National and provincial burden of disease attributable to fine particulate matter air pollution in China, 1990–2021: an analysis of data from the Global Burden of Disease Study 2021

Tanchun Yu, Yixuan Jiang*, Renjie Chen, Peng Yin, Huihuan Luo, Maigeng Zhou, Haidong Kan*

Summary

Background Fine particulate matter ($PM_{2\cdot5}$) is the leading environmental risk factor for mortality and disability worldwide. We aimed to evaluate the temporal trend in, and spatial distribution of, the disease burden attributable to $PM_{2\cdot5}$ in China from 1990 to 2021.

Methods Based on the methodology framework and general analytical strategies applied in the Global Burden of Diseases, Injuries, and Risk Factors Study 2021, we calculated the numbers, age-standardised rates, and percentage of deaths and disability-adjusted life-years (DALYs) attributable to $PM_{2\cdot5}$ air pollution from 1990 to 2021 at the national and provincial level in China, by disease, sex, and age groups. Exposure to $PM_{2\cdot5}$, including ambient $PM_{2\cdot5}$ pollution and household $PM_{2\cdot5}$ pollution from solid fuels, was evaluated across 33 provincial administrative units in China.

Findings In 2021, 2·3 million (95% uncertainty interval [UI] 1·8–2·9) deaths and 46·7 million (36·6–59·7) DALYs could be attributable to $PM_{2\cdot5}$ pollution in China, accounting for 19·4% (16·0–23·6) of total deaths and 11·6% (9·4–14·1) of total DALYs. Of these, 1·9 million (95% UI 1·3–2·3) deaths and 37·8 million (26·3–46·5) DALYs resulted from ambient exposure, while 0·4 million (0·1–1·3) deaths and 8·9 million (1·5–27·8) DALYs were due to household exposure from solid fuel use. Stroke, ischaemic heart disease, and chronic obstructive pulmonary disease were the leading three causes. Two peaks in the burden were observed: in children aged younger than 5 years, and in people aged 70 years and older. The percentage of deaths and DALYs due to ambient $PM_{2\cdot5}$ was higher in men, while that due to household $PM_{2\cdot5}$ was higher in women. Geographically, the disease burden from ambient $PM_{2\cdot5}$ was higher in north and northwest China, while that from household $PM_{2\cdot5}$ was higher in southwest China. From 1990 to 2021, age-standardised death rates attributable to total $PM_{2\cdot5}$ decreased by 66·0% (95% UI 57·7–73·1) and those attributable to household $PM_{2\cdot5}$ decreased by 92·2% (76·6–98·7), with larger reductions observed in east and south China. By contrast, the disease burden related to ambient $PM_{2\cdot5}$ continued to increase and only began to decline in the past decade.

Interpretation Despite the decline in the disease burden attributable to total $PM_{2\cdot5}$ in China during 1990–2021, ambient $PM_{2\cdot5}$ remains a major contributor to mortality and disability. This study highlights considerable spatial heterogeneity across different provinces and provides valuable insights for developing geographically tailored strategies for $PM_{2\cdot5}$ control and public health promotion in China. Stricter control of ambient air pollution is needed in northern and northwestern regions, while promoting clean cooking energy is more urgently warranted in southwestern areas.

Funding National Natural Science Foundation of China, National Key Research and Development Program of China, Shanghai Municipal Science and Technology Major Project, China Postdoctoral Science Foundation.

Lancet Planet Health 2025; 9: e174–85

*Contributed equally

Department of Nutrition and Health Education, National Institute for Nutrition and Health, Chinese Center for Disease Control and Prevention, Beijing, China (T Yu MS); **School of Public Health, Key Lab of Public Health Safety of the Ministry of Education and NHC Key Lab of Health Technology Assessment, Fudan University, Shanghai, China** (Y Jiang PhD, R Chen PhD, H Luo PhD, Prof H Kan PhD); **National Center for Chronic and Noncommunicable Disease Control and Prevention, Chinese Center for Disease Control and Prevention, Beijing, China** (P Yin PhD, Prof M Zhou PhD); **Children's Hospital of Fudan University, National Center for Children's Health, Shanghai, China** (Prof H Kan)

Correspondence to: Professor Haidong Kan, School of Public Health, Key Lab of Public Health Safety of the Ministry of Education and NHC Key Lab of Health Technology Assessment, Fudan University, Shanghai 200032, China **kanh@fudan.edu.cn**

or

Professor Maigeng Zhou, National Center for Chronic and Noncommunicable Disease Control and Prevention, Chinese Center for Disease Control and Prevention, Beijing 100050, China **zhoumaigeng@ncncd.chinacdc.cn**

Introduction

Fine particulate matter ($PM_{2\cdot5}$) air pollution was identified as the leading contributor to disability-adjusted life-years (DALYs) and the second primary risk factor for deaths worldwide in the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) 2021.[1] It was estimated that 7·8 million deaths were attributable to $PM_{2\cdot5}$ pollution globally, of which more than 2·2 million were reported in China alone. As the world's largest middle-income country, China faces the dual challenge of ambient $PM_{2\cdot5}$ pollution and household $PM_{2\cdot5}$ pollution from solid fuels, both of which contribute substantially to $PM_{2\cdot5}$-related health effects.[2] Since 2013, the Chinese Government has issued a series of air pollution control policies.[3,4] Most actions target ambient $PM_{2\cdot5}$ pollution, such as controlling industrial emissions, promoting electric vehicles, and reducing reliance on coal. Some measures, such as the switch of residential

Research in context

Evidence before this study

We searched Web of Science, Embase, and PubMed using the search terms "air pollution", "air pollutants", "fine particulate matter", "$PM_{2.5}$ exposure", "ambient particulate matter pollution", "household particulate matter pollution", "indoor particulate matter pollution", "mortality", "death", "morbidity", "DALY", "disease burden", and "China", without any language restrictions, for studies published from database inception up to July 15, 2024. Previous studies listed fine particulate matter ($PM_{2.5}$) air pollution as a leading environmental risk factor in China, but few studies have comprehensively assessed the temporal trend and regional distribution of the disease burden attributable to both ambient and household $PM_{2.5}$ pollution. Although a previous study examined the national burden before 2017, it did not provide annual estimates, and there has been no updated nationwide assessment of the current disease burden attributable to $PM_{2.5}$ air pollution in China.

Added value of this study

We conducted a comprehensive and up-to-date evaluation of the disease burden attributable to $PM_{2.5}$ exposure at national and provincial levels in China from 1990 to 2021, based on data from the Global Burden of Diseases, Injuries, and Risk Factors Study 2021. Over the past three decades, there has been a notable decrease in the disease burden attributable to $PM_{2.5}$ air pollution, especially in provinces of east and south China, which was primarily driven by the reduced burden due to household $PM_{2.5}$ pollution. However, ambient $PM_{2.5}$ remains a major risk factor, and only began to decrease in the past decade.

The burden attributable to both ambient and household $PM_{2.5}$ exposure was generally greater in children aged younger than 5 years, people aged older than 70 years, and individuals with cardiopulmonary diseases (ie, stroke, ischaemic heart disease, and chronic obstructive pulmonary disease). The percentage of death and DALYs due to ambient $PM_{2.5}$ was higher in men, while that due to household $PM_{2.5}$ was higher in women. Moreover, substantial geographical variations were observed. The risks associated with ambient $PM_{2.5}$ pollution were higher in provinces in north and northwest China, while the risks associated with household $PM_{2.5}$ pollution from solid fuel use were higher in southwest China.

Implications of all the available evidence

$PM_{2.5}$ air pollution remains a major risk factor for premature mortality and disability in China. The present study provides important insights into the corresponding disease burden during the past three decades and across different geographical regions and demographic groups. Targeted policies are urgently needed, including special protection measures for vulnerable populations such as children and older people, stricter control of ambient air pollution in the northern and northwestern regions, and the promotion of clean cooking energy in the southwestern region. Given the persistent burden of air pollution and the high proportion of people living in areas with $PM_{2.5}$ concentrations exceeding WHO guidelines globally, these findings could offer valuable lessons for other countries facing similar challenges.

energy from coal to natural gas or electricity, have contributed to reducing household air pollution from solid fuels.[5] Despite a notable decline in $PM_{2.5}$ concentrations over the past decade,[6] the absolute levels of $PM_{2.5}$ frequently exceeded recommended guidelines in certain regions,[7–9] thereby posing adverse effects on public health.

There are substantial variations in geographical features, sociodemographic characteristics, and economic development across the vast territory of China.[10,11] This diversity results in varying exposure to $PM_{2.5}$ air pollution and heterogeneous health impacts in different provinces.[2,12] Consequently, it is crucial to conduct provincial assessments on disease burden to account for these regional disparities.[6,13] Evaluating the temporal trends in disease burden over time is just as important. Despite several studies evaluating the spatiotemporal trends in $PM_{2.5}$-related burden across China, most focused on ambient $PM_{2.5}$ and covered a limited period. Although a previous study examined the national burden associated with both ambient and household $PM_{2.5}$ pollution from 1990 to 2017,[2] it did not provide annual estimates, and there has been no updated assessment since then. A comprehensive assessment by demographic group, such as age and sex, is also warranted. Such analyses could provide valuable insights into the disproportionate disease burden of $PM_{2.5}$ across different subpopulations.

