Assessing the disease burden of air pollution on children and adolescents in China from 1990 to 2019

Guoshuang Feng,[1,7] Juan Xia,[2,7] Xinyu Wang,[1] Hui Xu,[1] Chanjuan Hao,[3] Xin Zhang,[4] Jinlei Qi,[5] Peng Yin,[5] Huiyu Xu,[6] Yayuan Mei,[1] and Maigeng Zhou[5,*]
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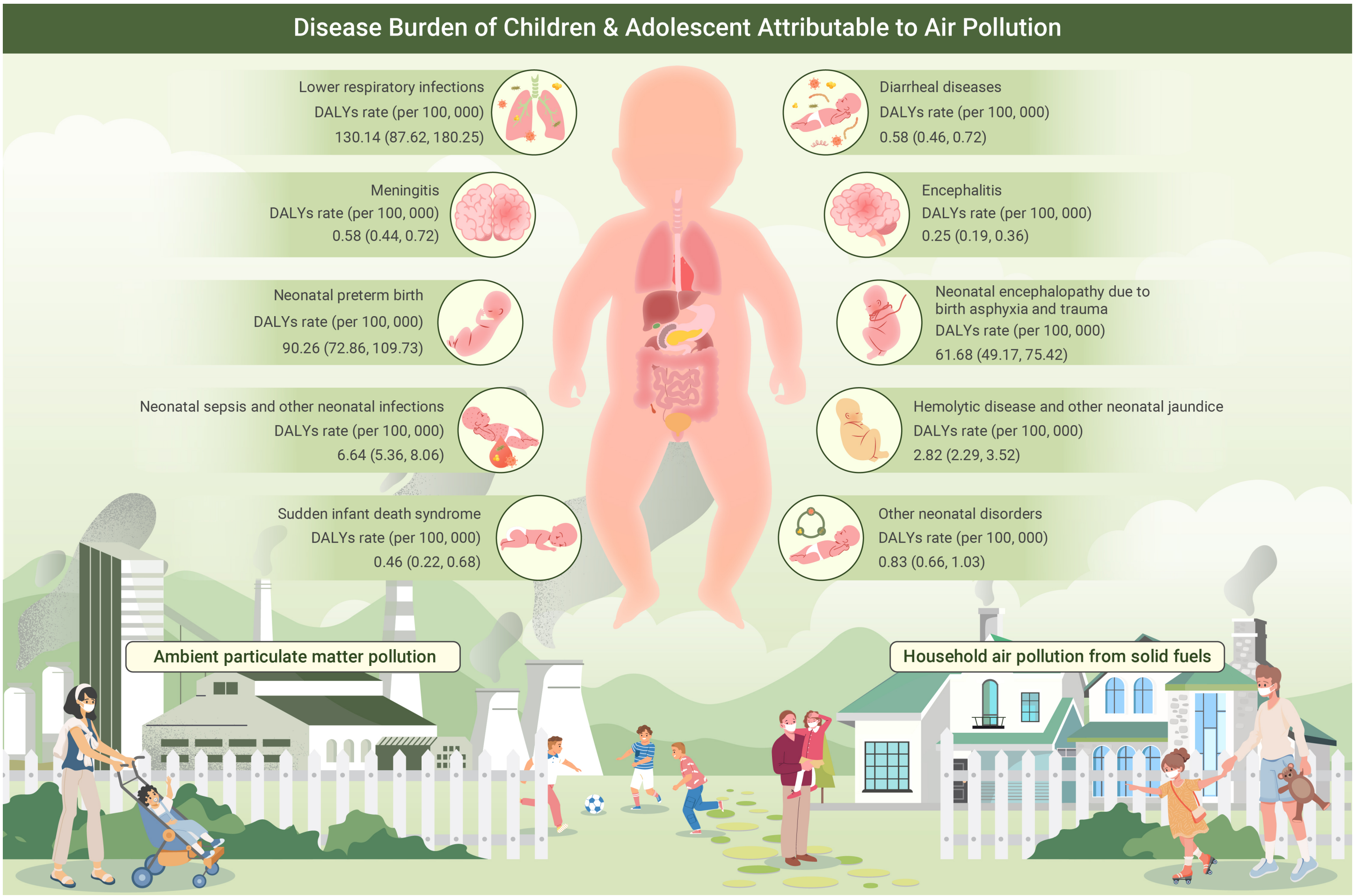
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- The disease burden attributable to air pollution in children decreased significantly from 1990 to 2019.
- Lower respiratory infections and neonatal preterm birth were the main air pollution-related diseases.
- Disease burden attributable to air pollution in children and adolescents varied across provinces.

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Air pollution is a pressing concern in China, particularly its adverse effects on vulnerable populations such as children and adolescents. This study aimed to elucidate the disease burden in children and adolescents attributable to air pollution in geographical areas across China from 1990 to 2019. We used the Global Burden of Diseases, Injuries, and Risk Factors Study 2019 methodology to estimate disease burden attributable to air pollution in 33 areas of China, including provinces, autonomous regions, municipalities, and special administrative regions. In 2019, approximately 10,511 childhood deaths and 932,095 disability-adjusted life-years (DALYs) were attributable to air pollution in China. The DALYs was higher for boys and infants <1 year than it was for girls. Lower respiratory infections, neonatal preterm birth, and neonatal encephalopathy caused by birth asphyxia and trauma were the main air pollution-related diseases. The disease burden attributable to air pollution in children and adolescents decreased significantly from 1990 to 2019; with the average annual percent change (AAPC) of −9.11% ([95%CI, −9.61% to −8.60%], P<0.001) for death rate, and −9.09% ([−9.59% to −8.58%], P<0.001) for DALYs rate. Disease burden attributable to air pollution in children and adolescents varied across provinces, with DALYs rate per 100,000 population ranged from 16.88 in Hong Kong to 2,152.54 in Tibet, peaking in the health area five. These findings highlight the necessity for province-specific research into the impacts of air pollution on childhood health in China, as well as improved air pollution control measures.

INTRODUCTION

Air pollution is a known catalyst for severe health issues, including stroke,[1] respiratory diseases,[2] heart diseases,[3] cancer,[4,5] and other illnesses.[6-9] The pervasive nature of air pollution, even at relatively low-risk thresholds, can have significant adverse health effects across large populations. Air pollution plays a substantial role in accelerating premature mortality and the global disease burden, with estimates indicating that air pollution accounts for approximately 7 million deaths every year, corresponding to one in six deaths worldwide.[10] Air pollution is also an especially pressing issue in China, with estimates showing that air pollution is responsible for more than a million deaths each year.[11,12] China faces the dual challenge of ambient and household air pollution exposure, which has long been a major environmental concern, with levels of fine particulate matter (PM2.5) and other pollutants frequently exceeding recommended guidelines in many cities and regions.[12]

With a population of 1.4 billion in 2020, spread across 31 provinces and municipalities,[13] China exhibits a diverse range of development levels. This diversity has led to a heterogeneous distribution of health risks and impacts across its vast territory. Understanding the disease burden on subpopulations, such as infants and adolescents, is crucial for crafting targeted strategies and prioritizing actions to enhance population health. While several studies have assessed the disease burden attributable to air pollution, the focus has predominantly been on adults,[7,12,14,15] economic impacts,[16–18] or analyses in different countries.[19] Therefore, understanding of the magnitude and regional distribution of the environmental burden among vulnerable populations, such as children and adolescents, is still incomplete. Air pollution poses a significant public health challenge, and affects individuals of all ages. Children and adolescents are especially susceptible because their bodies and immune systems are still developing, and the risk of sustaining lifelong health damage is a major concern.[20–22]

The aim of this study is to provide a comprehensive analysis of the disease burden in children and adolescents attributable to distinct sources of air pollution, namely ambient particulate matter and household air pollution, and to estimate the cumulative impact of overall air pollution. It particularly focuses on the provinces of China over a period spanning from 1990 to 2019, providing an in-depth overview of the regional implications and trends of this critical public health issue.

