

Long-term trends in urban NO₂ concentrations and associated pediatric asthma incidence: estimates from global datasets

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Abstract

Background: Combustion-related nitrogen dioxide (NO₂) air pollution is associated with pediatric asthma incidence. We estimated global surface NO₂ concentrations consistent with the Global Burden of Disease Study for 1990-2019 at 1km resolution, and concentrations and attributable pediatric asthma incidence trends in 13,189 cities from 2000-2019.

Methods: We scaled an existing surface annual average NO₂ concentrations dataset for 2010-2012 from a land use regression model (based on 5,220 NO₂ monitors in 58 countries and land use variables) to other years using NO₂ column densities from satellite and reanalysis datasets. We applied these concentrations to epidemiologically-derived concentration-response factors, population, and baseline asthma rates to estimate NO₂-attributable pediatric asthma incidence.

Findings: We estimated that 1.85 million (95% uncertainty interval: 0.93 – 2.8 million) new pediatric asthma cases were attributable to NO₂ globally in 2019, two-thirds of which occurred in urban areas. The fraction of pediatric asthma incidence that is attributable to NO₂ in urban areas declined from 20% in 2000 to 16% in 2019. Urban attributable fractions dropped in High-income (-41%), Latin America/Caribbean (-16%), Central Europe, Eastern Europe, and Central Asia (-13%), and Southeast Asia, East Asia, and Oceania (-6%), and rose in South Asia (+23%), Sub-Saharan Africa (+11%), and North Africa and Middle East (+5%) regions. The importance of NO₂ concentrations, pediatric population size, and asthma incidence rates in driving these changes differs regionally.

Interpretation: Despite improvements in some regions, combustion-related NO₂ pollution continues to be an important contributor to pediatric asthma incidence globally, particularly in cities.

Funding: Health Effects Institute, NASA

Research in context:

Evidence before this study: We searched PubMed and Google Scholar databases for studies published in English from the database inception until March 11, 2021, using the search terms (“NO₂” OR “nitrogen dioxide”) AND “asthma” AND “trends”. Previous studies have reported epidemiological analyses linking changes with asthma to changes in NO₂, or have assessed long-term trends in NO₂ concentrations in some countries or world regions. However, these studies provide little information about how NO₂ concentrations are changing in urban areas all around the world, and the influence those changes have on pediatric asthma incidence. An earlier study published in 2019 showed that over 4 million new pediatric asthma cases, representing ~13% of all pediatric asthma incidence worldwide in 2015, could be attributed to NO₂ pollution. Understanding temporal trends in NO₂-attributable pediatric asthma incidence could help inform asthma and air pollution mitigation strategies.

Added value of this study: We show that urban areas experience higher NO₂ concentrations and disease burdens compared with rural areas, with 16% of pediatric asthma incidence in urban areas estimated to be attributable to NO₂ pollution. We also find that the fraction of pediatric asthma incidence that is attributable to NO₂ declined in High-income, Latin American and Caribbean, Central Europe, Eastern Europe, and Central Asia from 2000 to 2019, and increased in the rest of the world, particularly in South Asia and Sub-Saharan Africa. In carrying out this work, we produced the most spatially resolved (1km x 1km) long-term (1990-2019) dataset of surface NO₂ concentrations, which is compatible with the Global Burden of Disease Study and is now publicly available. Our study also demonstrates the utility of satellite remote sensing for environmental and public health surveillance in urban areas worldwide.

Implications of all the available evidence: Current levels of NO₂ contribute substantially to pediatric asthma incidence, particularly in cities. Mitigating air pollution should be a critical element of children’s public health strategies.

Acknowledgements: This work was supported by grants from the Health Effects Institute/Bloomberg Philanthropies (Research Agreement #4977/20-11) and NASA (Grant #80NSSC19K0193). We gratefully acknowledge the developers of the OMI NO₂ concentration products, GHS-SMOD urban area dataset, GBD disease rate datasets, and Worldpop population dataset. We appreciate helpful discussions with Bryan Duncan. The contents of this article do not necessarily reflect the views of HEI, or its sponsors.

Data availability: NO₂ concentrations are available at:
https://figshare.com/articles/dataset/Global_surface_NO2_concentrations_1990-2020/12968114.

Estimated NO₂-attributable asthma incidence results are available at:
https://github.com/AMohegh/Asthma_NO2_urban

Author contributions: SCA, AM, and DG designed the study; PH, AL, and LL provided data; AM and GK carried out the calculations, SCA, AM, DG, MB, PH, AL, and SW contributed input on methods development; SCA and AM wrote the paper; all authors helped interpret results and reviewed the manuscript. AM, GK, and DG have verified the underlying data.

Declaration of interests: The authors declare no conflict of interest.

Introduction

Nitrogen dioxide (NO₂), a component of nitrogen oxides (NO_x), is a pervasive air pollutant that is a precursor for ground-level ozone and fine particulate matter (PM_{2.5}), the leading contributors to air pollution-related mortality.¹ Major anthropogenic NO₂ sources include on-road and non-road transportation tailpipe emissions (including heavy-, medium-, and light-duty vehicles, shipping, and aviation), power plants, industrial manufacturing, and agriculture.^{2–5} NO₂ is an effective tracer for anthropogenic fuel combustion generally, and traffic specifically, especially in urban areas.^{6–9} NO₂ concentration trends can be used to evaluate the efficacy of air pollution regulations, as well as effects of abrupt emission changes (e.g. power plant closures, new oil and gas fields, COVID-19 lockdowns).^{10–14}