We extracted data from GBD 2021 with the aim of comprehensively evaluating the impacts of $PM_{2.5}$ on death and DALYs at both the national and provincial levels in China during the 1990–2021 period. Through this up-to-date assessment, we aim to shed light on temporal trends and regional disparities in the $PM_{2.5}$-related burden in order to facilitate tailored interventions for mitigating the health risks associated with air pollution.

Methods

Overview

All data on the disease burden attributable to $PM_{2.5}$ air pollution were derived from GBD 2021. Details of the design and methodologies of GBD 2021 have been published elsewhere.[1,14] Here, we focused on both the national and provincial disease burden, as measured by deaths and DALYs, attributable to $PM_{2.5}$ air pollution in China. Overall, 33 provincial administrative units were investigated. The geographical locations of provincial administrative units in China are provided in the appendix (p 19). There was a waiver of ethical approval for this analysis because GBD data are anonymous and publicly accessible.

$PM_{2·5}$ air pollution estimation

We applied the methods developed by GBD 2021 to estimate both ambient and household $PM_{2·5}$ exposure.[1] A detailed description of the data sources and methodology is provided in the appendix (pp 3–7, 11–12). Briefly, for the measurement of ambient $PM_{2·5}$, satellite retrievals of aerosol optical depth, chemical transport model simulations, ground monitoring data, population data, and land use data were collected. A modelling approach, known as the Data Integration Model for Air Quality 2, was used by integrating data from different sources while mitigating potential biases and incorporating information such as within-country calibration variation. The population-weighted annual average of ambient $PM_{2·5}$ mass concentrations was estimated at a spatial resolution of 0·1°×0·1° (ie, 11×11 km). Exposure to household air pollution from solid fuels was estimated according to the proportion of individuals using solid cooking fuels and the level of exposure to $PM_{2·5}$ air pollution for these individuals. Data in China were extracted from multiple sources, including census data, China Chronic Disease and Risk Factor Surveillance, China Energy Statistical Yearbook, China Health and Nutrition Survey, China National Health Services Survey, the WHO Household Energy Database, and literature reviews. The solid fuels included in the analysis were wood, coal or charcoal, dung, and agricultural residues. A three-step modelling approach incorporating linear regression, spatiotemporal regression, and Gaussian process regression was used to estimate household $PM_{2·5}$ exposure at the individual level.

Disease burden attributable to $PM_{2·5}$ air pollution

In GBD 2021, the cause-specific burden of various risk factors was evaluated by calculating the attributable deaths and DALYs. Details of the methodology and input data have been described previously[1] and are provided in the appendix (pp 7–12).

One set of cause-specific risk curves were developed for household air pollution and ambient particulate matter pollution as distinct sources of $PM_{2·5}$. Data from cohort and case–control studies on ambient $PM_{2·5}$ pollution, as well as cohort studies, case–control studies, and randomised controlled trials on household solid fuel use for cooking were used. The meta-regression Bayesian, regularised, trimmed (MR-BRT) tool was used to generate relative risk estimates. The theoretical minimum risk exposure level was established with a uniform distribution with bounds defined by the average of the minimum and 5th percentiles from outdoor air pollution cohort studies in North America (2·4–5·9 μg/m³). Population attributable fractions were then calculated to determine the proportion of risk reduction achievable if the exposure was reduced to the theoretical minimum risk level. Finally, the burden attributable to the risk factor was estimated by multiplying cause-specific, age-specific, sex-specific, year-specific, and location-specific population attributable fractions with deaths and DALYs from 1990 to 2021.

See Online for appendix

In the present study, provincial mortality data in China were extracted from multiple sources, including surveillance systems (the National Disease Surveillance Points and the Maternal and Child Surveillance System), the China Cancer Registry, the Chinese Center for Disease Control and Prevention Cause of Death Reporting System, census data, national surveys, mortality data from the Macao Special Administrative Region and Hong Kong Special Administrative Region, and some published papers or reports. For non-fatal outcomes, data were primarily sourced from national surveys, the China Cancer Registry, hospital inpatient records, the Chinese Center for Disease Control and Prevention Cause-of-Death Reporting System, and some published papers or reports.

We calculated the number, age-standardised rates, and percentage of deaths and DALYs attributable to $PM_{2·5}$ air pollution in China from 1990 to 2021, by disease, sex, age groups, and provincial administrative units. The main diseases reported in the present analysis are: stroke; ischaemic heart disease; chronic obstructive pulmonary disease (COPD); tracheal, bronchus, and lung cancer; lower respiratory infections; diabetes, and neonatal disorders. We considered males and females separately. We included eight age groups: younger than 5 years, 5–14 years, 15–49 years, 50–54 years, 55–59 years, 60–64 years, 65–69 years, and 70 years and older. The division of the population aged 50 years and older into 5-year age groups was based on the results of our pre-analysis, which showed that disease burden increases substantially with age, particularly after age 50 years. Using 5-year intervals for this group allows for a more detailed and accurate assessment of the health challenges faced by older adults. To better depict the regional heterogeneity in disease burden, we categorised the 33 provincial administrative units into seven main regions based on their natural, cultural, and socio-economic characteristics, as well as their geographical location. The seven regions are as follows: north China, which comprises Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia; northeast China, which comprises Heilongjiang, Jilin, and Liaoning; east China, which comprises Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, and Shandong; central China, which comprises Henan, Hubei, and Hunan; south China, which comprises Guangdong, Guangxi, Hainan, Hong Kong, and Macao; southwest China, which comprises Chongqing, Sichuan, Guizhou, Yunnan, and Tibet; and northwest China, which comprises Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. To investigate the