MATERIALS AND METHODS

Overview

The China Province-Level Disease Burden Initiative, a component of the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) 2019, provides estimates of disease burden for Chinese provinces. In GBD 2019, the disease burden attributable to air pollution was modeled using DisMod-MR 2.1 and a spatiotemporal Gaussian process regression mixed effect model. A comprehensive description of the metrics, data sources, and statistical modelling in GBD 2019 has been documented elsewhere.[12,23] Our estimations focused on exposure to ambient particulate matter pollution (defined as the annual gridded concentration of PM2.5), and household air pollution (defined as the percentage of households using solid cooking fuels and the corresponding exposure to PM2.5) in China. Detailed methodologies for measuring exposure to ambient particulate matter pollution and household air pollution due to use of solid cooking fuels, as well as the estimation of deaths and disability-adjusted life-years (DALYs) attributable to air pollution, have been described extensively elsewhere .[12] In brief, the estimates of ambient PM2.5 exposure in China were obtained from chemical transport model simulations combined with satellite retrievals of aerosol optical depth, calibrated to available ground monitoring data in a Bayesian hierarchical model; and estimates of household air pollution were modeled using a three-step modelling strategy that uses linear regression, spatiotemporal regression, and Gaussian Process Regression. The relative risks for mortality from the outcomes due to ambient and household air pollution were estimated using non-linear integrated exposure-response functions based on published cohort studies, as described elsewhere in detail.[12] The research and data used in GBD 2019 adhere to the standards set by the Guidelines for Accurate and Transparent Health Estimates Reporting. As this study relied solely on de-identified and aggregated data, requirements for informed consent and ethical approval were deemed not applicable.

Table 1. Childhood disease burden attributable to air pollution in China in 2019

	Deaths (95% UI) (thousands)			DALYs (95% UI) (thousands)		
	Air pollution	Ambient particulate matter pollution	Household air pollution from solid fuels	Air pollution	Ambient particulate matter pollution	Household air pollution from solid fuels
Sex						
Boy	6.15 (4.72, 7.76)	4.41 (3.29, 5.77)	1.74 (0.90, 2.84)	545.01 (418.04, 687.92)	391.06 (291.52, 512.22)	153.95 (80.73, 251.44)
Girl	4.36 (3.49, 5.33)	3.12 (2.39, 3.98)	1.24 (0.65, 1.99)	387.09 (309.67, 473.19)	277.17 (212.42, 352.60)	109.91 (58.08, 176.45)
Age group						
<1	9.55 (7.64-11.85)	6.84 (5.29-8.71)	2.71 (1.46-4.31)	849.68 (679.40,1053.11)	608.71 (470.58, 774.27)	240.97 (129.75, 383.28)
1-4	0.58 (0.38-0.82)	0.41 (0.28-0.59)	0.16 (0.07-0.30)	50.54 (33.37, 72.45)	36.41 (24.36, 52.13)	14.13 (5.80, 26.21)
5-9	0.19 (0.13-0.27)	0.14 (0.09-0.20)	0.05 (0.02-0.10)	16.72 (11.24, 23.65)	12.09 (8.22, 17.24)	4.62 (1.95, 8.66)
10-14	0.09 (0.06-0.13)	0.07 (0.04-0.09)	0.03 (0.01-0.05)	7.80 (5.24, 10.73)	5.62 (3.73, 7.96)	2.18 (0.93, 4.09)
15-19	0.09 (0.06-0.13)	0.07 (0.05-0.10)	0.03 (0.01-0.05)	7.37 (4.96, 10.35)	5.40 (3.63, 7.64)	1.97 (0.80, 3.68)
All causes	10.51 (8.34, 13.05)	7.53 (5.77, 9.64)	2.98 (1.57, 4.74)	932.10 (740.26,156.45)	668.23 (512.64, 854.09)	263.87 (139.51,420.76)
Lower respiratory infections	4.43 (2.98, 6.13)	3.14 (2.12, 4.41)	1.29 (0.56, 2.31)	390.31 (262.77, 540.60)	276.70 (187.05, 388.38)	113.61 (49.72, 202.39)
Diarrheal diseases	0.02 (0.01, 0.02)	0.01 (0.01, 0.01)	0.01 (0.00, 0.01)	1.75 (1.38, 2.17)	1.18 (0.85, 1.59)	0.57 (0.34, 0.86)
Meningitis	0.02 (0.01, 0.02)	0.01 (0.01, 0.02)	0.01 (0.00, 0.01)	1.74 (1.32, 2.17)	1.26 (0.91, 1.66)	0.47 (0.26, 0.76)
Encephalitis	0.01 (0.01, 0.01)	0.01 (0.00, 0.01)	0.00 (0.00, 0.00)	0.75 (0.56, 1.08)	0.56 (0.39, 0.83)	0.19 (0.10, 0.33)
Neonatal preterm birth	3.04 (2.45, 3.70)	2.21 (1.65, 2.78)	0.83 (0.46, 1.32)	270.70 (218.51, 329.10)	197.09 (147.18, 247.58)	73.61 (41.30, 117.34)
Neonatal encephalopathy due to birth asphyxia and trauma	2.08 (1.66, 2.55)	1.48 (1.11, 1.90)	0.60 (0.34, 0.94)	184.99 (147.46, 226.21)	131.93 (98.77, 168.69)	53.06 (30.47, 83.51)
Neonatal sepsis and other neonatal infections	0.22 (0.18, 0.27)	0.16 (0.12, 0.21)	0.06 (0.03, 0.09)	19.91 (16.08, 24.16)	14.83 (11.22, 18.84)	5.08 (2.77, 8.22)
Hemolytic disease and other neonatal jaundice	0.09 (0.08, 0.12)	0.06 (0.05, 0.08)	0.03 (0.02, 0.05)	8.47 (6.87, 10.55)	5.79 (4.27, 7.53)	2.69 (1.60, 4.03)
Other neonatal disorders	0.58 (0.46, 0.71)	0.42 (0.32, 0.54)	0.16 (0.09, 0.25)	51.84 (41.34, 63.55)	37.66 (28.15, 48.49)	14.18 (8.16, 22.35)
Sudden infant death syndrome	0.02 (0.01, 0.02)	0.01 (0.01, 0.02)	0.00 (0.00, 0.01)	1.37 (0.65, 2.05)	1.02 (0.48, 1.58)	0.35 (0.15, 0.63)

Definition

In this study, the childhood age group included children and adolescents from 0 to 19 years. Aligning with the framework of the GBD Compare Tool and the GBD Results Tool, we categorized this age range into five distinct groups: under 1 year, 1 to 4 years, 5 to 9 years, 10 to 14 years, and 15 to 19 years. The number of deaths, mortality rates, and DALYs attributable to air pollution in children and adolescents were calculated by considering factors such as age, sex, year, and province.

