone, followed by increases in several high-income regions, including western Europe and high-income Asia Pacific.

Lastly, we found wide regional variation, in terms of the magnitude of their contribution, in drivers of observed trends in estimated ozone-attributable mortality, ozone concentrations, population, and baseline chronic respiratory disease rates (figure 4). We found that in most regions, changes in ozone, followed by population, had the most profound effect on estimated mortality. In a few regions, including high-income Asia Pacific and East Asia, changes in baseline disease rates were key drivers of change in attributable mortality. We also found that, despite decreases in ozone concentrations in some regions, such as in high-income North America and central Latin America, increases in population and baseline disease are continuing to drive increases in ozone-attributable mortality.

Discussion

We estimated that there were 132 900 (46%) more ozone-attributable deaths worldwide in 2019 than in 2000. We found that ozone exposure is increasing worldwide, with the largest increases in population-weighted ozone concentration and ozone-attributable mortality rate occurring in peri-urban areas, where ozone exposure is currently disproportionately affecting health. The fraction of the global burden of ozone-attributable mortality occurring in peri-urban areas remained unchanged from 2000 to 2019 (56%), and the fraction of global population residing in peri-urban areas decreased from 49% to 47%. Urban areas have gained in their share of both global ozone-attributable burden (from 35% to 37%; 54 000 more deaths) and population (from 38% to 40%; 819 million more inhabitants). Projections of the global population show that the proportion of the world's population in urban areas is expected to increase to 68% by 2050, and that cities will absorb virtually all of the future growth of the world's population.[22] These projections, coupled with our findings of increasing urban ozone-attributable burden, suggest that reducing emissions in areas that affect urban ozone exposure will become increasingly important.