	Total $PM_{2.5}$ pollution			Ambient $PM_{2.5}$ pollution			Household $PM_{2.5}$ pollution from solid fuels		
	Death (thousands)	Age-standardised death rate per 100 000	Percentage of deaths	Death (thousands)	Age-standardised death rate per 100 000	Percentage of deaths	Death (thousands)	Age-standardised death rate per 100 000	Percentage of deaths
All cause	2273·4 (1771·1–2892·7)	125·1 (97·6–157·9)	19·4% (16·0–23·6)	1857·4 (1300·5–2293·5)	102·3 (71·9–126·3)	15·9% (11·1–18·7)	415·5 (63·6–1346·1)	22·8 (3·5–73·9)	3·5% (0·5–11·4)
Disease									
Stroke	785·9 (568·8–1045·2)	41·7 (30·4–55·4)	30·3% (23·8–38·2)	640·8 (409·6–837·3)	34·1 (21·9–44·4)	24·7% (16·6–30·4)	145·0 (21·2–463·3)	7·6 (1·1–24·2)	5·6% (0·8–18·2)
Ischaemic heart disease	681·9 (493·9–883·6)	38·6 (28·0–49·6)	34·8% (27·2–42·5)	570·5 (354·8–760·5)	32·3 (19·9–43·1)	29·2% (18·3–37·2)	111·2 (15·9–363·2)	6·2 (0·9–20·3)	5·7% (0·8–18·5)
COPD	497·0 (354·0–710·5)	28·2 (20·0–40·2)	38·7% (29·6–53·7)	388·2 (280·1–500·8)	22·1 (16·0–28·4)	30·2% (23·0–35·5)	108·8 (16·6–374·4)	6·1 (0·9–20·7)	8·5% (1·2–28·6)
Tracheal, bronchus, and lung cancer	211·4 (132·1–299·9)	10·1 (6·3–14·4)	26·0% (16·9–35·0)	178·6 (103·4–257·0)	8·5 (5·0–12·3)	22·0% (13·5–30·5)	32·6 (4·5–110·6)	1·6 (0·2–5·3)	4·0% (0·6–13·7)
Lower respiratory infections	57·4 (8·0–98·8)	3·9 (0·6–6·6)	27·8% (3·9–45·9)	46·4 (6·2–83·4)	3·1 (0·4–5·6)	22·4% (3·0–38·9)	11·0 (0·8–35·2)	0·8 (0·1–2·4)	5·3% (0·4–17·5)
Diabetes	35·1 (21·6–51·4)	1·8 (1·1–2·6)	19·7% (12·3–27·3)	29·4 (15·5–45·3)	1·5 (0·8–2·3)	16·5% (8·8–23·7)	5·7 (1·1–17·5)	0·3 (0·1–0·9)	3·2% (0·6–9·9)
Neonatal disorders	4·6 (3·7–5·7)	0·9 (0·7–1·1)	16·7% (14·4–19·0)	3·5 (1·9–4·8)	0·7 (0·4–0·9)	12·5% (6·9–16·3)	1·1 (0·3–2·8)	0·2 (0·1–0·5)	4·2% (1·1–10·0)
Sex									
Male	1305·0 (990·3–1734·8)	169·7 (131·1–221·1)	19·1% (15·9–23·2)	1092·6 (768·8–1397·1)	142·5 (101·5–178·9)	16·0% (12·1–18·6)	212·1 (28·5–751·3)	27·1 (3·6–96·7)	3·1% (0·4–10·3)
Female	968·4 (716·5–1242·1)	94·8 (70·0–121·7)	19·9% (15·8–24·1)	764·8 (500·1–1000·1)	75·0 (49·1–98·0)	15·8% (10·4–19·1)	203·4 (33·0–629·7)	19·8 (3·2–61·1)	4·2% (0·6–12·9)
Age									
<5 years	7·5 (4·9–10·2)	9·7 (6·4–13·2)	8·7% (6·1–11·3)	5·6 (3·0–8·5)	7·3 (3·8–11·0)	6·5% (3·6–9·3)	1·9 (0·5–4·9)	2·4 (0·6–6·3)	2·2% (0·5–5·5)
5–14 years	0·4 (0·1–0·8)	0·2 (0·0–0·4)	1·1% (0·2–2·0)	0·3 (0·0–0·6)	0·2 (0·0–0·3)	0·9% (0·1–1·6)	0·1 (0·0–0·4)	0·1 (0·0–0·2)	0·3% (0·0–0·9)
15–49 years	66·2 (50·5–87·3)	10·0 (7·6–13·2)	8·3% (7·0–10·0)	54·1 (36·4–68·2)	8·2 (5·5–10·3)	6·8% (4·8–8·0)	12·1 (1·9–39·0)	1·8 (0·3–5·9)	1·5% (0·2–4·8)
50–54 years	63·9 (47·8–84·4)	52·9 (39·5–69·8)	13·2% (11·1–15·8)	51·9 (34·6–66·3)	43·0 (28·6–54·8)	10·8% (7·6–12·9)	12·0 (1·9–38·0)	9·9 (1·5–31·5)	2·5% (0·4–7·9)
55–59 years	98·2 (74·0–129·4)	89·3 (67·3–117·7)	14·8% (12·3–17·6)	79·9 (53·5–102·1)	72·6 (48·7–92·8)	12·0% (8·6–14·3)	18·3 (2·8–59·4)	16·7 (2·5–54·0)	2·7% (0·4–8·8)
60–64 years	119·6 (90·6–156·8)	163·8 (124·1–214·8)	16·6% (13·8–19·9)	98·0 (67·2–124·1)	134·2 (92·0–170·0)	13·6% (9·7–16·2)	21·6 (3·3–71·0)	29·6 (4·5–97·2)	3·0% (0·4–9·8)
65–69 years	226·1 (172·6–297·4)	294·8 (225·0–387·7)	18·4% (15·4–22·0)	184·3 (125·9–233·5)	240·3 (164·1–304·4)	15·0% (10·6–17·7)	41·7 (6·3–134·7)	54·4 (8·2–175·6)	3·4% (0·5–11·0)
≥70 years	1691·4 (1315·6–2127·5)	1417·8 (1102·7–1783·3)	22·0% (18·0–26·9)	1383·2 (985·0–1704·7)	1159·4 (825·6–1428·8)	18·0% (12·7–21·2)	307·8 (47·0–1008·8)	258·0 (39·4–845·6)	4·0% (0·6–13·1)

Data in parentheses are 95% uncertainty intervals (UIs). COPD=chronic obstructive pulmonary disease. $PM_{2.5}$=fine particulate matter.

Table 1: **Deaths, age-standardised death rates, and percentage of deaths attributable to particulate matter air pollution in China in 2021, stratified by causes, sex, and age**

influence of socioeconomic status, we stratified the 33 provincial administrative units into three groups using the 33rd and 67th percentiles of Sociodemographic Index (SDI; ie, low SDI, medium SDI, and high SDI regions).

The results were presented as mean values and 95% uncertainty intervals (UIs), which were calculated on the basis of the 2·5th and 97·5th percentile values across 500 random draws from the posterior distribution for each step in the modelling process. These simulations were also conducted separately by cause, sex, age, province, and year to fully account for the heterogeneity across these dimensions. All statistical analyses were conducted with R software (version 4.3.2) using the ggplot2 package.

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

In 2021, there were 2·3 million (95% UI 1·8–2·9) deaths attributable to total $PM_{2.5}$ pollution, 1·9 million (1·3–2·3)

	Total $PM_{2·5}$ pollution			Ambient $PM_{2·5}$ pollution			Household $PM_{2·5}$ pollution from solid fuels		
	DALY (thousands)	Age-standardised DALY rate per 100 000	Percentage of DALYs	DALY (thousands)	Age-standardised DALY rate per 100 000	Percentage of DALYs	DALY (thousands)	Age-standardised DALY rate per 100 000	Percentage of DALYs
All cause	46 676·9 (36 578·7–59 744·1)	2436·9 (1919·7–3069·4)	11·6% (9·4–14·1)	37 805·9 (26 280·5–46 518·7)	1970·1 (1373·0–2423·2)	9·4% (6·7–11·3)	8858·3 (1494·8–27 820·5)	466·1 (81·6–1455·8)	2·2% (0·4–7·0)
Disease									
Stroke	16 063·2 (11 839·7–21 366·6)	792·5 (585·1–1051·4)	30·2% (23·7–38·1)	13 062·2 (8372·8–16 941·1)	645·3 (415·1–837·0)	24·6% (16·5–30·1)	2997·1 (445·1–9497·7)	147·0 (21·8–465·0)	5·6% (0·8–18·3)
Ischaemic heart disease	12 382·4 (8855·4–16 200·9)	640·4 (460·3–834·1)	34·7% (27·0–42·3)	10 338·1 (6438·6–13 889·9)	535·4 (334·6–716·6)	29·0% (18·1–37·0)	2041·5 (290·2–6614·1)	104·8 (14·9–340·5)	5·7% (0·8–18·5)
COPD	9157·7 (6641·9–12 975·6)	473·1 (343·3–670·2)	38·7% (29·7–53·9)	7144·2 (5169·6–9045·6)	370·0 (268·8–466·8)	30·2% (22·9–35·6)	2011·4 (299·0–6837·9)	103·0 (15·3–347·5)	8·5% (1·2–28·9)
Tracheal, bronchus, and lung cancer	4894·7 (3064·9–6925·0)	226·5 (141·6–320·6)	25·9% (16·9–34·9)	4125·8 (2375·3–5932·5)	190·9 (110·0–274·3)	21·8% (13·4–30·4)	766·7 (107·2–2581·3)	35·5 (5·0–119·5)	4·0% (0·6–13·8)
Lower respiratory infections	1149·4 (173·5–1938·3)	98·2 (16·4–164·2)	28·0% (4·3–46·3)	909·8 (129·9–1629·7)	76·3 (12·3–137·6)	22·1% (3·3–38·4)	238·9 (18·8–761·9)	21·8 (2·1–68·1)	5·8% (0·5–18·6)
Diabetes	2274·2 (1317·2–3507·1)	110·8 (63·9–170·7)	19·4% (12·1–27·0)	1913·2 (1035·9–3044·0)	93·3 (51·0–149·1)	16·3% (8·8–23·4)	360·3 (58·9–1106·0)	17·4 (2·8–54·0)	3·1% (0·5–9·6)
Neonatal disorders	414·4 (331·0–517·4)	78·0 (62·3–97·5)	9·1% (7·5–11·0)	310·9 (171·7–435·0)	58·5 (32·3–81·9)	6·8% (3·7–9·3)	103·3 (27·3–250·8)	19·4 (5·1–47·2)	2·3% (0·6–5·5)
Sex									
Male	27 564·6 (20 899·0–36 346·1)	3132·2 (2419·0–4065·4)	12·2% (10·1–14·9)	22 931·8 (16 132·9–29 420·4)	2604·3 (1840·5–3286·1)	10·2% (7·5–11·9)	4625·3 (719·0–15 765·0)	527·1 (85·0–1807·2)	2·0% (0·3–6·7)
Female	19 112·3 (14 683·4–23 915·4)	1872·0 (1458·8–2327·4)	10·8% (8·5–13·4)	14 874·1 (9412·9–19 254·7)	1455·3 (915·8–1878·7)	8·4% (5·4–10·5)	4233·0 (741·3–12 858·2)	416·2 (75·3–1247·0)	2·4% (0·4–7·1)
Age									
<5 years	678·4 (444·3–919·3)	873·4 (572·1–1183·6)	7·4% (5·1–9·6)	507·9 (266·4–768·3)	653·9 (343·1–989·2)	5·5% (3·0–7·9)	170·1 (40·8–442·1)	219·0 (52·5–569·2)	1·8% (0·5–4·7)
5–14 years	37·4 (5·0–63·6)	20·6 (2·8–35·0)	0·4% (0·1–0·7)	28·3 (3·7–51·7)	15·6 (2·0–28·4)	0·3% (0·0–0·6)	9·1 (0·8–29·1)	5·0 (0·4–16·0)	0·1% (0·0–0·3)
15–49 years	4019·9 (3170·9–5185·3)	606·0 (478·1–781·7)	4·2% (3·4–5·2)	3281·9 (2273·5–4163·0)	494·8 (342·8–627·6)	3·4% (2·3–4·2)	736·8 (122·7–2309·3)	111·1 (18·5–348·2)	0·8% (0·1–2·4)
50–54 years	2894·3 (2236·3–3770·5)	2394·8 (1850·4–3119·7)	8·5% (6·9–10·4)	2343·7 (1566·3–2969·7)	1939·2 (1296·0–2457·1)	6·9% (4·7–8·4)	549·8 (89·7–1716·7)	454·9 (74·2–1420·4)	1·6% (0·3–5·1)
55–59 years	3872·9 (3006·9–5019·3)	3522·6 (2735·0–4565·4)	10·0% (8·2–12·3)	3137·4 (2099·9–3945·5)	2853·7 (1910·0–3588·7)	8·1% (5·5–9·7)	734·3 (119·9–2311·3)	667·9 (109·0–2102·3)	1·9% (0·3–6·1)
60–64 years	3965·0 (3103·7–5115·8)	5431·2 (4251·4–7007·4)	11·9% (9·8–14·5)	3233·7 (2190·3–4040·2)	4429·4 (3000·3–5534·1)	9·7% (6·8–11·6)	730·3 (118·9–2337·0)	1000·3 (162·8–3201·1)	2·2% (0·3–7·2)
65–69 years	6262·9 (4897·5–8103·2)	8165·0 (6385·0–10 564·3)	13·9% (11·4–17·0)	5074·6 (3425·4–6314·8)	6615·8 (4465·8–8232·7)	11·3% (7·9–13·5)	1186·6 (193·6–3765·4)	1547·0 (252·4–4909·1)	2·6% (0·4–8·5)
≥70 years	24 946·1 (19 565·8–31 372·1)	20 909·7 (16 399·9–26 295·9)	18·2% (14·9–22·2)	20 198·3 (14 260·7–24 765·3)	16 930·1 (11 953·2–20 758·1)	14·8% (10·6–17·6)	4741·4 (794·0–15 054·0)	3974·2 (665·6–12 618·2)	3·5% (0·6–10·9)