Beyond its role in PM_{2.5} and ozone formation, NO₂ itself has been associated with adverse health outcomes including asthma exacerbation.^{15,16} Epidemiological studies have also found associations between transportation-related air pollutants with new onset asthma in children.^{17,18} While the putative agent in the traffic-related air pollution mixture remains unknown, epidemiological studies are relatively consistent in their finding that NO₂ is significantly associated with pediatric asthma incidence, while the evidence for other traffic-related air pollutants (e.g. PM_{2.5}) is more mixed.^{17,18} Previous health impact assessments have linked NO₂ with ~13% of the global pediatric asthma burden, and up to ~50% in the most populated 250 cities worldwide.^{19,20}

NO_x emissions and NO₂ concentrations have changed dramatically in response to socioeconomic changes and regulation, even prior to the large-scale activity changes during the COVID-19 pandemic.^{21–25} In the U.S., average NO₂ concentrations dropped ~50% from the 1980s to 2010s,²⁶ with larger drops near major roadways²⁶ and point sources.¹⁰ In the last two decades, U.S. NO_x emissions fell ~3–6% per year as vehicles got more fuel efficient and cleaner and power plants shifted from coal to relatively cleaner fuels (e.g. natural gas).^{11,27,28} NO₂ concentrations have also decreased in Europe, though more slowly.^{29,30} In contrast, NO₂ has increased in India,³¹ the Middle East,³² and Eastern Europe.²³ In China, NO_x emissions peaked around 2011/2012 and subsequently declined.^{33–35}

NO₂ pollution is a pediatric health challenge in cities, driven by higher population growth, particularly in Asia and Africa where NO₂ concentrations have risen since 2000, and higher asthma rates in cities compared with national averages. Previous research on NO₂ temporal

trends have focused on small subsets of cities and have not considered its health impacts, precluding globally consistent comparisons of trends in NO₂ concentrations and associated health burdens. The global coverage and long continuous record of satellite remote sensing since the 1990s makes it possible to track NO₂ concentrations globally.^{36–39} Additionally, the high spatial resolution of current satellites can capture NO₂ variation at urban and intra-urban scales.^{40,41}

Here we investigate long-term trends of annual average NO₂ concentrations and associated pediatric asthma burdens in 13,189 urban areas over the past two decades globally. We first generate a new gridded global surface annual average NO₂ concentration dataset from 1990 to 2019 that is compatible with the spatiotemporal coverage of the Global Burden of Disease (GBD) Study. We then explore trends in NO₂ concentrations and attributable pediatric asthma incidence for urban areas from 2000 to 2019, for which estimated concentrations have greater certainty due to available ground monitoring. Finally, we deconstruct the drivers of these trends to explore the influence of NO₂ concentrations versus demographic changes.

Methods

We integrated global environmental and demographic datasets from different sources to generate new estimates of surface NO₂ concentrations globally and NO₂-attributable pediatric asthma incidence in cities. The analysis was done in Python (version 3.6.7).

Globally gridded NO₂ concentrations

We generated a new dataset of surface annual average NO₂ concentrations at 0.0083° (~1 km²) resolution in five-year increments from 1990-2010 and annually from 2010-2019, consistent with the GBD 2020 analysis years. We used an existing global NO₂ concentration dataset (2010-2012 average) at 100m resolution from a land use regression (LUR) model described by Larkin et al.^{8,42} and made adjustments to correct for a high bias in rural areas and to scale concentrations to additional years (Figure S1). A full description of the methods and data sources used to construct the concentration dataset is in the Supplemental Material.

For the base year 2011, we used the Larkin et al.⁴² LUR estimates directly in all gridcells categorized as “urban” according to the Global Human Settlement Model grid⁴³ or that include major roadways. The LUR used annual measurements from 5,220 air monitors in 58 countries (mostly in Europe, North America, and Asia) with inputs from road networks and other land use variables and satellite NO₂ column observations. Globally, the model captured 54% of NO₂ variation, with a mean absolute error of 3.7 ppb. Model performance differed regionally: R² varied from 0.42 in Africa to 0.67 in South America. In North America, Europe, and Asia, R² (0.52 for each region) approximately matched the global average (0.54). For rural areas, we found that the Larkin et al.⁴² dataset was biased high, and therefore adjusted concentrations using surface NO₂ concentrations derived from Ozone Monitoring Instrument (OMI) satellite NO₂ columns (Figure S2). After adjusting the 2011 rural NO₂ concentration estimates, we scaled all 2011 gridcell concentrations to the GBD 2020 analysis period (1990-2019) using the MERRA-2

reanalysis product⁴⁴ for 1990, 1995, and 2000 and OMI NO₂ column densities for 2005-2019 (Figure S3).

As Larkin et al.⁴² demonstrated that their NO₂ concentrations agreed well with urban ground observations, we added evaluations of the changes made in this work: 1) we compared our 2011 rural NO₂ concentration estimates to the European Monitoring and Evaluation Program (EMEP) ground monitoring dataset, which has a large number of stations in rural areas, while “rural” monitors in other ground monitoring networks are often located directly downwind from urban areas; 2) we compared our 2019 concentrations in urban and rural areas against 4,348 monitors in the U.S., Canada, and Europe.

While we created this spatially (all urban and rural areas globally) and temporally complete (1990-2019) concentration dataset for compatibility with the GBD 2020, we focused our trend analysis on urban areas over the last two decades (2000-2019), for which estimated concentrations have greater certainty due to available ground monitoring.

NO₂-attributable pediatric asthma incidence

We estimated NO₂-attributable cases of pediatric asthma incidence using an epidemiologically-derived concentration response function, following previous studies^{19,20} (Equation 1):

$$\text{Equation 1: } Burden_{k,a} = \sum_{\text{Grid cells in } k} Inc_{c,a} \times Pop_{i,j,a} \times (1 - e^{-\beta X_{i,j}})$$

where *Burden* is the NO₂-attributable asthma incidence in city *k* for age group *a*, *Inc* is the baseline asthma incidence rate for age group *a* and country *c*, *Pop* is the population in gridcell *i,j* for age group *a*, β is the concentration response factor relating the NO₂ concentration with increased risk of pediatric asthma incidence, and *X* is the annual average NO₂ concentration in gridcell *i,j*. We regridded all datasets to 1km resolution and estimated NO₂-attributable asthma incidence in each gridcell. We previously found that this resolution balances accuracy with computational efficiency in estimating city-level NO₂-attributable disease burdens.²⁰ We sum results across all gridcells within each city for a city-level total.