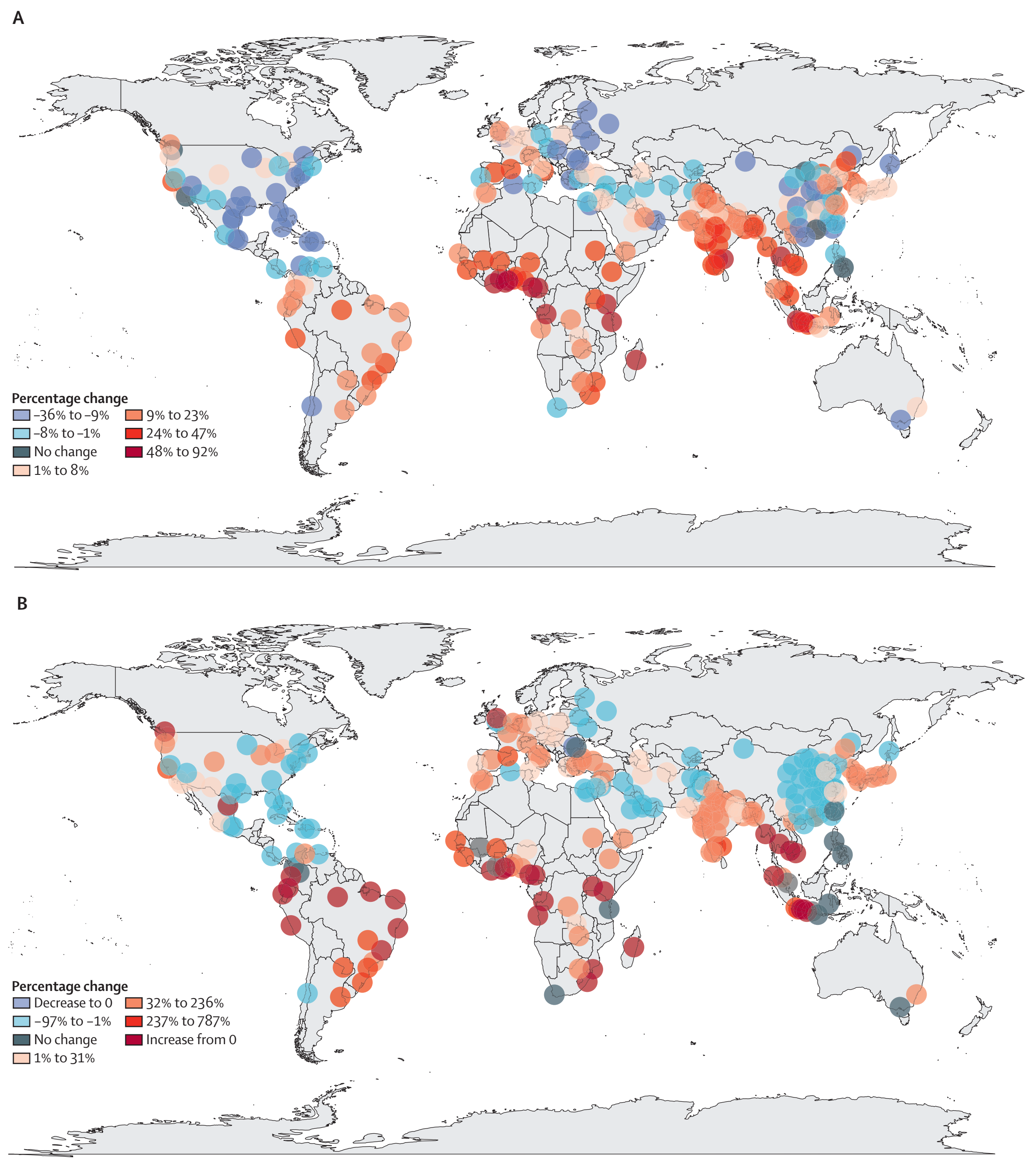

Figure 3: **Percentage change in population-weighted mean ozone season daily maximum 8 h mixing ratio concentration (A) and ozone-attributable mortality rate (B), for the 250 most populous cities worldwide from 2000 to 2019**
Bucharest, Romania was the only city to show a decrease to 0 in ozone-attributable mortality rate.

Our study provides a comprehensive and globally consistent evaluation of long-term ozone and ozone-attributable mortality trends for cities worldwide. We found that across 12 946 cities globally, average population-weighted mean ozone concentration increased between 2000 and 2019 by 11%, from 46 ppb to 51 ppb. The number of cities worldwide with concentrations greater than the WHO peak season ozone standard of 60 μg/m³ (~30 ppb)[23] increased from 11 568 (89%) in 2000 to 12 433 (96%) in 2019. We observed increasing population-weighted mean ozone trends for cities of most world regions, although urban ozone in regions of central Europe, eastern Europe, high-income North America, western Europe, the Caribbean, central Latin America, and east Asia had decreasing trends. Across regions worldwide, trends in annual average

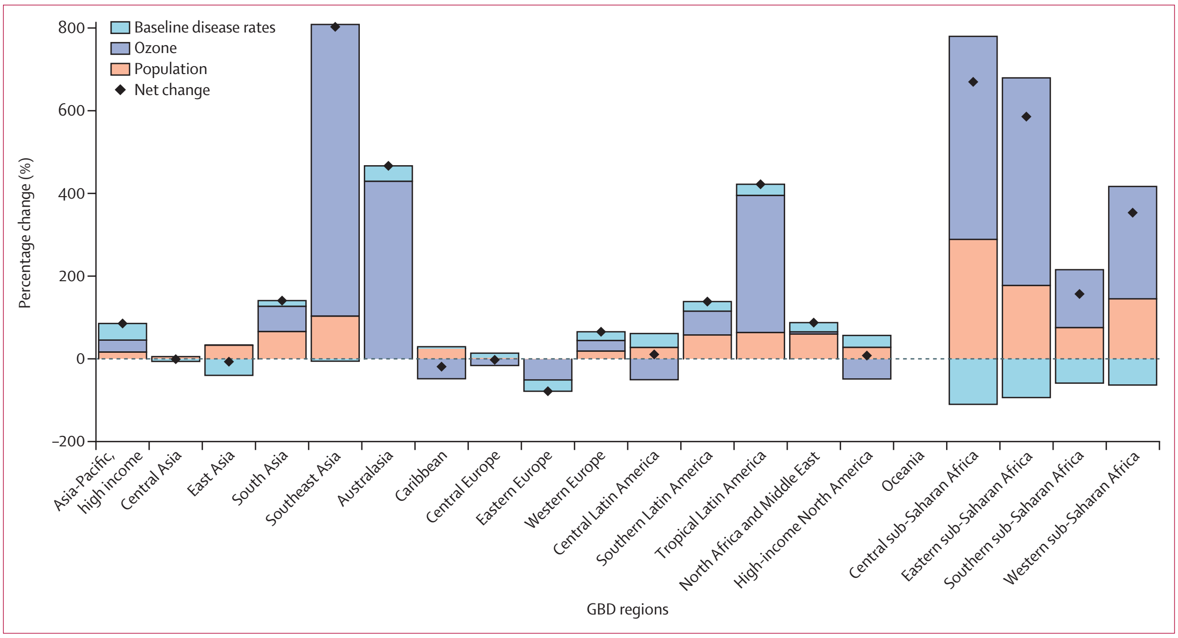

Figure 4: **Percent contribution of health impact function parameters to the change in ozone-attributable mortality from 2000 to 2019 for all urban areas across GBD regions**