Data in parentheses are 95% uncertainty intervals (UIs). COPD=chronic obstructive pulmonary disease. DALY=disability-adjusted life-year. $PM_{2·5}$=fine particulate matter.

Table 2: **DALYs, age-standardised DALY rates, and percentage of DALYs attributable to particulate matter air pollution in China in 2021, stratified by causes, sex, and age**

deaths due to ambient exposure, and 0·4 million (0·1–1·3) deaths due to household exposure from solid fuels; total $PM_{2·5}$ pollution accounted for 19·4% (16·0–23·6) of all deaths in China, ambient exposure accounted for 15·9% (11·1–18·7), and household exposure from solid fuels accounted for 3·5% (0·5–11·4; table 1). The estimated age-standardised death rate was 125·1 (97·6–157·9) per 100 000 for total $PM_{2·5}$ pollution, 102·3 (71·9–126·3) per 100 000 for ambient $PM_{2·5}$ pollution, and 22·8 (3·5–73·9) per 100 000 for household $PM_{2·5}$ from solid fuels. Among different diseases, the age-standardised death rates attributable to $PM_{2·5}$ pollution were highest for stroke, followed by ischaemic heart disease, COPD, tracheal, bronchus, and lung cancer, lower respiratory infections, diabetes, and neonatal disorders. Similar patterns were observed for DALYs attributable to $PM_{2·5}$ pollution (table 2).

Considerable regional disparities were found in the disease burden attributable to $PM_{2·5}$ pollution in 2021 (figures 1, 2; appendix pp 13–14). The age-standardised

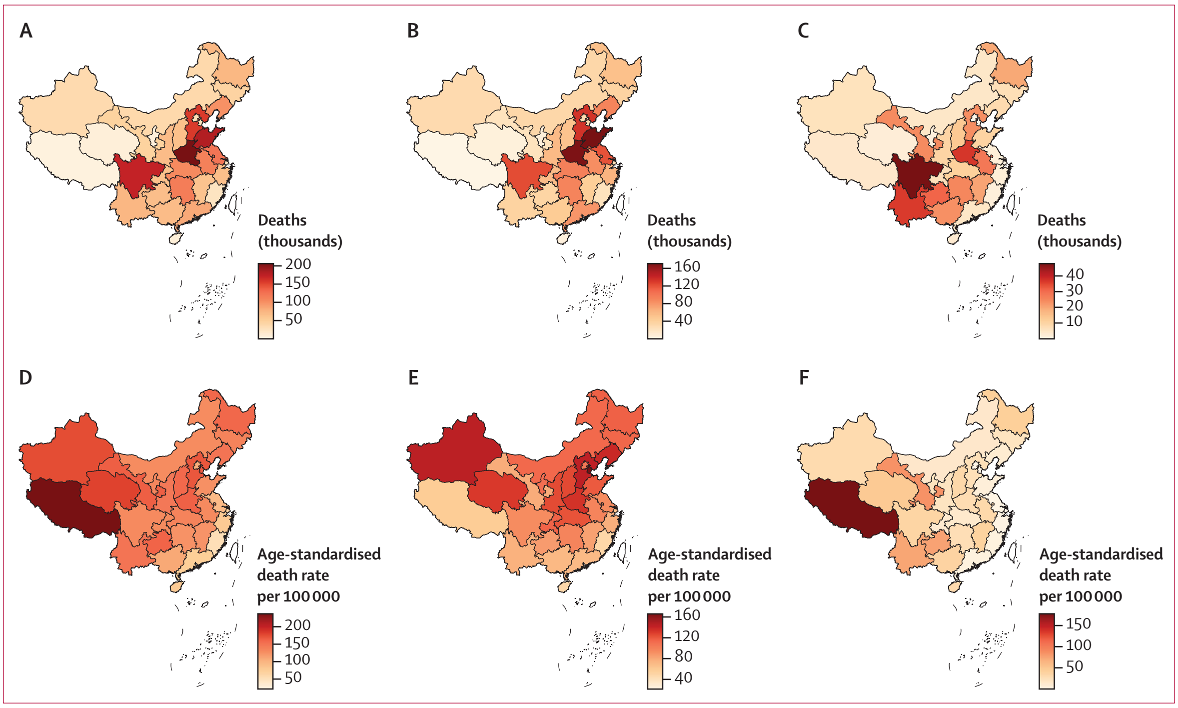

Figure 1: **Deaths and age-standardised death rates attributable to particulate matter air pollution in provinces of China in 2021**
(A) Deaths attributable to total particulate matter air pollution. (B) Deaths attributable to ambient particulate matter air pollution. (C) Deaths attributable to household air pollution from solid fuels. (D) Age-standardised death rates attributable to total particulate matter air pollution. (E) Age-standardised death rates attributable to ambient particulate matter air pollution. (F) Age-standardised death rates attributable to household air pollution from solid fuels.