We applied a relative risk (RR) of 1.26 [95% uncertainty interval (UI): 1.1 – 1.37] per 10 ppb annual average NO₂ concentration increase from a large epidemiological meta-analysis, and calculated uncertainty in NO₂-attributable pediatric asthma incidence using the statistical error in this RR estimate.¹⁷ As RR error is static over time it does not influence temporal trends. We used a low concentration threshold of 2 ppb annual average NO₂ concentration, the 5th percentile of the minimum concentrations reported by the studies in the meta-analysis. Alternative low-concentration thresholds would not substantially affect estimated trends in NO₂-attributable asthma incidence, since thresholds are applied uniformly across gridcells and only 3% of year-specific urban concentrations were below 2 ppb.

We used population estimates from Worldpop⁴⁵ from 2000-2019 for ages 1-4, 5-9, 10-14, and 15-18 years old at ~1km resolution, and summed results across age groups for total NO₂-attributable pediatric asthma incidence. National baseline annual asthma incidence rates from

2000-2019 were from the GBD 2019 Study. Urban area boundaries were from the GHS-SMOD Urban Centre dataset for 2015 (latest year, applied here to all years).⁴³ We consider gridcells and *in-situ* monitors (used to evaluate the concentration dataset) to be part of an “urban cluster” if they are located in “urban” and “suburban” areas in the GHS-SMOD dataset, defined as areas with >300 people per km² that are part of clusters with >5,000 people. All other gridcells and monitors are considered “rural”. World regions definitions are from the GBD 2019 Study (Table S2 and Figure S4).¹

Drivers of change

To disentangle the drivers of temporal trends in NO₂-attributable pediatric asthma incidence, we isolated the contribution of exposure, population size, and baseline asthma rates using: 1) the core results with annually varying data inputs, and 2) three sets of simulations in which we revert one contributing parameter back to 2000 (see Supplemental Material for more details). Cohen et al.⁴⁶ used a similar approach for disentangling drivers of national PM_{2.5} disease burdens. We ignored interactions between the contributing factors (e.g. the influence of changing NO₂ concentrations on baseline asthma rates), as we considered them to be minor relative to many other influences on these multi-factorial parameters (e.g. the effects of health care advances on baseline asthma rates).

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. SA and AM had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

Our new NO₂ concentration dataset reduces the 2010-2012 Larkin et al.⁴² rural high concentrations bias [mean bias (MB) reduced from 2.4 to 1.0 ppb; Table S1 and Figure S6] and captures observed surface-level concentrations in both urban and rural areas in 2019 (MB = 3.3, 1.7, and 2.3 in Canada, U.S., and Europe, respectively; Figure S7). See the Supplemental Material for further evaluation description and results. Estimated NO₂ concentrations are highest in the most populated regions of the world, including North America, Europe, and South and East Asia throughout the time period (Figure 1). Cities with the 10 highest NO₂ concentrations in 2019 were located in the Middle East (Lebanon, Iraq, Iran), China, and Russia (Figure S8).

We estimated that the global population-weighted average annual mean NO₂ concentration was 6.6 ppb in 2019, leading to 1.85 million (95% UI: 0.93 – 2.8 million) new asthma cases among children worldwide that year, or 8.5% (95% UI: 4.3% – 12.8%) of all pediatric asthma incidence (Figure 2). Approximately two-thirds of NO₂-attributable pediatric asthma incidence occurred in the 13,189 urban areas (1.22 million cases; 95% UI: 0.60 – 1.8 million). Compared with rural areas, urban areas had 2-4 times higher population-weighted NO₂ concentrations (10.6 ppb in urban areas versus 4.2 ppb in rural areas), NO₂-attributable asthma cases (1.22 million versus

0.63 million), NO₂-attributable asthma cases per 100,000 (156 versus 40), and attributable fractions (16.4% versus 4.5%) in 2019.

Focusing on urban areas in the last two decades, we found that annual average NO₂ concentrations decreased by 13%, from 12.2 ppb in 2000 to 10.6 ppb in 2019, with a steady decline from 2011 to 2019 after rising from 2000 to 2011 (Figure 2). NO₂ concentrations in High-income cities exceeded the global average throughout the time period, despite declining 38% from 17.6 ppb in 2000 to 11.0 ppb in 2019 (Figure 3). Contrastingly, concentrations in South Asia and Sub-Saharan Africa rose by 18% (8.6 to 10.1 ppb) and 11% (6.4 to 7.1 ppb), respectively, but remained lower than the global urban average throughout the time period. These large regional groupings of cities obscure contrasting trends between sub-regions in some cases (Figure S9).

We estimated that ~1.2 million pediatric asthma cases in urban areas globally were attributable to NO₂ pollution in both 2000 and 2019, though the rate per 100,000 children declined 14% from 176 to 156 per 100,000 children as the urban pediatric population grew by 12% (Figure 2). High-income cities had the most NO₂-attributable asthma incidence in 2019, with 341,000 cases or 28% of the global urban total, despite having only 14% of the global urban pediatric population (Figure 4 and Table S4). While total NO₂-attributable pediatric asthma cases were in the most populated cities of the world (Figure S10), all 10 highest attributable rates were in the U.S. (Figure S11). Contrastingly, cities in South Asia, with approximately a quarter of the global pediatric population, only accounted for 7% of global urban NO₂-attributable pediatric asthma incidence. NO₂-attributable pediatric asthma incidence rates were also highest in the High-income region (311 attributable cases per 100,000 children) and were an order of magnitude lower in South Asia (50).