Consistent with previous research in China,[14] this study also categorized the 33 provinces, autonomous regions, municipalities, and special administrative regions of China into five health areas based on their health metrics. Health area one includes 6 areas (Beijing, Hong Kong, Macao, Shanghai, Tianjin, and Zhejiang) that had the lowest mortality; health area two includes 6 provinces (Fujian, Guangdong, Hainan, Hubei, Hunan, and Jiangsu) that had relatively high life expectancy and the lowest mortality rates due to ischemic heart disease (IHD) and stroke; provinces in health area three (including Anhui, Hebei, Heilongjiang, Henan, Inner Mongolia, Jilin, Liaoning, Ningxia, Shaanxi, Shandong, and Shanxi) are characterized by middle life expectancy and higher levels of mortality due to four major cancers, IHD and stroke; provinces in health area four (including Chongqing, Gansu, Jiangxi, Sichuan, and Yunnan) have lower than average life expectancy but low mortality from IHD and stroke and high mortality from Chronic Obstructive Pulmonary Disease (COPD); health area five (including Guangxi, Guizhou, Qinghai, Tibet, and Xinjiang) have lower than average life expectancy, low mortality from IHD, and high mortality from COPD.

Statistical analysis

Number of deaths, DALYs and estimated annual percentage change (EAPC) were adopted to quantify the diseases burden attributable to air pollution in children and adolescents. The average annual percent change (AAPC) and corresponding 95% confidence interval (CI) were calculated by Joinpoint regression model[24,25] analysis to assess the magnitude and direction of temporal trends in deaths and DALYs for the disease burden attributable to air pollution in children and adolescents. The EAPC of the mortality rate (AMR) was determined using a log-linear model, $\ln(AMR) = \beta_0 + \beta_1 X + \varepsilon$, where X is the calendar year, and EAPC is obtained using the equation $100 \times (exp(\beta_1) - 1)$.[26] The uncertainty of parameters was calculated for each quantity of interest using a Monte Carlo simulation method.

Fixed base ratio development rate, sequential ratio development rate, and average rate of development were calculated by the following equations to describe the trend of dynamic series. These are defined as follows: Fixed base ratio development rate=a_n/a_0; sequential ratio development rate=a_n/a_{n-1}; average rate of development=$\sqrt[n]{a_n/a_0}$, where a_n is the index value of the reporting period, a_{n-1} is the index value previous of the reporting period, a_0 is the index value of the baseline, and n is the number of periods observed in addition to the base period.

All statistical analyses were performed using SAS software 9.4 (SAS Institute Inc., Cary, NC, USA), unless stated otherwise. The Joinpoint regression model was fitted using the Joinpoint Regression Program software (Version 4.9.1.0. April, 2022; Statistical Research and Applications Branch, National Cancer Institute). Graphs were plotted using GeoDa (version 1.18.0.0), R software (Version 4.3.0) and GraphPad Prism version 9 for Windows (San Diego,

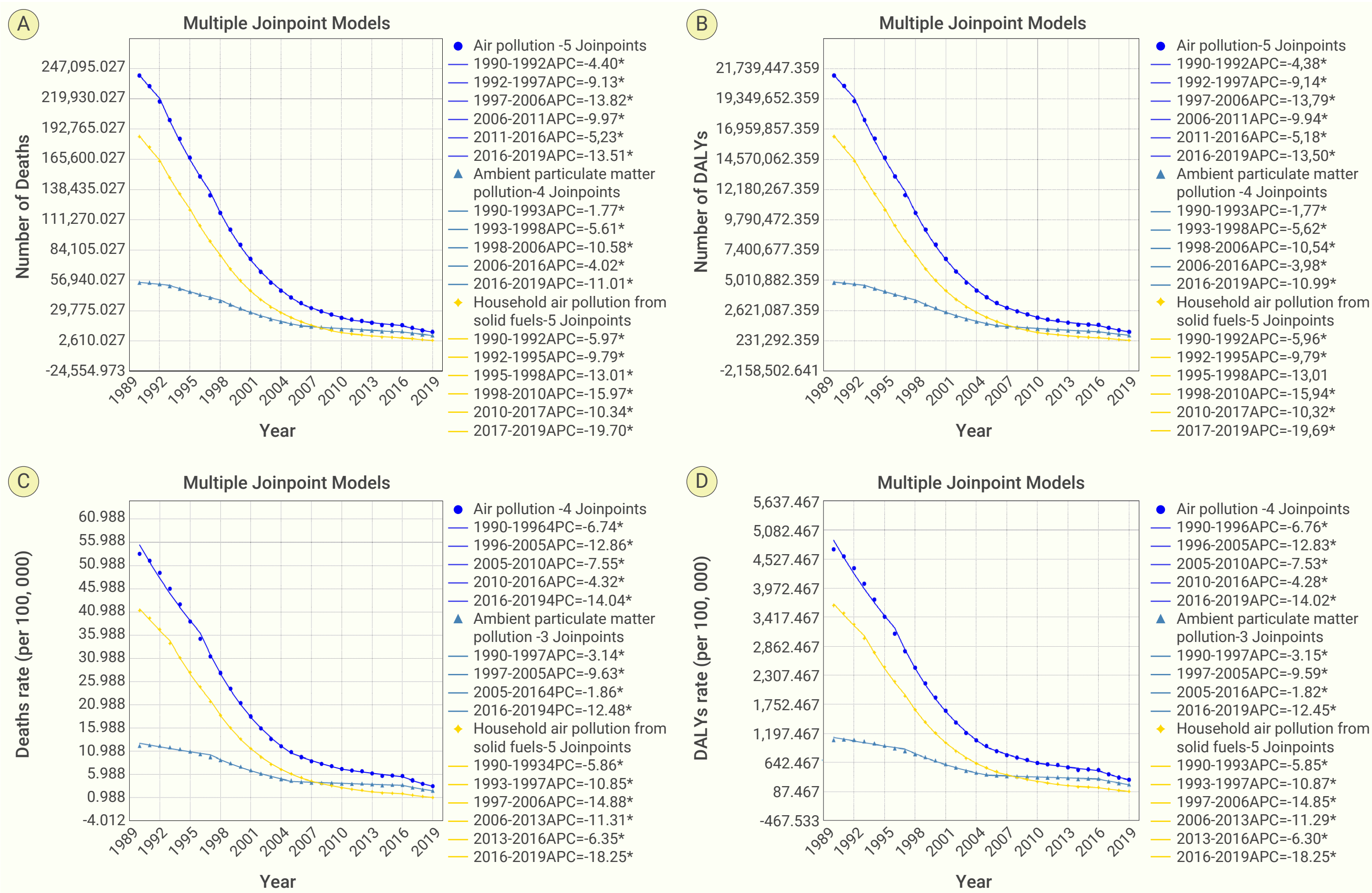

Figure 1. Trends for childhood disease burden attributable to air pollution in China from 1990 to 2019 (A) Number of deaths. (B) Number of DALYs(disability-adjusted life-years). (C) Death rate. (D) DALYs rate.

California, USA).

RESULTS

Nationally in China, air pollution resulted in 10,511 (95% uncertainty interval[95%UI] 8,344-13,047) deaths and 932,095 (740,255-1,156,450) DALYs among children and adolescents in 2019 (Table 1). The diseases burden of children and adolescents attributable to air pollution was approximately 72% from ambient particulate matter pollution and 28% from household air pollution from solid fuels. A notable gender disparity was observed in the impact of air pollution, the incidences of deaths and DALYs were higher in boys than they were in girls. Furthermore, within the childhood age groups, infants <1 year suffered the highest number of deaths and DALYs attributable to air pollution (Table 1). Lower respiratory infections constituted the highest proportion of categorized childhood diseases burden attributable to air pollution (42.2%), followed by neonatal preterm birth (28.9%) and neonatal encephalopathy caused by birth asphyxia and trauma (19.8%).