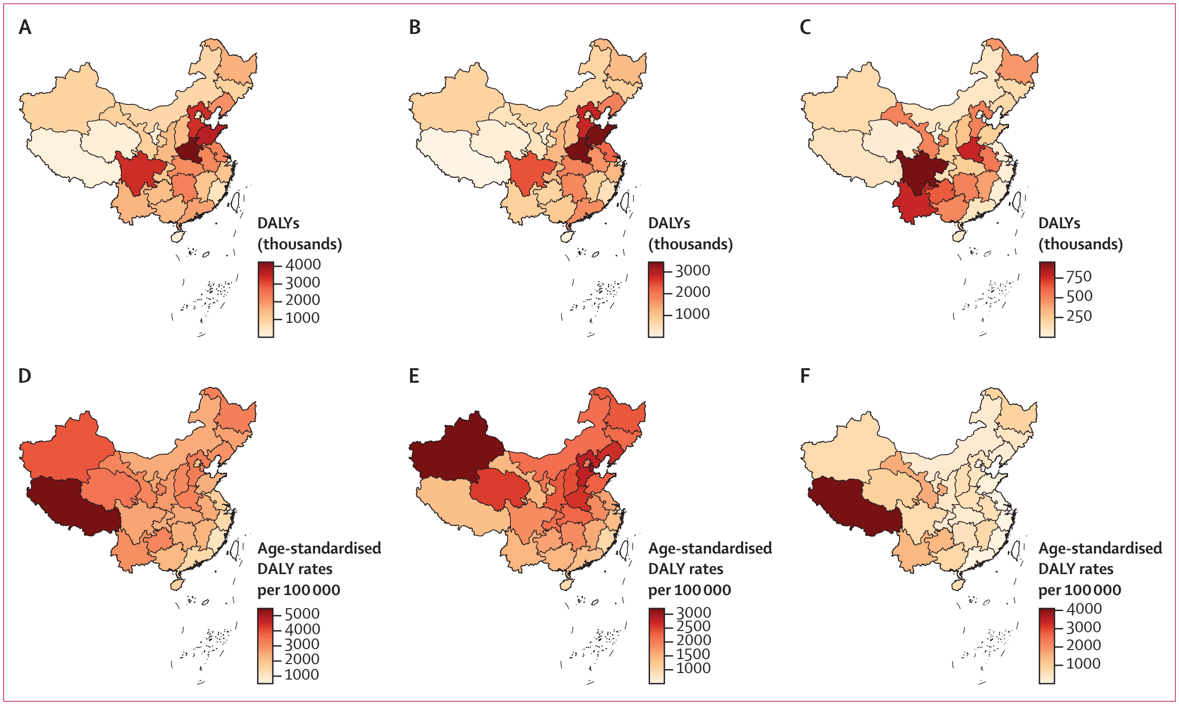

Figure 2: **DALYs and age-standardised DALY rates attributable to particulate matter air pollution in provinces of China in 2021**
(A) DALYs attributable to total particulate matter air pollution. (B) DALYs attributable to ambient particulate matter air pollution. (C) DALYs attributable to household air pollution from solid fuels. (D) Age-standardised DALY rates attributable to total particulate matter air pollution. (E) Age-standardised DALY rates attributable to ambient particulate matter air pollution. (F) Age-standardised DALY rates attributable to household air pollution from solid fuels. DALY=disability-adjusted life-year.

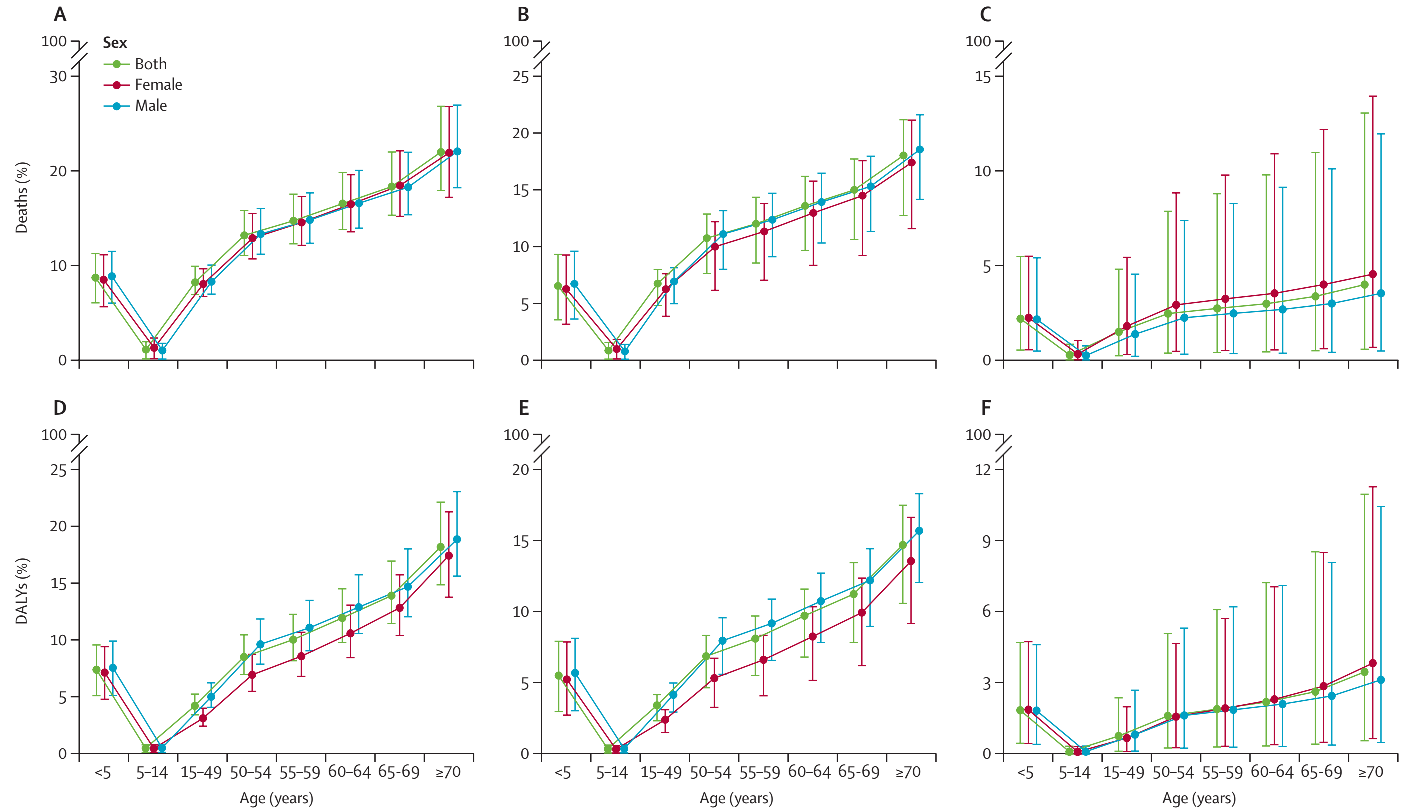

Figure 3: **Percentage of deaths and DALYs attributable to particulate matter air pollution across age groups and stratified by sex in China in 2021**
(A) Percentage of deaths attributable to total particulate matter air pollution. (B) Percentage of deaths attributable to ambient particulate matter air pollution. (C) Percentage of deaths attributable to household air pollution from solid fuels. (D) Percentage of DALYs attributable to total particulate matter air pollution. (E) Percentage of DALYs attributable to ambient particulate matter air pollution. (F) Percentage of DALYs attributable to household air pollution from solid fuels. DALY=disability-adjusted life-year.

death rate attributable to total $PM_{2·5}$ pollution was highest in Tibet (236·6 [95% UI 121·2–379·0] per 100 000) and Qinghai (180·8 [124·0–249·7] per 100 000), and lowest in Hong Kong (21·9 [14·9–30·2] per 100 000) and Macao (32·7 [23·5–43·4] per 100 000). Generally, the disease burden derived from ambient $PM_{2·5}$ pollution was higher in north China and northwest China, while that from household $PM_{2·5}$ pollution was higher in southwest China. Specifically, the age-standardised death rate attributable to ambient $PM_{2·5}$ pollution was highest in Tianjin (165·7 [129·6–209·5] per 100 000) and lowest in Hong Kong (21·8 [14·8–30·2] per 100 000), while the age-standardised death rate attributable to household $PM_{2·5}$ pollution was highest in Tibet (177·4 [47·3–341·8] per 100 000) and lowest in Macao (0·0 [0·0–0·0] per 100 000). The disease burden also varied among regions with different SDIs (appendix p 20). For ambient $PM_{2·5}$ pollution, the disease burden was highest in medium SDI regions, followed by high SDI and low SDI regions. For household $PM_{2·5}$ pollution, the disease burden was highest in the low SDI region, followed by medium SDI and high SDI regions. Similar trends were found in the distribution of DALYs attributable to $PM_{2·5}$ air pollution.

There were obvious differences in the disease burden by age group and sex (tables 1, 2; figure 3). The lowest attributable burden was observed in individuals aged 5–14 years, with an attributable death rate of 0·2 (95% UI 0·0–0·4) per 100 000 population and DALY rate of 20·6 (2·8–35·0) per 100 000 population. Two peaks in the burden were observed, in children aged younger than 5 years and in people aged 70 years and older. Furthermore, the percentage of deaths attributable to ambient $PM_{2·5}$ was slightly higher in men (16·0% [95% UI 12·1–18·6]) than in women (15·8% [10·4–19·1]); however, the pattern was reversed for household $PM_{2·5}$ from solid fuels, with attributable percentages of 3·1% (0·4–10·3) for men and 4·2% (0·6–12·9) for women. Similar patterns were observed for DALYs attributable to $PM_{2·5}$ pollution.