The fraction of pediatric asthma incidence that was estimated to be attributable to NO₂ across all 13,189 urban areas globally dropped from 19.7% in 2000 to 16.4% in 2019 (Figure 2). Urban attributable fractions dropped between 2000 and 2019 in High-income (-41%), Latin America and Caribbean (-16%), Central Europe, Eastern Europe, and Central Asia (-13%), and Southeast Asia, East Asia, and Oceania (-6%) regions, and rose in South Asia (+23%), Sub-Saharan Africa (+11%), and North Africa and Middle East (+5%) regions. The large decrease in High-income cities is partly driven by even larger drops in North America (-52%; Figure S8). The 35% increase in Central Europe, Eastern Europe, and Central Asia was driven by >50% increases in Central Asia and Eastern Europe, balanced by a 14% decrease in Central Europe. In 2019, regional urban average attributable fractions ranged from 10% in Sub-Saharan Africa to 20% in Central Europe, Eastern Europe, and Central Asia and North Africa and Middle East. As for concentrations, the 10 highest attributable fractions were located in Lebanon, Iraq, Iran, China, and Russia (Figure S11).

Estimated temporal trends in urban NO₂-attributable pediatric asthma incidence are driven by simultaneous and often competing changes in NO₂ concentrations, pediatric population, and asthma incidence rates (Figure 5). Australasia and High-income Asia Pacific are the only regions where declining concentrations, pediatric population size, and asthma rates all contribute to overall drops in NO₂-attributable pediatric asthma incidence. The opposite occurred in Central,

South, and Southeast Asia, and in North Africa and the Middle East, where concentrations, pediatric population, and asthma rates all rose. In High-income North America, Western Europe, and several other regions, declining NO₂ concentrations were offset by increases in asthma incidence rates and/or pediatric population size. These competing influences changed over time, with declining concentrations becoming more influential over time in North America and Southern Latin America, and population growth becoming more influential in North Africa and Middle East and Southern Sub-Saharan Africa (Figure S12).

Discussion

We estimated that 1.84 million (95% UI: 0.93 – 2.8 million) pediatric asthma cases globally could be attributable to NO₂ pollution in 2019. Despite having only one-third of the global pediatric population, urban areas had two-thirds of NO₂-attributable pediatric asthma incidence. The NO₂-attributable fraction of pediatric asthma incidence in urban areas globally declined from 20% in 2000 to 16% in 2019. Regional trends were inconsistent: urban average attributable fractions dropped in High-income cities; Latin America and Caribbean; Central Europe, Eastern Europe, and Central Asia; and Southeast Asia, East Asia, and Oceania, and rose in South Asia; Sub-Saharan Africa; and North Africa and Middle East. The drivers of temporal trends in NO₂ concentrations and pediatric asthma burdens were also inconsistent regionally, with declining NO₂ concentrations in some regions counteracted by increases in pediatric population size and asthma incidence rates.

Our study is consistent with the broader literature demonstrating that NO₂ is largely an urban pollutant.^{7,47–49} Estimated NO₂ concentration trends are consistent with recent studies using satellite data to investigate NO₂ concentration trends during 2004-2018 for the U.S., Europe, China, India, and Japan.^{23,31,50} For example, Qu et al.⁵¹ also showed a similar decrease in U.S. NO₂ concentrations based on ground observations, satellite data, and modeling outputs from 2006-2016, and Henneman et al.²⁶ showed a similar decrease using ground observations from 1980-2020. A recent study focused on biomass burning in the equatorial Africa region found declining concentrations from 2005 to 2017⁵², while we found an increase in Sub-Saharan Africa from 2000-2019. A biomass burning decline in the region may be smaller and offset by anthropogenic emission changes in populated urban areas.

While our new NO₂ dataset leverages advantages of different data sources, concentrations remain uncertain. Many cities, particularly in low- and middle-income countries (LMICs), still lack ground NO₂ monitors, challenging calibration and evaluation of LUR models.⁴² Urban NO₂ concentrations are therefore more certain in North America, Europe, and Asia, compared with Africa and South America. Rural concentrations are uncertain globally with limited ground monitoring outside of urban areas. Scaling the 2010-2012 LUR NO₂ concentrations to other years assumes that the land use predictors are static over time. This assumption is likely supported by slow changes in road density and volume and urban form, but over the two decades explored here, some land use evolution is likely⁵³, particularly in rapidly developing LMICs. The directional impact of these uncertainties on results is unknown.

Our estimate of the global burden of NO₂ on pediatric asthma incidence in 2019 is less than half of the 4.2 million found by Achakulwisut et al.¹⁹ for 2015. Our results for India are also lower than previous estimates while our U.S. results are higher.^{17,20} Several factors explain this discrepancy. First, our new NO₂ concentrations correct for a high rural NO₂ bias, leading to lower NO₂-attributable asthma incidence estimates, especially in countries with larger rural populations (e.g. India). Second, GBD 2019 baseline asthma rates are much lower than in previous versions, except in high income areas (e.g. U.S.), due to a change in the case definition used which lowered estimated rates in most places and raised them for the U.S.⁵⁴ For example, baseline pediatric asthma incidence rates in 2015 (the year analyzed by Mohegh et al.²⁰) in the GBD 2019 were 81% of GBD 2017 values. Contrastingly, U.S. pediatric asthma incidence rates were a factor of 2.2 higher in the GBD 2019 versus GBD 2017. Changes in baseline asthma rates approximately proportionally affect estimated NO₂-attributable pediatric asthma incidence. Our NO₂ attributable fraction result in High-Income North America in 2019 (17.3%) was similar to a previous estimate for the U.S. in 2000 (17.9%), though our NO₂ concentrations were lower (10.9 ppb in urban areas vs. 13.2 ppb overall).⁴⁷ The different analysis years are important since, as we have shown, NO₂ concentrations trends are changing rapidly.