Over the past three decades, the numbers of childhood deaths and DALYs attributable to air pollution have declined significantly, as evidenced by the AAPC of -9.11% (95% confidence interval, 95%CI [-9.61% to -8.60%], $P<0.001$) for death rate, and -9.09% ([-9.59% to -8.58%], $P<0.001$) for DALYs rate (Table S1). As shown in figure 1, both the death rate and DALYs rate have significantly decreased since 1990, with the most notable declines occurring between 2016 and 2019 (death rate: APC= -14.04% [-16.64% to -11.35%], $P<0.001$; DALYs rate: -14.02% [-16.63% to -11.33%], $P<0.001$), followed by the period from 1996 to 2005. The proportion of DALYs attributed to household air pollution from solid fuels in children and adolescents also decreased from 1990 to 2019, with no significant differences across various age groups (supplementary figure1). Since 2007, the childhood diseases burden caused by ambient particulate matter pollution has significantly exceeded that caused by household air pollution from solid fuels (Figure 1, Tables S2-S3).

The proportion of disease type caused by air pollution in children and adolescents has also varied over the past 3 decades, with a significant decrease in the proportion of lower respiratory infections compared with other disease types (Figure 2, Tables S4-S7). The average rate of development for the DALYs burden attributable to air pollution in children and adolescents by disease types from 1990 to 2019 was 0.878 for lower respiratory infections, 0.882 for diarrheal diseases, 0.915 for meningitis, 0.919 for hemolytic disease and other neonatal jaundice, 0.932 for neonatal encephalopathy caused by birth asphyxia and trauma, 0.932 for neonatal preterm birth, 0.945 for encephalitis, 0.947 for other neonatal disorders, 0.958 for sudden infant death syndrome, and 0.961 for Neonatal sepsis and other neonatal infections, respectively. This ranking is the same for DALYs burden attributable to ambient particulate matter pollution (Table S8), and household air pollution from solid fuels (Table S9).

In 2019, the death rate attributable to air pollution in children and adolescents varied significantly across Chinese provinces. Tibet experienced the highest rate, with 24.41 (16.31 to 33.44) deaths per 100,000 population, whereas Hong Kong had the lowest rate with 0.18(0.08 to 0.33) per 100,000 population. Generally, the disease burden attributable to air pollution in children and adolescents was more pronounced in health areas four and five compared with other health areas in China. Specifically, the death rate per 100,000 population caused by ambient particulate matter pollution was highest in Xinjiang (12.18, 7.88 to 17.04), and the death rate per 100,000 population caused by household air pollution from solid fuels was highest in Tibet (20.81, 13.37 to 29.87) (Table 2). From 1990 to 2019, the death rate attributable to air pollution in children and adolescents declined in all provinces of China (Figure 3).

The DALYs rate per 100,000 populations attributable to air pollution in children and adolescents in 2019 varied markedly across provinces. The DALYs rate was highest in Tibet (2,152.54, 1,439.47 to 2,950.11), followed by Xinjiang

Table 2. Childhood mortality attributable to air pollution in five health areas of China in 2019 and changes in mortality rates from 1990 to 2019 (95%UI)

	Air pollution		Ambient particulate matter pollution		Household air pollution from solid fuels	
	Mortality (per 100,000)	Percentage change (%)	Mortality (per 100,000)	Percentage change (%)	Mortality (per 100,000)	Percentage change (%)
China	3.50 (2.78, 4.35)	-93.45(-94.95, -91.30)	2.51 (1.93, 3.22)	-79.39(-88.59,-55.34)	0.99 (0.52, 1.58)	-97.60(-98.66,-96.07)
Global	27.67 (22.46, 33.96)	-65.50(-71.97,-57.11)	9.37 (6.50, 12.78)	-32.23(-52.19,-1.63)	18.31 (13.35, 24.01)	-72.43(-78.09,-65.24)
Health area one						
Beijing	1.72 (1.03, 2.43)	-77.43(-87.54,-60.29)	1.69 (1.01, 2.41)	-66.99(-83.00,-34.34)	0.03 (0.01, 0.08)	-98.85(-99.65,-97.27)
Hong Kong	0.18 (0.08, 0.33)	-89.79(-95.37,-78.99)	0.17 (0.08, 0.31)	-81.77(-92.36,-57.41)	0.01 (0.00, 0.03)	-98.76(-96.90,-99.67)
Macao	0.48 (0.26, 0.80)	-91.89(-95.43,-85.66)	0.46 (0.25, 0.77)	-86.28(-93.22,-71.28)	0.02 (0.00, 0.06)	-99.15(-99.71,-98.04)
Shanghai	1.49 (0.71, 2.41)	-78.52(-89.91,-59.45)	1.47 (0.69, 2.35)	-67.86(-85.30,-32.52)	0.03 (0.01, 0.08)	-98.83(-99.68,-96.88)
Tianjin	2.32 (1.48, 3.27)	-80.21(-88.11,-67.95)	2.27 (1.45, 3.17)	-64.62(-81.21,-28.67)	0.06 (0.01, 0.15)	-98.95(-99.69,-97.36)
Zhejiang	1.34 (0.65, 2.18)	-94.66(-97.48,-90.26)	1.21 (0.59, 1.96)	-84.71(-93.80,-62.99)	0.13 (0.04, 0.30)	-99.26(-99.79,-98.11)
Health area two						
Fujian	2.07 (1.06, 3.33)	-94.2(-97.16,-89.92)	1.58 (0.79, 2.54)	-76.98(-90.47,-39.27)	0.49 (0.16, 1.03)	-98.31(-99.43,-96.23)
Guangdong	1.27 (0.68, 1.95)	-92.09(-95.93,-86.35)	1.15 (0.61, 1.77)	-78.82(-90.58,-52.51)	0.12 (0.03, 0.31)	-98.84(-99.64,-97.29)
Hainan	3.20 (1.65, 5.00)	-92.64(-96.38,-86.85)	1.84 (0.94, 3.08)	-67.17(-85.94,-19.03)	1.35 (0.55, 2.53)	-96.42(-98.52,-92.96)
Hubei	3.92 (2.57, 5.45)	-92.69(-95.41,-88.22)	3.19 (2.07, 4.55)	-78.47(-88.56,-49.50)	0.73 (0.29, 1.47)	-98.11(-99.19,-96.04)
Hunan	2.29 (1.41, 3.20)	-96.26(-97.83,-94.03)	1.63 (1.01, 2.34)	-89.07(-94.86,-74.17)	0.66 (0.28, 1.25)	-98.57(-99.38,-97.25)
Jiangsu	1.41 (0.76, 2.04)	-94.26(-97.04,-90.33)	1.27 (0.70, 1.86)	-84.33(-93.00,-65.82)	0.14 (0.04, 0.31)	-99.16(-99.72,-98.06)
Health area three						
Anhui	3.30 (2.00, 4.78)	-93.25(-96.09,-88.64)	2.39 (1.46, 3.58)	-77.48(-89.57,-40.90)	0.90 (0.38, 1.62)	-97.64(-98.98,-95.30)
Hebei	3.92 (2.54, 5.33)	-87.6(-92.19,-80.55)	3.26 (2.05, 4.41)	-66.69(-82.65,-27.80)	0.66 (0.27, 1.26)	-96.98(-98.74,-93.86)
Heilongjiang	3.06 (1.74, 4.42)	-89.27(-94.16,-81.78)	2.34 (1.32, 3.43)	-65.09(-83.43,-20.81)	0.72 (0.26, 1.38)	-96.70(-98.64,-93.18)
Henan	3.42 (2.21, 4.92)	-94.37(-96.67,-90.99)	2.66 (1.67, 3.85)	-84.12(-92.54,-62.83)	0.77 (0.30, 1.46)	-98.26(-99.29,-96.43)
Inner Mongolia	3.41 (1.93, 5.18)	-91.95(-95.68,-85.81)	2.38 (1.29, 3.67)	-65.14(-84.60,-13.74)	1.03 (0.38, 2.03)	-97.11(-98.93,-93.90)
Jilin	1.94 (1.17, 2.77)	-91.07(-94.9,-85.44)	1.59 (0.93, 2.30)	-73.41(-87.62,-40.57)	0.35 (0.12, 0.74)	-97.76(-99.18,-95.16)
Liaoning	2.49 (1.44, 3.61)	-87.51(-93.21,-79.15)	2.18 (1.22, 3.20)	-69.13(-84.97,-33.38)	0.31 (0.11, 0.66)	-97.62(-99.10,-94.90)
Ningxia	3.87 (2.17, 5.77)	-95.01(-97.23,-91.79)	2.86 (1.59, 4.34)	-84.69(-93.09,-61.56)	1.01 (0.40, 1.91)	-98.29(-99.30,-96.60)
Shaanxi	3.72 (2.38, 5.23)	-95.1(-97.07,-92.12)	2.90 (1.78, 4.17)	-84.94(-92.65,-64.13)	0.81 (0.33, 1.63)	-98.57(-99.40,-96.80)
Shandong	2.68 (1.60, 3.74)	-89.61(-94.17,-82.76)	2.27 (1.38, 3.18)	-73.37(-86.93,-41.26)	0.41 (0.16, 0.88)	-97.61(-99.06,-94.78)
Shanxi	3.87 (2.43, 5.35)	-88.61(-93.29,-81.86)	2.93 (1.85, 4.15)	-63.02(-82.56,-14.17)	0.94 (0.39, 1.78)	-96.39(-98.43,-92.87)
Health area four						
Chongqing	3.57 (2.14, 5.30)	-94.02(-96.51,-90.55)	2.77 (1.62, 4.14)	-82.05(-91.66,-57.97)	0.80 (0.32, 1.56)	-98.19(-99.27,-96.36)
Gansu	4.97 (2.89, 7.26)	-93.83(-96.65,-89.34)	2.63 (1.43, 4.17)	-80.47(-91.48,-46.99)	2.34 (1.08, 3.89)	-96.51(-98.40,-93.56)
Jiangxi	4.33 (2.61, 6.09)	-94.5(-96.81,-91.78)	2.89 (1.66, 4.21)	-79.48(-90.33,-50.58)	1.44 (0.61, 2.58)	-97.78(-99.01,-96.02)
Sichuan	4.78 (3.20, 6.49)	-94.71(-96.61,-92.09)	3.32 (2.19, 4.62)	-84.76(-92.58,-62.00)	1.46 (0.66, 2.57)	-97.86(-99.00,-96.09)
Yunnan	5.45 (3.28, 7.98)	-95.29(-97.34,-92.49)	2.65 (1.60, 4.15)	-81.55(-91.61,-51.01)	2.80 (1.28, 4.84)	-97.24(-98.70,-94.97)
Health area five						
Guangxi	2.72 (1.70, 3.85)	-94.33(-96.43,-91.39)	1.85 (1.12, 2.73)	-81.01(-90.72,-56.10)	0.87 (0.36, 1.59)	-97.72(-98.94,-95.86)
Guizhou	5.83 (3.76, 8.16)	-96.11(-97.46,-94.18)	2.95 (1.79, 4.39)	-83.95(-92.78,-54.69)	2.87 (1.40, 4.79)	-97.82(-98.86,-96.28)
Qinghai	7.93 (4.82, 11.32)	-91.03(-94.68,-85.75)	5.04 (3.12, 7.34)	-71.44(-86.10,-27.18)	2.89 (1.22, 5.20)	-95.92(-98.13,-92.32)
Tibet	24.41 (16.31, 33.44)	-84.48(-89.3,-77.65)	3.60 (2.01, 5.78)	-47.82(-76.50,49.32)	20.81 (13.37, 29.87)	-86.16(-90.94,-79.53)
Xinjiang	15.84 (10.76, 21.47)	-83.14(-88.56,-75.4)	12.18 (7.88, 17.04)	-54.76(-74.78,-3.11)	3.66 (1.48, 6.77)	-94.54(-97.26,-89.93)