From 1990 to 2021, there was a general reduction in the national disease burden attributable to total $PM_{2·5}$ pollution (figure 4; appendix pp 15–16). The age-standardised death rate decreased from 367·6 (95% UI 317·1–421·3) per 100 000 to 125·1 (97·6–157·9) per 100 000 over this period, corresponding to a reduction of 66·0% (57·7–73·1). This decline was primarily driven by the reduction in the death rate attributable to household

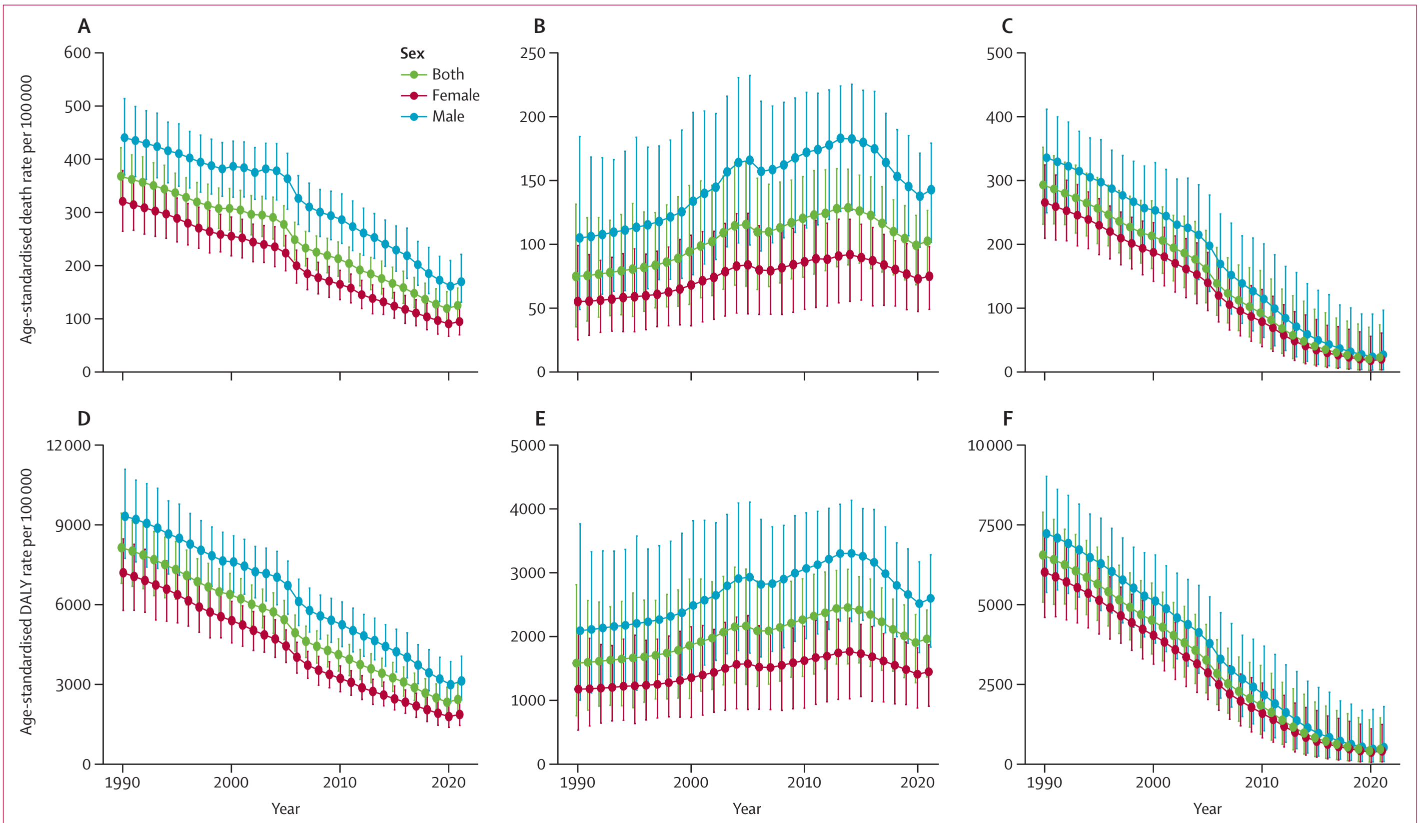

Figure 4: **Annual age-standardised death and DALY rates attributable to particulate matter air pollution in China from 1990 to 2021**
(A) Age-standardised death rates (per 100 000) attributable to total particulate matter air pollution. (B) Age-standardised death rates (per 100 000) attributable to ambient particulate matter air pollution. (C) Age-standardised death rates (per 100 000) attributable to household air pollution from solid fuels. (D) Age-standardised DALY rates (per 100 000) attributable to total particulate matter air pollution. (E) Age-standardised DALY rates (per 100 000) attributable to ambient particulate matter air pollution. (F) Age-standardised DALY rates (per 100 000) attributable to household air pollution from solid fuels. DALY=disability-adjusted life-year.

$PM_{2\cdot5}$ from solid fuels, which dropped from 292·7 (231·2–351·5) per 100 000 to 22·8 (3·5–73·9) per 100 000, corresponding to a reduction of 92·2% (76·6–98·7). For ambient $PM_{2\cdot5}$, there was an increase in the disease burden during the first two decades, and a notable decline thereafter. We also observed a slight increase in age-standardised death and DALY rates attributable to both ambient and household $PM_{2\cdot5}$ exposure from 2020 to 2021. The rank of age-standardised death rates attributable to $PM_{2\cdot5}$ for major diseases during 1990–2021 is illustrated in the appendix (pp 21–22), with COPD ranking first in 1990 and stroke ranking first in 2021. We observed a substantial decrease in the burden of major diseases attributable to household $PM_{2\cdot5}$ pollution, whereas increases were found in the burden of stroke, ischaemic heart disease, tracheal, bronchus, and lung cancer, and diabetes attributable to ambient $PM_{2\cdot5}$ pollution.

From 1990 to 2021, substantial geographical variations were observed in the temporal trends of the disease burden attributable to $PM_{2\cdot5}$ pollution. The annual age-standardised death and DALY rates across different provinces are presented in the appendix (pp 23–28). Most provinces showed a steady decline in the disease burden attributable to total and household $PM_{2\cdot5}$ pollution, with more pronounced decreases generally observed in provinces in east and south China (appendix pp 29–30). Specifically, the largest decline in age-standardised death rates attributable to total $PM_{2\cdot5}$ was found in Fujian (81·6% [95% UI 74·4–86·2]) and the largest decline attributable to household $PM_{2\cdot5}$ was found in Beijing (99·7% [98·0–100·0]), while the smallest decline attributable to total $PM_{2\cdot5}$ was found in Hebei (46·0% [30·4–58·8]) and the smallest decline attributable to household $PM_{2\cdot5}$ was found in Tibet (73·1% [50·4–92·6]; appendix pp 17–18). The disease burden attributable to ambient $PM_{2\cdot5}$ pollution showed an initial increase in most provinces during the first two decades and began to decline around 2013. In Beijing, Tianjin, Shanghai, Zhejiang, and Guangdong, the corresponding burden started to decrease earlier, approximately after 2005. Exceptions were observed in Hong Kong and Macao, where the burden showed a consistent decline throughout the entire period. The percentage changes in disease burden during 1990–2013 and 2013–2021 are illustrated in the appendix (pp 31–32). The burden from ambient $PM_{2\cdot5}$ increased substantially from 1990 to 2013 in all provinces except for Beijing, Shanghai, Hong Kong, and Macao, and declined from 2013 to 2021 in all provinces except Tibet. The largest increases in age-standardised death rates during 1990–2013 were observed in Hebei and Inner Mongolia, while the largest decreases during 2013–2021 occurred in Hong Kong and Zhejiang.

Discussion

Based on data from GBD 2021, this study provides an up-to-date and comprehensive estimate of the absolute numbers, age-standardised rates, and percentage of deaths and DALYs attributable to $PM_{2\cdot5}$ air pollution in different provincial units of China. A substantial decrease in the disease burden resulting from household $PM_{2\cdot5}$ pollution was observed from 1990 to 2021, while the burden from ambient $PM_{2\cdot5}$ began to decrease approximately in the past decade. A higher burden was observed in children aged younger than 5 years, people aged older than 70 years, and those with cardiopulmonary diseases. The percentage of the disease burden from ambient $PM_{2\cdot5}$ was higher in men, while that from household $PM_{2\cdot5}$ was higher in women. Evident geographical variations were found, with north and northwest China showing a higher burden from ambient $PM_{2\cdot5}$, while southwest China had a higher burden from household $PM_{2\cdot5}$.

Our analyses reported 1·9 million deaths due to ambient $PM_{2\cdot5}$ and 416 000 deaths attributable to household $PM_{2\cdot5}$. These estimates are higher than those derived from a previous study based on GBD 2017 data, which reported 852 000 deaths due to ambient $PM_{2\cdot5}$ and 271 000 deaths attributable to household $PM_{2\cdot5}$.[2] The observed differences can largely be attributed to methodological advancements, particularly the shift from the Integrated Exposure Response function in GBD 2017 to the MR-BRT model in GBD 2021. The MR-BRT model removed the need for active smoking data and secondhand smoking data to anchor the curve at higher exposures and incorporated recent studies from high-exposure regions such as China, which allowed for more reliable estimates.[1] We also compared our estimates with those based on local empirical data in China. For the ambient $PM_{2\cdot5}$-related burden, Liang and colleagues[6] estimated that annual premature deaths ranged from 1·5 million to 2·2 million during 2000–16. Xiao and colleagues[15] reported a decrease in deaths attributable to ambient $PM_{2\cdot5}$, from 1·75 million in 2013 to 1·39 million in 2020. Several earlier studies on the ambient $PM_{2\cdot5}$-related burden before 2016 generally reported lower estimates, ranging from 964 000 to 1·37 million deaths.[16–20] For the household $PM_{2\cdot5}$-related burden, existing studies typically considered indoor $PM_{2\cdot5}$ from various sources and thus yielded higher estimates.[12,21] Future research differentiating the burden attributable to household $PM_{2\cdot5}$ from solid fuel use for cooking is still warranted. Differences across studies are likely to result from variations in data sources, exposure assessment methods, and exposure–response relationships. Our study, based on the most recent dataset in China and the updated GBD 2021 framework, provides robust and reliable estimates of the disease burden from both ambient and household $PM_{2\cdot5}$ pollution from 1990 to 2021.