The health impact assessment method also introduces uncertainties. While we used national pediatric asthma rates, asthma prevalence varies within countries.⁴⁷ Living in urban areas has been associated with increased risk of asthma prevalence in LMICs⁵⁵ and asthma-related emergency department visits and hospitalizations in the U.S.⁵⁶ Similarly, temporal trends in baseline asthma incidence may differ in urban areas compared with national averages, especially in rapidly urbanizing LMICs. If asthma prevalence is higher in urban areas compared with national averages, NO₂-attributable asthma incidence may be underestimated. In addition, it is currently unknown whether pediatric asthma incidence is associated with NO₂, the traffic-related air pollution mixture, or the broader combustion-related air pollution mixture. Finally, the 1km resolution of our NO₂ concentration estimates may not capture areas with co-located steep spatial gradients in concentrations and population, potentially leading NO₂-attributable asthma incidence to be underestimated.

Despite these uncertainties and limitations, our results demonstrate the important influence of combustion-related air pollution on children's health in cities globally. In places that have effective air quality management programs (e.g. U.S., Europe), NO₂ concentrations have been trending downward for decades, with benefits for children's respiratory health. Even with these improvements, current NO₂ levels contribute substantially to pediatric asthma incidence, highlighting that mitigating air pollution should be a critical element of children's public health strategies. For cities that have not benefited from strong local or national-scale air quality management programs, the experience of cities that have such programs demonstrates that addressing combustion-related air pollution can lead to major air quality and public health improvements over relatively short time frames (years). These air quality improvements can be achieved through either end-of-pipe emission control technologies such as catalytic converters or avoiding the combustion in the first place, which would have additional benefits from reduced greenhouse gas emissions.

Our study demonstrates the value of satellite remote sensing and statistical models for tracking NO₂ pollution and for environmental health surveillance at local, national, and global scales. The combination of methods offers strengths beyond the capabilities of each technique alone: a long and consistent observational record of NO₂ column densities from satellites with the high spatial resolution of surface concentration predictions from LUR models. Future studies may leverage these data sources and others, including new satellite sensors that have higher temporal and spatial resolutions, mobile monitoring, distributed ground sensor networks, and chemical transport models, to further improve the accuracy and spatiotemporal resolution of NO₂ concentration estimates. Further, our study shows the importance of considering demographic changes over time for understanding air pollution health risks. Improved and more widely accessible information about disease rates, and capturing population distribution and movement, will enable more accurate and highly resolved air pollution health impact assessments.

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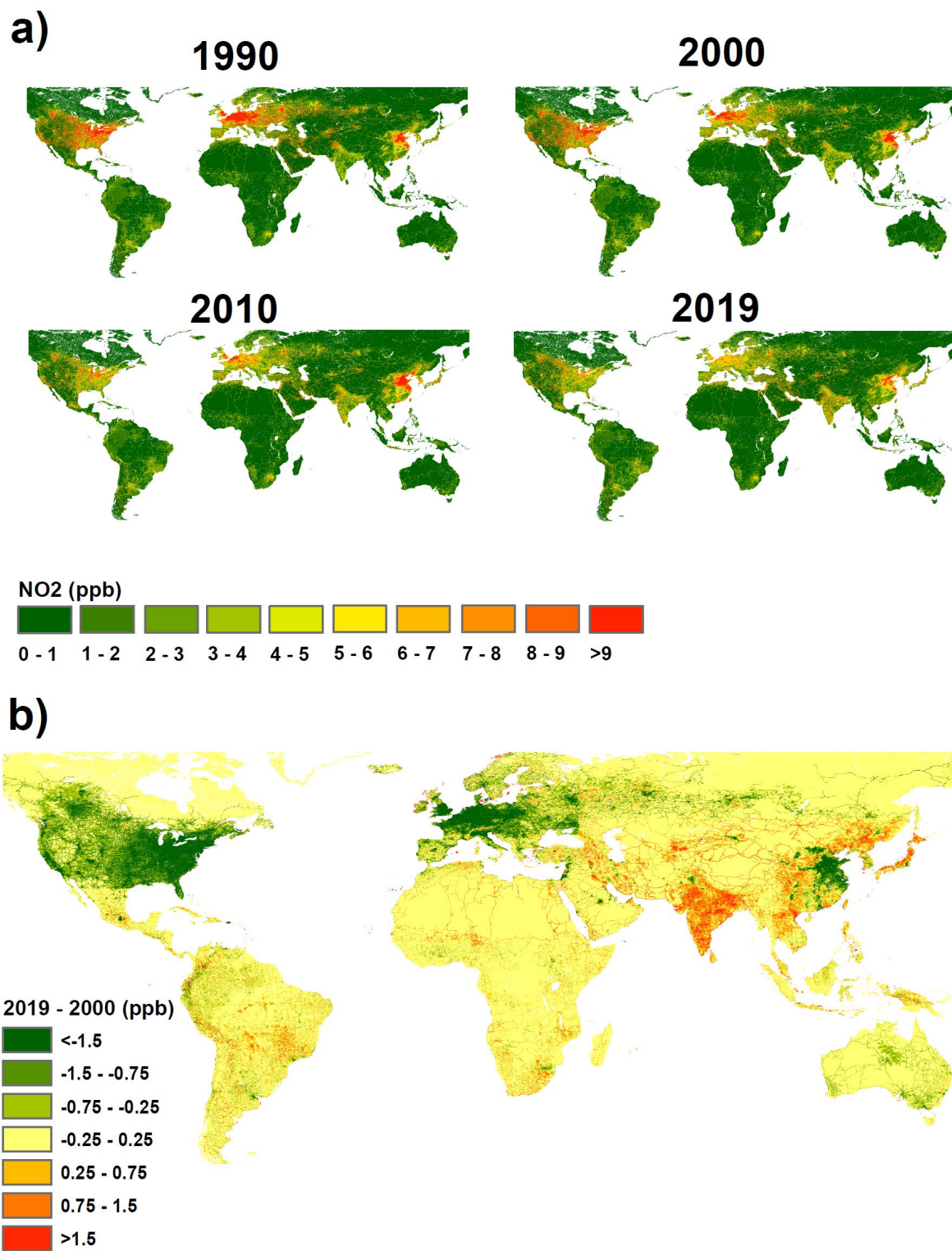
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602 Figure 1. Annual average NO₂ concentrations at 1km x 1km resolution in a) 1990, 2000, 2010
603 and 2019 and b) difference between 2019 and 2000.