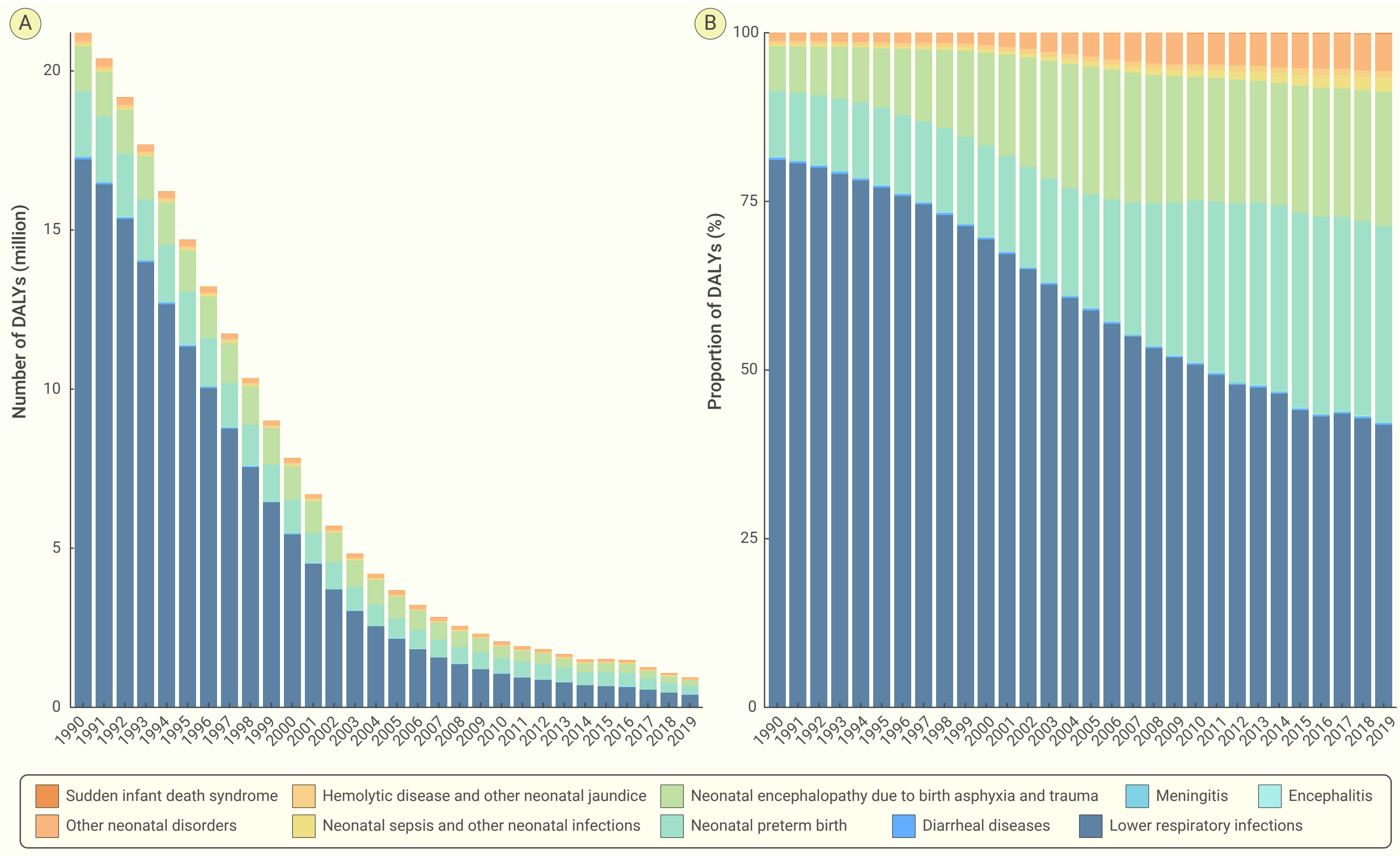

Figure 2. Absolute (A) and proportional (B) DALYs attributable to air pollution in children and adolescents by disease types in China from 1990 to 2019.