The present study highlights the burden of wide-spectrum diseases attributable to $PM_{2\cdot5}$ exposure. Stroke, ischaemic heart disease, and COPD remain major causes of both death and DALYs attributable to $PM_{2\cdot5}$, with tracheal, bronchus, and lung cancer, as well as lower respiratory infections, also contributing substantially. Compared to the previous study by Yin and colleagues[2] based on GBD 2017, our research further estimated the burden of neonatal disorders attributable to $PM_{2\cdot5}$ exposure. Moreover, recent studies have increasingly identified associations between $PM_{2\cdot5}$ and other conditions such as dementia and chronic kidney disease, suggesting these should also be considered as risk–outcome pairs in future GBD assessments.[22] In fact, all the aforementioned diseases were ranked as key contributors to total premature mortality and rising health-care costs, both in China and globally.[14,23] Together, these findings underscore the substantial health impacts of $PM_{2\cdot5}$ air pollution and underscore the urgent need for effective $PM_{2\cdot5}$ control and reduction policies to mitigate the overall disease burden.

Considerable age and sex disparity in the burden was observed. In general, the disease burden from both ambient and household $PM_{2\cdot5}$ exposure was greater in children aged younger than 5 years and individuals aged older than 70 years. Similar findings were reported in previous studies.[24,25] Young children's bodies and organs are inherently immature and thus might be more sensitive to air pollution.[26] Older individuals might be more vulnerable due to the functional degeneration of multiple physical systems as they age. We also observed the lowest $PM_{2\cdot5}$-related burden in children aged 5–14 years. This can be explained by two main factors. On the one hand, the inherently lower death and DALY rates in this age group play a key role. According to GBD 2021, the all-cause death and DALY rates for children aged 5–14 years are the lowest among all age groups,[14,23] which suggests that children in this age range are generally in good health with relatively fewer life-threatening conditions. On the other hand, the leading causes of deaths and DALYs in this age group, such as unintentional injuries, are less likely to be directly influenced by long-term exposure to air pollutants.[1] The percentage of deaths and DALYs attributable to ambient $PM_{2\cdot5}$ was higher in men than in women, while the pattern was reversed for household $PM_{2\cdot5}$ from solid fuels. The GBD 2021 Risk Factors Collaborators reported higher ambient $PM_{2\cdot5}$ exposure in men, and higher household $PM_{2\cdot5}$ exposure in women, for China.[1] This reversal might be explained by the differing social roles of men and women—a trend observed in many countries worldwide, including China. Women often bear the responsibility for household tasks such as cooking, which can lead to a higher frequency of exposure to household air pollution.[27,28] By contrast, men are more likely to be engaged in outdoor labour-intensive work, potentially leading to higher ambient $PM_{2·5}$ exposure.

There was substantial geographical heterogeneity in the disease burden, with a higher burden from ambient $PM_{2·5}$ in north and northwest China and a higher burden from household $PM_{2·5}$ in southwest China. Variations in $PM_{2·5}$ pollution, socioeconomic factors, and meteorological characteristics might contribute to this diversity.[2] Specifically, provinces in north China, such as Hebei and Tianjin, typically face elevated levels of ambient $PM_{2·5}$ pollution, primarily due to industrial activities and coal burning.[29] Therefore, stricter regulations on industrial emissions and promotion of clean energy are crucial in these regions. In northwest China, particularly in arid regions such as Xinjiang, high ambient $PM_{2·5}$ concentrations are often exacerbated by dusty storms.[30] Here, improving the ecological environment by restoring vegetation cover and implementing better land management practices can help mitigate particulate matter pollution.[30] By contrast, southwest China, characterised by high altitude, low temperatures, and extensive rural areas, has higher levels of household $PM_{2·5}$ pollution due to solid fuel use.[21] To address this issue, efforts should focus on improving access to clean cooking technologies, such as improved stoves and alternative clean fuels. Findings on the higher disease burden in low SDI and medium SDI regions further supported the role of socioeconomic factors in shaping geographical disparity. In medium SDI regions, efforts should focus on controlling ambient $PM_{2·5}$ pollution, while in low SDI regions priority should be given to improving access to and adoption of clean fuels for cooking.

From 1990 to 2021, China implemented a series of air pollution control policies, mainly in three phases.[4,31] The early phase (1990–2000) focused on sulphur dioxide and acid rain, with measures including limiting coal sulphur content and enforcing emissions standards.[4] During the transitional phase (2001–10), the focus expanded to sulphur dioxide, nitrogen oxides, and inhalable particulate matter. Key actions included implementing desulphurisation and denitration facilities in coal power plants, and controlling industrial emissions and dust.[31] Specific regions, including the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Pearl River Delta, implemented joint prevention and control of air pollution, and were encouraged to control $PM_{2·5}$ and ozone.[4] During the third phase (2011–present), the focus shifted to $PM_{2·5}$, ozone, and volatile organic compound pollution. The Air Pollution Prevention and Control Action Plan, launched in 2013, outlined stringent strategies to improve ambient air quality, including controlling industrial emissions, optimising industrial structure by upgrading traditional industries with more efficient and environmentally friendly technologies, promoting clean energy, and developing monitoring systems.[3,31] Meanwhile, the Residential Coal Switch Policy was implemented to reduce household coal consumption and increase clean energy use.[5] Both policies prioritised the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Pearl River Delta. China implemented the Blue Sky Defense Battle in 2018, and the Action Plan for Continuous Improvement of Air Quality in 2023. Both plans expanded key regions, set more refined targets, and promoted coordinated efforts to reduce $PM_{2·5}$ and address multi-pollutant pollution.

The spatiotemporal trends in the disease burden from ambient $PM_{2·5}$ in our study align with the timeline of policy implementation. Consistent with previous studies,[6,15,17] the disease burden increased in most provinces before 2013, and declined significantly thereafter. Prioritised areas including the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Pearl River Delta generally showed larger decreases. A novel finding is that the burden in Beijing, Tianjin, Shanghai, Zhejiang, and Guangdong began decreasing as early as 2005, coinciding with the earlier implementation of $PM_{2·5}$ pollution controls in these regions.[4] We also observed a slight increase in the burden from 2020 to 2021, which still warrants further investigation. Compared to previous studies, our study covers a longer time period and thus offers a unique long-term perspective on the temporal trend of $PM_{2·5}$ pollution impacts. As the majority of the Chinese population still resides in areas exceeding WHO's annual $PM_{2·5}$ guideline level of 5 μg/m³,[13] further comprehensive measures to mitigate ambient particulate matter pollution are urgently needed.

Over the past three decades, the disease burden attributable to household $PM_{2·5}$ from solid fuels significantly declined, especially in provinces from more developed regions such as east and south China. Previous evidence has also shown an increase in per capita clean energy consumption and a decline in non-clean energy use in China in the past decades.[32] This trend could be largely due to China's rapid economic growth and urbanisation, which correlated with the adoption of clean energy in households.[33] The Residential Coal Switch Policy also contributed to mitigating household air pollution, particularly in the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Pearl River Delta.[5] However, Tibet had the smallest reduction in disease burden, highlighting an urgent need to improve household air quality and accelerate clean energy adoption in this region. A slight increase in the disease burden from household $PM_{2·5}$ was observed after 2020, similar to the trend seen for ambient $PM_{2·5}$, which warrants further investigation.

Our study provides a comprehensive and up-to-date assessment of the temporal trend in, and spatial distribution of, the disease burden attributable to both ambient and household $PM_{2\cdot5}$ in China. The use of updated methodologies and the most recent dataset ensures robust and reliable estimates. The results offer valuable insights for evidence-based policy formulation and air quality management in China and other countries facing similar challenges.