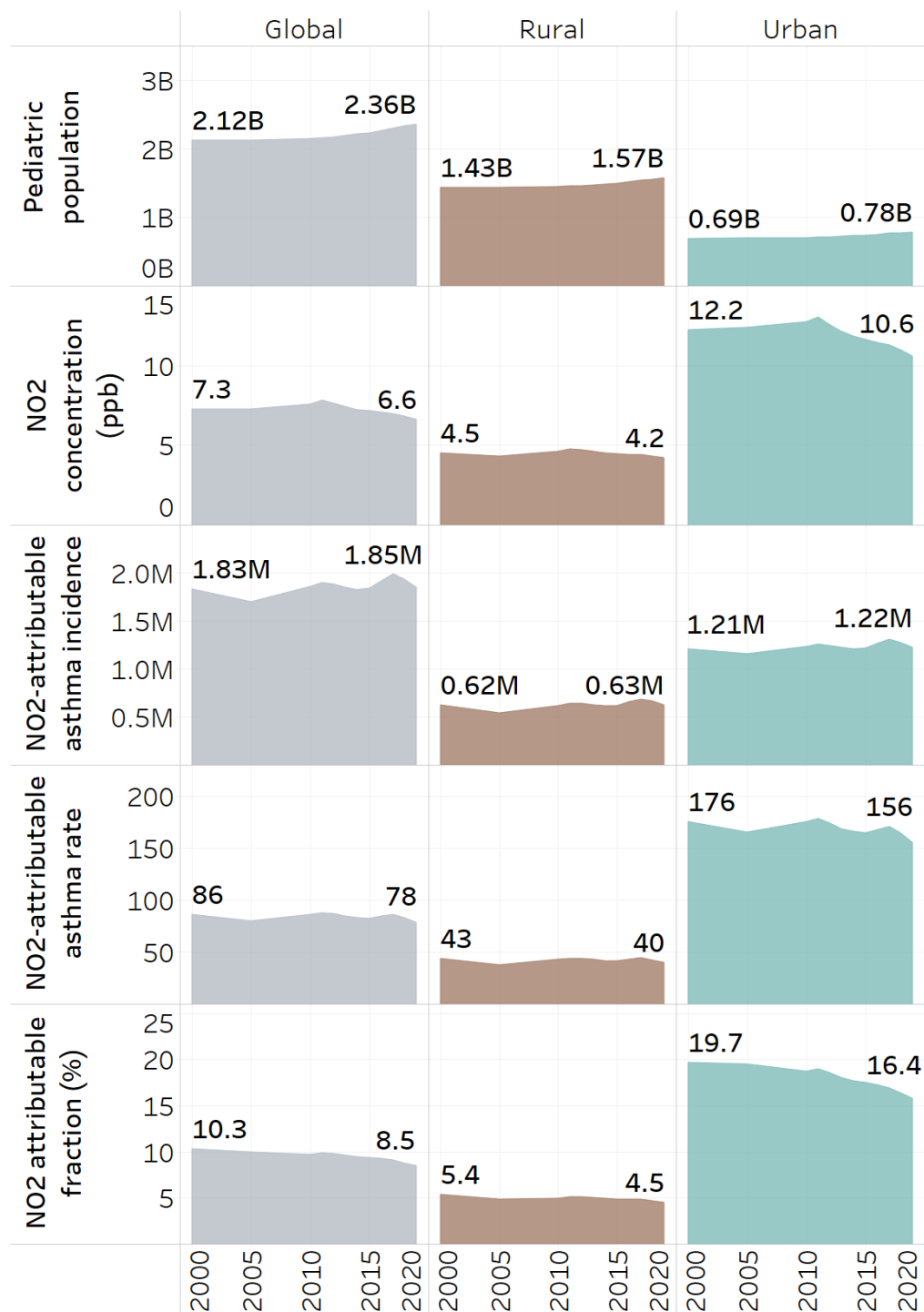
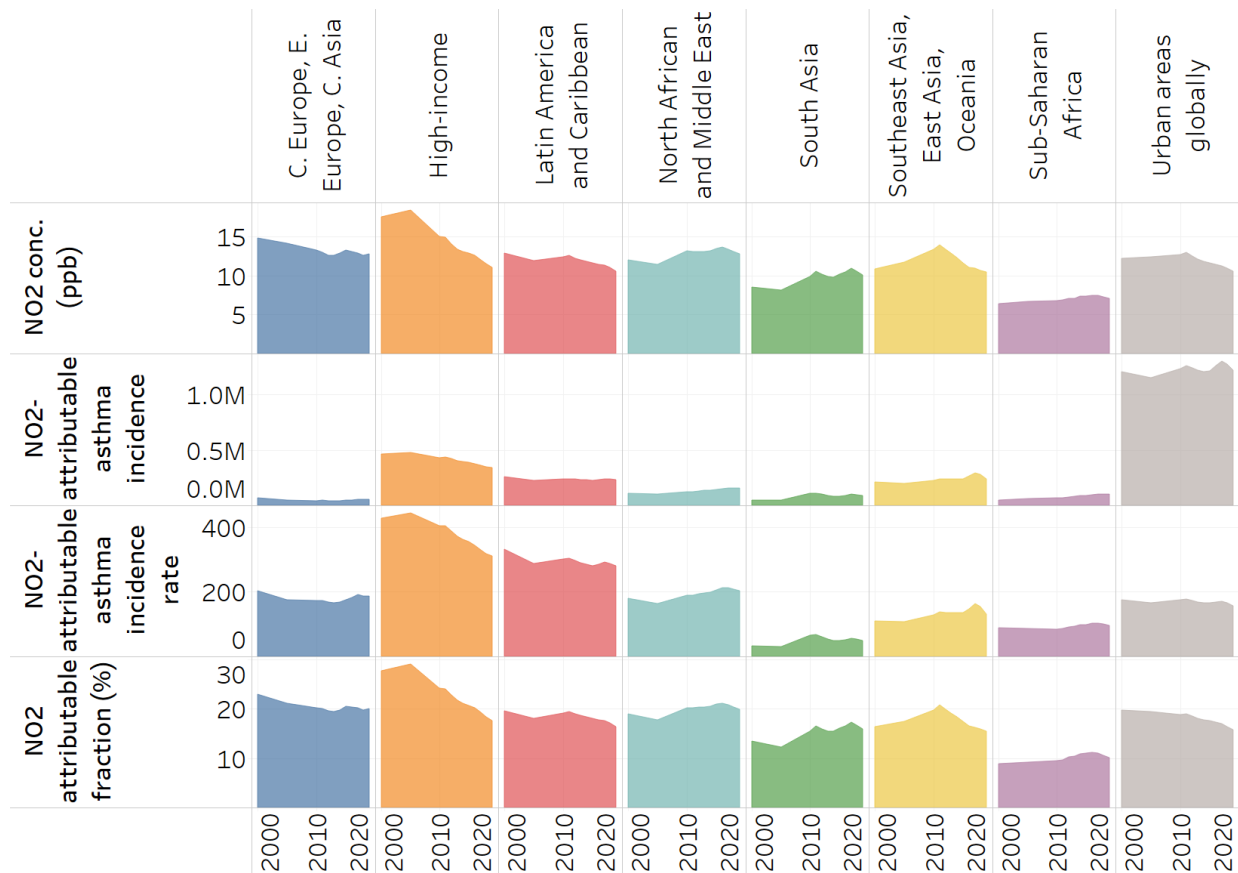