(1,399.31, 948.75 to 1,897.39), and the lowest rates were recorded in Hong Kong (16.88, 7.98 to 29.81), and Macao (43.37, 23.66 to 71.49). Specifically, the DALYs rate per 100,000 population attributable to ambient particulate matter pollution was highest in Xinjiang (1,075.91, 695.05 to 1,506.16), and the rate attributable to household air pollution from solid fuels was highest in Tibet (1,835.17, 1,179.83 to 2,633.97), as detailed in Table S10. From 1990 to 2019, the DALYs rate per 100, 000 population that was attributable to air pollution in children and adolescents declined in all provinces of China (Figure S2).

Lower respiratory infections constituted the largest proportion of categorized childhood disease DALYs burden in most of the provinces in China, followed by neonatal preterm birth, and neonatal encephalopathy due to birth asphyxia and trauma. However, in the provinces of Shandong, Liaoning, Zhejiang, Jiangsu, Inner Mongolia, Shanghai, and Beijing, neonatal preterm birth constituted the largest proportion of the DALYs burden. Together, these three diseases contributed nearly 80% of the total disease burden caused by air pollution among children and adolescents in all provinces (Figure 4). The highest proportional burden of lower respiratory infections was in the Macao Special Administrative Region of China (58.44%), followed by Xinjiang (56.20%), Tibet (53.87%), Guizhou (52.41%), and Yunnan (50.81%). The highest proportional burden of neonatal preterm birth was in Shandong (39.65%), followed by Liaoning (38.04%), and Tianjin (37.80%). The highest proportional burden of neonatal encephalopathy due to birth asphyxia and trauma was found in Anhui (26.63%), followed by Shaanxi (25.29%), and Shanghai (24.73%). Across all childhood age groups, a consistently higher proportional disease burden was attributed to lower respiratory infections.

Figure 5 shows the temporal trend of the childhood disease burden attributable to air pollution across various health areas in China. For respiratory infections and tuberculosis, as well as enteric infections, the DALYs rates attributable to air pollution generally increased from health area one to health area five. In health area five, which includes Guangxi, Guizhou, Qinghai, Tibet, and Xinjiang, had the highest DALYs rates for respiratory infections and tuberculosis, and enteric infections attributable to air pollution among children and adolescents. For maternal and neonatal disorders, other infectious diseases, and other non-communicable diseases, the DALYs rates due to air pollution varied across the different health areas. Cities in health area three experienced the highest DALYs rates. Notably, health area one recorded the lowest burden attributable to air pollution for all diseases types among children and adolescents.

DISCUSSION

We analyzed the spatiotemporal trends of childhood DALYs and deaths attributable to air pollution at both the national and provincial levels in China. In 2019, air pollution was responsible for approximately 10,511 (8,344-13,047) deaths and 932,095 (740,255-1,156,450) DALYs among Chinese children, they were highest in the <1 year age group and higher in boys than they were in girls. The disease burden attributable to air pollution in children and adolescents has decreased markedly from 1990 to 2019, with mortality and DALYs decreasing by 93.45% and 93.41%, respectively. The disease burden attributable to air pollution in children and adolescents varied considerably across provinces, with the DALYs rate per 100,000 population ranging from 16.88 (7.98-29.81) in Hong Kong to 2,152.54 (1,439.47-2,950.11) in Tibet. The highest rates were observed in health area five. Nationally, lower respiratory infections were the predominant contributor to the childhood disease burden attributed to air pollution, followed by neonatal preterm birth and neonatal encephalopathy caused by birth asphyxia and trauma.

Children, particularly those <1 year of age, are more vulnerable to the effects of air pollution than adults. The GBD 2019 data show that the age-standardized DALYs rate per 100,000 populations attributable to air pollution in China was 2,269.89 (1,958.19, 2,618.19), whereas the DALYs rate per 100,000 populations in children <1 year was 5,763.14 (4,636.34, 7,128.88) which was significantly higher than in adults ≥20 years (1,465.46 [1,252.37, 1,702.68]).[27] Children's body and organs are still in the development stage, and the higher levels of physical activity, along with faster and deeper breath-

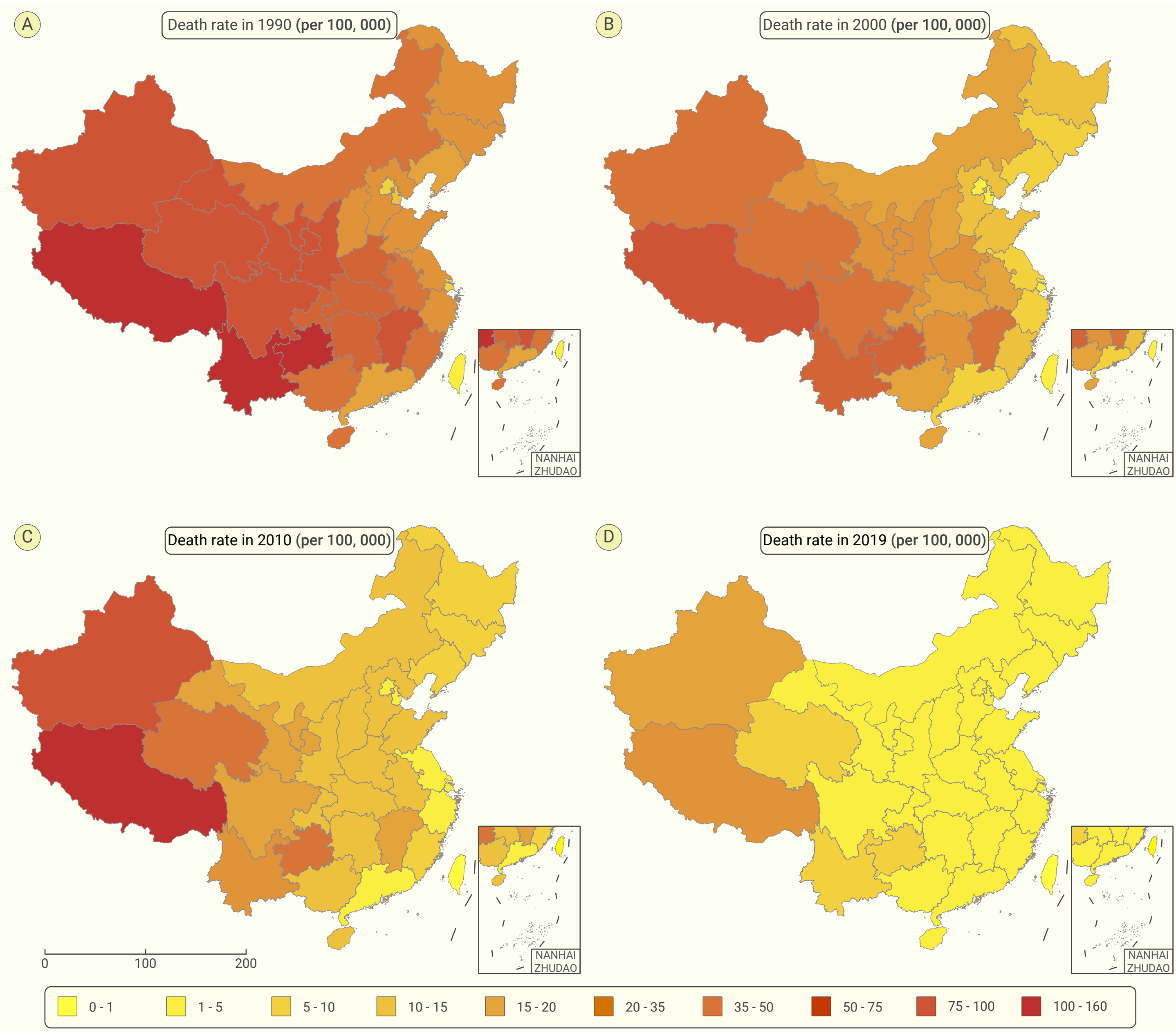

Figure 3. Death rate attributable to air pollution in children and adolescents in province of China in 1990, 2000, 2010, and 2019.