Andean Latin America is not included in this figure as ozone-attributable mortality for this region increased from 0 in 2000, which resulted in 2019 with an infinite percent change. GBD=Global Burden of Diseases, Injuries, and Risk Factors Study.

ozone-attributable mortality rates for cities closely followed trends for annual ozone concentrations but appeared to be amplified when average percent changes in population-weighted ozone concentrations and baseline chronic respiratory disease rates were of similar magnitude. Our results are also comparable with existing studies investigating trends in $PM_{2·5}$ and NO_2 concentrations and their attributable disease burden for 13 000 cities worldwide between the years 2000 and 2019 (appendix p 3).[21,24]

Our findings are consistent with previous studies, which have observed decreasing ozone trends across URCAs of the USA[25,26] and increasing ozone trends in cities of Europe,[27,28,25] China,[29–34] Brazil,[35] and Iran.[36] We saw declines in ozone and ozone-attributable mortality across all URCAs of high-income North America. Additionally, population-weighted ozone decreased across the majority of the most populated cities in the USA and increased in some cities in western USA. A 2015 study reported similar decreasing trends during summer and winter, across urban, suburban, and rural locations and across all regions of the country, showing the large-scale success of US control strategies targeted at decreasing peak ozone concentrations.[26] A 2021 study of cities within EU member countries reported increasing trends of ozone concentrations and ozone-related deaths between 2000 and 2017. Although we similarly observed increasing urban ozone trends in urban areas of western Europe, we dissimilarly found decreasing trends in population-weighted ozone concentrations across urban areas of central and eastern Europe. We speculate that variation in ozone concentrations by URCAs both within and across regions could reflect differing sensitivity regimens for ozone to nitrogen oxides (NOx) and volatile organic compounds (VOC), as shown in previous studies.[26,34,37] Further evaluation of NOx–O_3-VOC regimens across URCAs, as well as other key drivers of ozone concentration trends across regions, is needed.

As we identified in our previous analyses of ozone and ozone-attributable mortality in 2019,[12] our study and methodology have several important limitations and uncertainties (appendix p 4). In addition to being unable to account for all the uncertainties inherent in the health impact assessment inputs and assumptions, the availability of ozone monitoring data, as well as information on population and baseline chronic respiratory disease, remains scarce in some regions, and particularly for low-income and middle-income countries. Furthermore, ozone estimates in these regions are based primarily on bias-corrected model estimates. Consequently, sparse data availability in these regions contributes to greater uncertainty and a reduced capability to resolve fine-scale differences in urban and peri-urban areas.

Despite these limitations and uncertainties, our results advance beyond previous studies by extending the global coverage to thousands of cities, as opposed to hundreds of cities, and provide a longer temporal record of city-level trends than previously reported. Additionally, our findings provide a consistent characterisation and analysis of ozone exposure and attributable burden by URCA worldwide, showing the importance of peri-urban areas for ozone-related health effects. Lastly, our results highlight the influence of demographic factors, including population and baseline disease, in shaping ozone burden worldwide, and the need for these factors to be considered by air pollution mitigation strategies. For example, despite decreases in baseline chronic respiratory disease risk in regions of Asia and Africa, ozone concentrations and population are continuing to drive ozone-attributable chronic respiratory disease mortality in these regions, and thus ozone precursor emissions in these regions are of increasing importance. Our results can be used by policy makers to inform air pollution and climate change mitigation actions by individual cities and across cities that are members of urban sustainability networks.

Contributors

SCA and DAM conceptualised the project; MND, JSB, MLS, JJW, K-LC, and ORC contributed to the development and verification of the ozone dataset used in this analysis. DAM did the analysis and had primary responsibility for writing the manuscript, to which all authors contributed. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Declaration of interests

The views in this manuscript are those of the authors alone and do not necessarily reflect the policy of their employers. DAM declares employment relationship with the US Environmental Protection Agency not affiliated with the submitted work. All other authors declare no competing interests.

Data sharing

Baseline disease rates from the Institute for Health Metrics and Evaluation (IHME) are available from http://ghdx.healthdata.org/gbd-results-tool. WorldPop datasets are available at www.worldpop.org/. Ozone datasets are available upon request from JJW (jasonwest@unc.edu). The estimated urban ozone-attributable concentrations and mortality results are available at https://blogs.gwu.edu/sanenberg/.

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