Figure 2. Trends (2000-2019) in population-weighted annual average NO₂ concentrations (ppb), NO₂-attributable pediatric asthma incidence, NO₂-attributable pediatric asthma incidence rate (per 100,000 children), and NO₂ attributable fraction globally (%), in all rural areas, and in 13,189 urban areas. Uncertainty intervals for NO₂-attributable pediatric asthma incidence are not shown since they are based on error in the relative risk estimate, which is constant over time.

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Figure 3. Trends (2000-2019) in population-weighted annual average NO₂ concentrations (ppb), NO₂-attributable pediatric asthma incidence (cases), NO₂-attributable pediatric asthma rates (per 100,000 children), and NO₂ attributable fraction (% of all pediatric asthma incidence) in urban areas in each sub-region. Results for each subregion within each super-region are shown in Figure S8. Uncertainty intervals for NO₂-attributable pediatric asthma incidence are not shown since they are based on error in the relative risk estimate, which is constant over time.

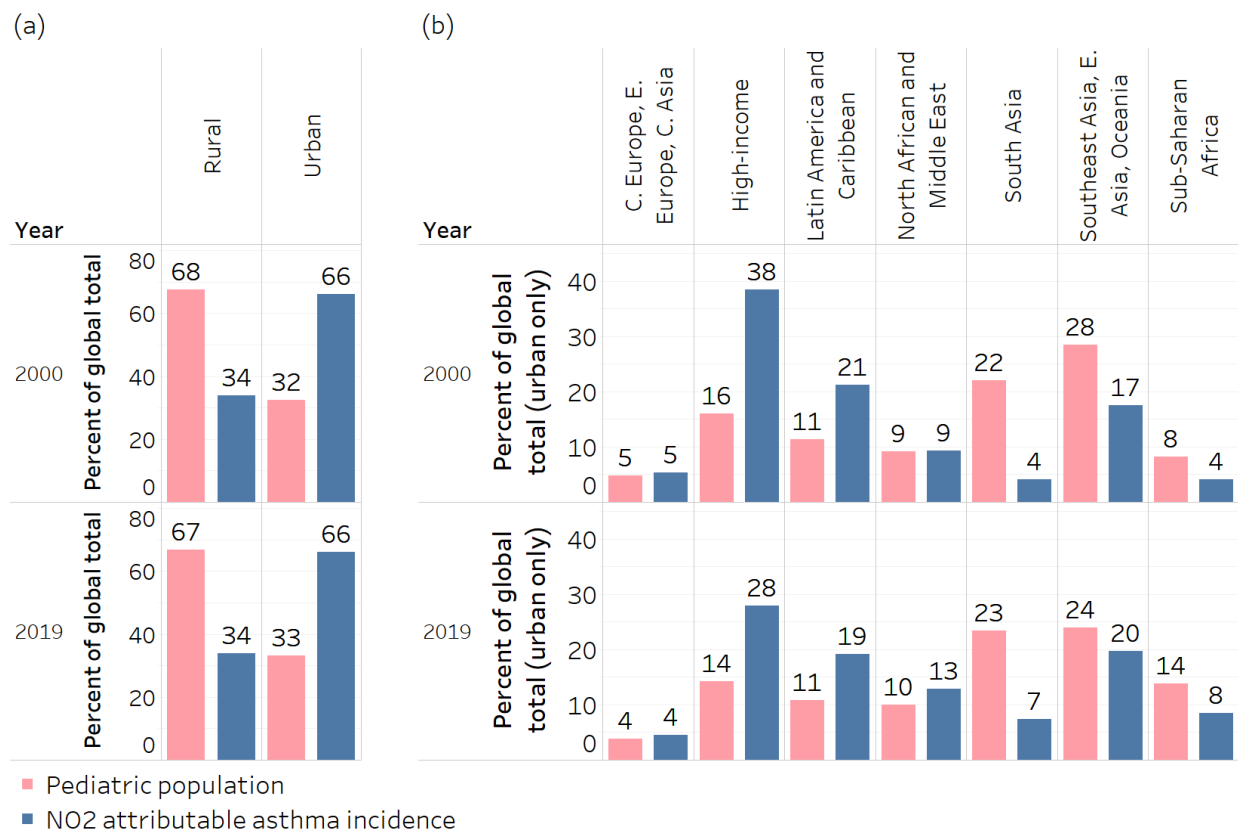


Figure 4. Percent of global total pediatric population and NO₂-attributable asthma cases in 2000 and 2019, for a) all rural areas and 13,189 urban areas globally, and b) urban areas within each region.

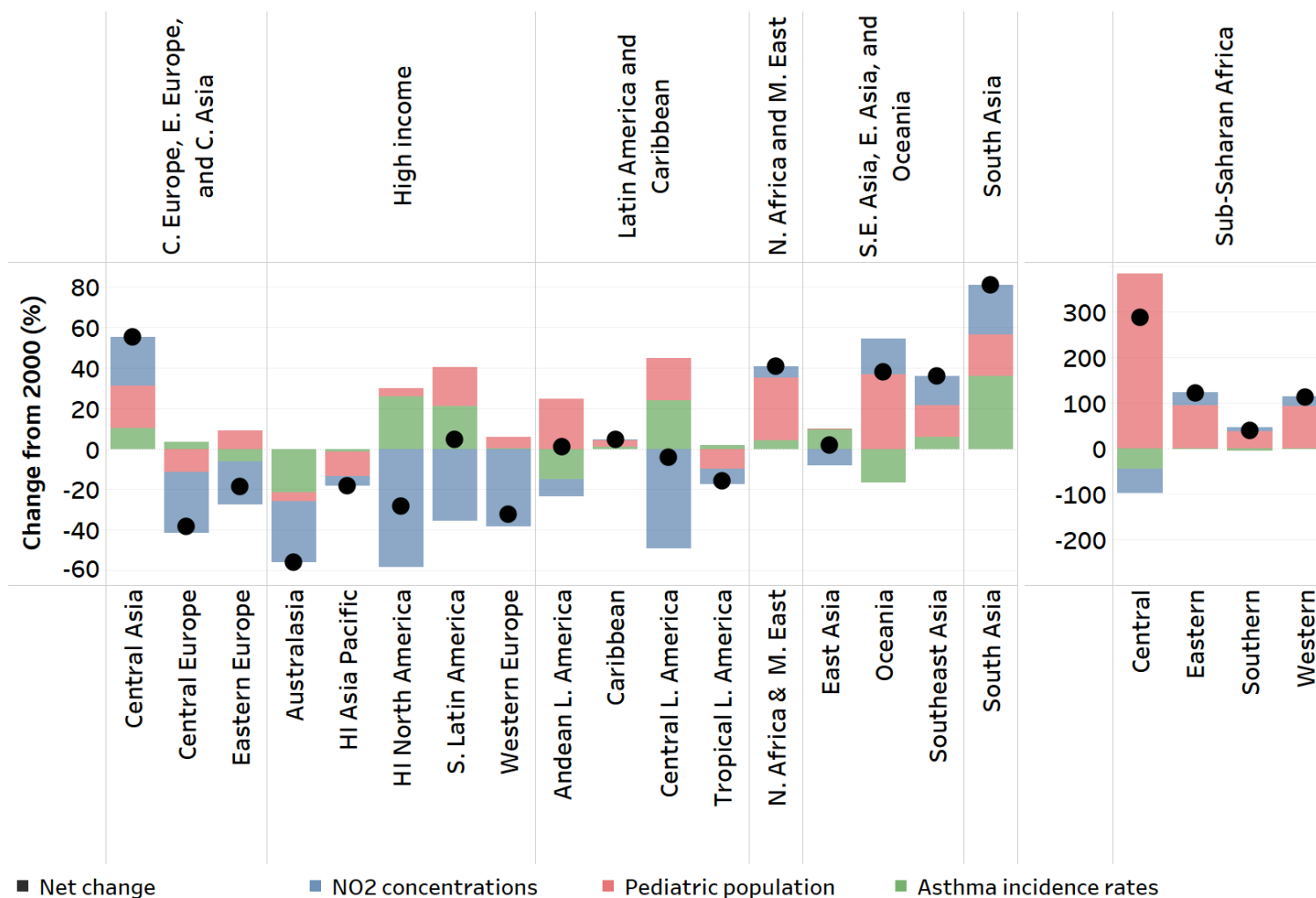


Figure 5. Contribution of pediatric population, baseline pediatric asthma rates, and NO₂ concentrations to changes in estimated NO₂-attributable pediatric asthma incidence between 2000 and 2019 for each sub-region. A different y-axis is used for regions in Sub-Saharan Africa. Results for the full time period are shown in Figure S11.