ing, make them particularly susceptible to harm from air pollution.[28] Indeed, exposure to air pollution has been reported to be associated with children's growth and development,[29,30] risk of macrosomia,[31] neurodevelopmental and neurodegenerative disorders,[32,33] and lung-function development,[34] which can have a lifelong impact on children, leading to a higher disease burden compared with that of adults exposed to the same pollution levels. Additionally, infants and children are uniquely sensitive to air pollution may also due to the lack of control over the environment they live in.

Over the past 30 years, childhood deaths and DALYs attributable to household air pollution from solid fuels and ambient particulate matter pollution have markedly decreased, especially from household air pollution. Prior to 2007, household air pollution from solid fuels was the predominant risk factor, but post-2007, ambient particulate matter pollution became the primary source of air pollution. This shift in risk factors coincides with China's rapid economic growth and urbanization. Traditional solid fuels (e.g., coal and biomass) have increasingly been replaced by cleaner energy sources such as electricity and gas for household use.[35,36] This transition is likely a major factor in the diminished role of household air pollution from solid fuels as the leading risk factor for childhood disease burden. More comprehensive actions to tackle ambient particulate matter pollution should be developed and implemented in the future. Notably, however, in certain scenarios, for example the lockdown measures during the COVID-19 pandemic, the impact from increased exposure to household air pollution is not negligible.[37] Such situations suggest a continued need for vigilance and adaptable approaches to air pollution control, particularly in unique situations where traditional exposure patterns may change.

In agreement with previous findings,[12] we found that the disease burden attributable to air pollution in children and adolescents varied across the provinces, with the DALYs rate per 100,000 population ranging from 16.88 (Hong Kong) to 2,152.54 (Tibet), indicating significant disparities in socioeconomic development, disease burden, and risk factor control among these areas. The disease burden attributable to ambient particulate matter pollution and household air pollution from solid fuels were all highest in health area five. These findings support the notion[38,39] that provinces with stringent air pollution regulations and a service-oriented economy, such as Beijing, Shanghai, Hong Kong, et al. tend to have lower disease burdens, whereas provinces with less stringent enforcement or those that are heavily industrialized tend to have higher disease burden. Additionally, the high disease burden

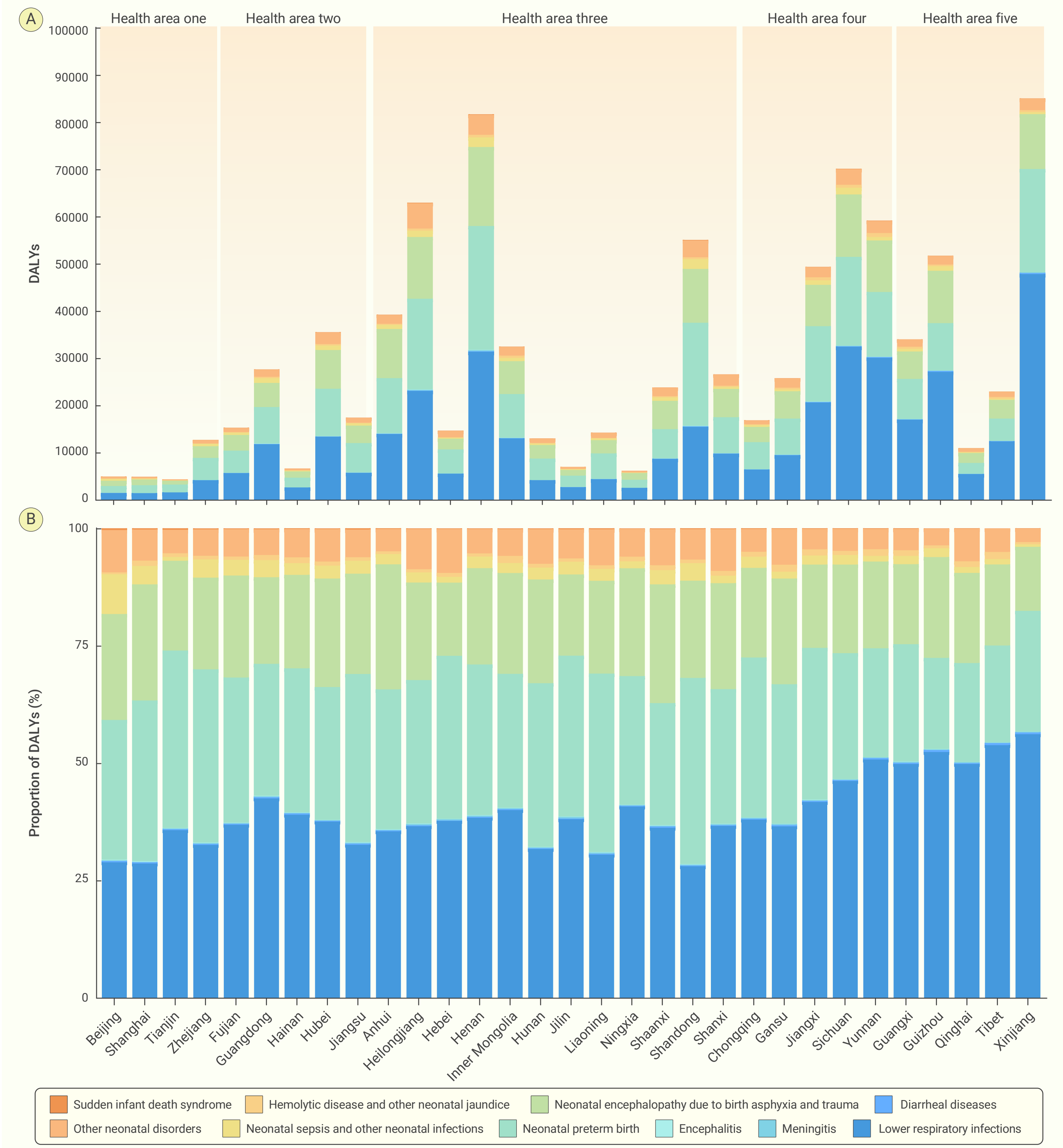

Figure 4. Absolute (A) and proportional (B) DALYs attributable to air pollution in children and adolescents by disease types in the provinces of China in 2019.

attributable to air pollution in children and adolescents in Tibet, Xinjiang and Qinghai may also due to their unique environmental, geographic, and socio-economic conditions. Tibet, Xinjiang, and Qinghai are all located in the high-altitude and remote western part of China, which has some of the most severe air pollution worldwide due to its geography and climate, and is close to heavily industrialized areas such as Mongolia and India. Furthermore, the socio-economic conditions in these regions are not as developed as those in other areas of China, leading to higher poverty levels and lack of access to healthcare. In the future, governments, health organizations, and other stakeholders should pay more attention and work together to create and implement policies to reduce the disease burden attributable to air pollution in children and adolescents in these areas. Such policies may include investing in green infrastructure such as trees and green spaces, and educating the population about how to reduce air pollution and related diseases in children and adolescents.

In adults, air pollution primarily contributes to the burden of cardiovascular and cerebrovascular diseases,[7,40] whereas, in Chinese children and adolescents, the predominant diseases are lower respiratory infections, neonatal

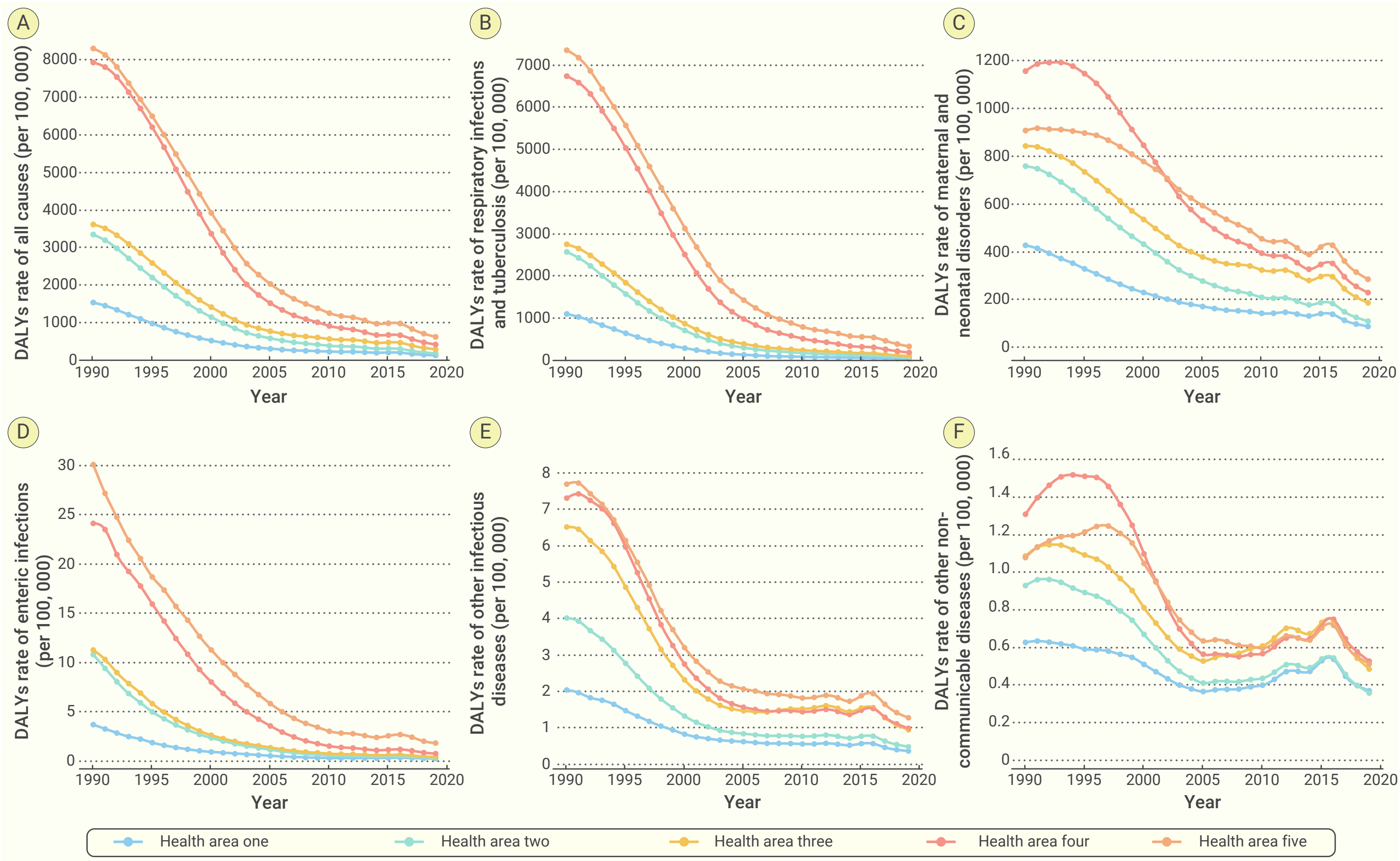

Figure 5. Temporal trend for childhood disease burden attributable to air pollution by five health areas in China from 1990 to 2019, both sexes combined.

preterm birth, and neonatal encephalopathy caused by birth asphyxia and trauma. Children have higher respiration rates relative to their body weight than adults because of their proportionally larger lung surface area,[41] which leads them to inhale more air. When the air is polluted with harmful contaminants, there is increased risk of subsequent health issues. Additionally, children's immune systems are still in the development stage and therefore their defense mechanism against infection is weaker than that of adults.[42] Furthermore, the epithelial lining of children's lungs is less developed and more permeable to contaminants than that of adults. Such premises are supported by mechanistic evidence that air pollution affects cellular and molecular systems, causing an altered immune response, abnormal respiratory functions, and lung diseases.[43–45] Therefore, province-specific efforts to control air pollution in China are crucial. Such measures will significantly reduce the disease burden of lower respiratory infections and neonatal disorders in children, thereby addressing a critical public health concern and improving the overall well-being of this vulnerable population.

The general limitations inherent in using GBD methodologies to evaluate risk factors have been well-documented in previous research.[46] Specifically for this study, one limitation is that the disease burden was calculated at the provincial level, and therefore heterogeneity that may exist locally within each province was not considered. Another limitation is that only household air pollution from solid fuels was used to estimate the disease burden attributable to household air pollution, and the absence of estimates on household solid fuel used for heating may mean that household air pollution was underestimated. Despite these limitations, to our knowledge, this is the first analysis to comprehensively quantify the disease burden in children and adolescents attributable to air pollution in the geographical profile across China from 1990 to 2019. The findings at the provincial-level are a valuable resource for planning and implementing interventions specifically tailored to the unique circumstances of each province. Such targeted approaches are crucial for effectively addressing the unique challenges posed by air pollution in the different areas of China.

In summary, air pollution remains a significant public health issue in China, particularly affecting the health of children and adolescents. Province-specific initiatives to control air pollution are crucial for effectively addressing the unique challenges posed by air pollution in different regions of China.

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AUTHOR CONTRIBUTIONS

Among the authors in the list, MGZ managed the overall research enterprise and contributed to the conception and design of the study. GSF and JX conducted the data analysis and wrote the first draft of the manuscript. XYW, HX, CJH, XZ, JLQ, and PY participated in the data preparation, verification, and interpretation. MGZ, XYW, HX, CJH, XZ, JLQ, PY, HYX, and YYM helped to improve the manuscript and provided important comments on the manuscript. GSF and JX revised and completed the final manuscript. All authors reviewed and approved the final manuscript, and the corresponding author MGZ had final responsibility for the decision to submit for publication.

DECLARATION OF INTERESTS

Guoshuang Feng, as The Innovation Medicine Editorial Board members, were not involved in the manuscript's review or decision. Peer review was conducted independently. The other authors declare no competing interests.

ETHICAL STATEMENT AND PATIENT CONSENT

The research and data used in GBD 2019 adhere to the standards set by the Guidelines for Accurate and Transparent Health Estimates Reporting. As this study relied solely on de-identified and aggregated data, requirements for informed consent and ethical approval were deemed not applicable.

DATA AND CODE AVAILABILITY

Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

SUPPLEMENTAL INFORMATION

It can be found online at https://doi.org/10.59717/j.xinn-med.2024.100057

LEAD CONTACT WEBSITE

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