Several limitations of this study should be acknowledged. First, fixed-site monitoring stations for $PM_{2\cdot5}$ concentrations in China were widely established only since 2013, and satellite-based estimates have only been available since 1998. Consequently, there were inevitably exposure misclassifications in $PM_{2\cdot5}$ concentrations for earlier years. Second, the spatial resolution of the air pollution data (ie, $0\cdot1°\times0\cdot1°$) used in the present study is relatively coarse, which might limit the precision of estimates at smaller scales. Future studies would benefit from exposure data with higher spatial resolution. Third, our assessment of the disease burden attributable to household $PM_{2\cdot5}$ only considered solid fuel use for cooking, excluding other sources such as heating, which have also been linked to mortality and morbidity.[34,35] Consequently, this might result in underestimation of the true disease burden attributable to household $PM_{2\cdot5}$. Fourth, due to the unavailability of detailed time-activity data, this study did not account for the time people spent outdoors or indoors, which might also lead to exposure misclassifications. Future studies integrating time-activity patterns could help address this issue and improve exposure accuracy. Fifth, we only assessed disease burden at the provincial level, potentially overlooking considerable heterogeneity among different counties within the same province. There might also be uncaptured uncertainty in regions without sufficient data. Finally, we did not consider the potential interactions between $PM_{2\cdot5}$ and other co-pollutants such as nitrogen dioxide and ozone, which could affect the accuracy of the disease burden estimates.[36,37]

In summary, despite substantial improvements in China's air quality over the past decades, the persistent disease burden associated with $PM_{2\cdot5}$ pollution, especially ambient $PM_{2\cdot5}$ pollution, remains a major concern. The burden is higher in children aged younger than 5 years, people aged older than 70 years, and those with cardiopulmonary diseases. Evident geographical variations were found, with higher burdens due to ambient $PM_{2\cdot5}$ in north and northwest China, and higher burdens due to household $PM_{2\cdot5}$ in southwest China. To address these challenges, targeted policies are urgently needed, including special protection for vulnerable populations, stricter control of ambient air pollution in northern and northwestern regions, and the promotion of clean energy for cooking in southwestern areas. All these measures are essential to mitigate the overall disease burden attributable to $PM_{2\cdot5}$ pollution in China.

Contributors

TY and YJ did the formal data analysis and drafted the initial manuscript. RC, PY, and HL curated the data and provided important suggestions on methodology. HK and MZ contributed to study conceptualisation, data curation, and supervision. TY, YJ, HK, and MZ verified the underlying data. All authors contributed to the critical review and revision of the manuscript for important intellectual content and endorsed the final version for submission. The corresponding authors attest that all listed authors meet the authorship criteria and that no others meeting the criteria have been omitted. The corresponding authors had full access to all the data in the study and had final responsibility for the decision to submit the manuscript for publication after obtaining approval from all coauthors.

Declaration of interests

We declare no competing interests.

Data sharing

To download GBD data used in the analyses, please visit the Global Health Data Exchange GBD 2021 website (https://vizhub.healthdata.org/gbd-results/). The data at the provincial level used for the analyses are available by email request to the corresponding authors.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (grant number 82030103), the National Key Research and Development Program of China (grant number 2022YFC3702701), Shanghai Municipal Science and Technology Major Project (grant number 2023SHZDZX02), and China Postdoctoral Science Foundation (grant number 2023M740649).

References

1 GBD 2021 Risk Factors Collaborators. Global burden and strength of evidence for 88 risk factors in 204 countries and 811 subnational locations, 1990–2021: a systematic analysis for the Global Burden of Disease Study 2021. *Lancet* 2024; **403:** 2162–203.

2 Yin P, Brauer M, Cohen AJ, et al. The effect of air pollution on deaths, disease burden, and life expectancy across China and its provinces, 1990–2017: an analysis for the Global Burden of Disease Study 2017. *Lancet Planet Health* 2020; **4:** e386–98.

3 Chen Z, Wang JN, Ma GX, Zhang YS. China tackles the health effects of air pollution. *Lancet* 2013; **382:** 1959–60.

4 Wang W, Chai F, Ren Z, et al. Process, Achievements and experience of air pollution control in China since the founding of the People's Republic of China 70 years ago. *Huanjing Kexue Yanjiu* 2019; **32:** 1621–35.

5 Liu C, Zhu B, Ni J, Wei C. Residential coal-switch policy in China: development, achievement, and challenge. *Energy Policy* 2021; **151:** 112165.

6 Liang F, Xiao Q, Huang K, et al. The 17-y spatiotemporal trend of $PM_{2.5}$ and its mortality burden in China. *Proc Natl Acad Sci USA* 2020; **117:** 25601–08.

7 Zhang Q, Meng X, Shi S, Kan L, Chen R, Kan H. Overview of particulate air pollution and human health in China: evidence, challenges, and opportunities. *Innovation* 2022; **3:** 100312.

8 Meng X, Liu C, Zhang L, et al. Estimating $PM_{2.5}$ concentrations in northeastern China with full spatiotemporal coverage, 2005–2016. *Remote Sens Environ* 2021; **253:** 253.

9 Xiao Q, Geng G, Liang F, et al. Changes in spatial patterns of $PM_{2.5}$ pollution in China 2000–2018: Impact of clean air policies. *Environ Int* 2020; **141:** 105776.

10 Chen Y, Guo F, Wang J, Cai W, Wang C, Wang K. Provincial and gridded population projection for China under shared socioeconomic pathways from 2010 to 2100. *Sci Data* 2020; **7:** 83.

11 Zhao X, Zhou W, Han L, Locke D. Spatiotemporal variation in $PM_{2.5}$ concentrations and their relationship with socioeconomic factors in China's major cities. *Environ Int* 2019; **133:** 105145.

12 Liu N, Liu W, Deng F, et al. The burden of disease attributable to indoor air pollutants in China from 2000 to 2017. *Lancet Planet Health* 2023; **7:** e900–11.

13 Shi S, Wang W, Li X, et al. Evolution in disparity of $PM_{2.5}$ pollution in China. *Eco Environ Health* 2023; **2:** 257–63.

14 GBD 2021 Diseases and Injuries Collaborators. Global incidence, prevalence, years lived with disability (YLDs), disability-adjusted life-years (DALYs), and healthy life expectancy (HALE) for 371 diseases and injuries in 204 countries and territories and 811 subnational locations, 1990–2021: a systematic analysis for the Global Burden of Disease Study 2021. *Lancet* 2024; **403:** 2133–61.

15 Xiao Q, Geng G, Xue T, et al. Tracking $PM_{2.5}$ and O_3 pollution and the related health burden in China 2013–2020. *Environ Sci Technol* 2022; **56:** 6922–32.

16 Wang Q, Wang J, He MZ, Kinney PL, Li T. A county-level estimate of $PM_{2.5}$ related chronic mortality risk in China based on multi-model exposure data. *Environ Int* 2018; **110:** 105–12.

17 Liu M, Huang Y, Ma Z, et al. Spatial and temporal trends in the mortality burden of air pollution in China: 2004-2012. *Environ Int* 2017; **98:** 75–81.

18 Maji KJ, Ye WF, Arora M, Shiva Nagendra SM. $PM_{2.5}$-related health and economic loss assessment for 338 Chinese cities. *Environ Int* 2018; **121:** 392–403.

19 Liu J, Han Y, Tang X, Zhu J, Zhu T. Estimating adult mortality attributable to $PM_{2.5}$ exposure in China with assimilated $PM_{2.5}$ concentrations based on a ground monitoring network. *Sci Total Environ* 2016; **568:** 1253–62.

20 Xie R, Sabel CE, Lu X, et al. Long-term trend and spatial pattern of $PM_{2.5}$ induced premature mortality in China. *Environ Int* 2016; **97:** 180–86.

21 Yang J, Lin Z, Shi S. Household air pollution and attributable burden of disease in rural China: A literature review and a modelling study. *J Hazard Mater* 2024; **470:** 134159.

22 Bowe B, Xie Y, Yan Y, Al-Aly Z. Burden of cause-specific mortality associated with $PM_{2.5}$ air pollution in the United States. *JAMA Netw Open* 2019; **2:** e1915834.

23 GBD 2021 Causes of Death Collaborators. Global burden of 288 causes of death and life expectancy decomposition in 204 countries and territories and 811 subnational locations, 1990–2021: a systematic analysis for the Global Burden of Disease Study 2021. *Lancet* 2024; **403:** 2100–32.

24 Peled R. Air pollution exposure: who is at high risk? *Atmos Environ* 2011; **45:** 1781–85.

25 Di Q, Dai L, Wang Y, et al. Association of short-term exposure to air pollution with mortality in older adults. *JAMA* 2017; **318:** 2446–56.

26 Feng G, Xia J, Wang X, et al. Assessing the disease burden of air pollution on children and adolescents in China from 1990 to 2019. *Innov Med* 2024; **2:** 100057.

27 Austin KF, Mejia MT. Household air pollution as a silent killer: women's status and solid fuel use in developing nations. *Popul Environ* 2017; **39:** 1–25.

28 Shin HH, Maquiling A, Thomson EM, Park IW, Stieb DM, Dehghani P. Sex-difference in air pollution-related acute circulatory and respiratory mortality and hospitalization. *Sci Total Environ* 2022; **806:** 150515.

29 Zhang X, Gu X, Cheng C, Yang D. Spatiotemporal heterogeneity of $PM_{2.5}$ and its relationship with urbanization in North China from 2000 to 2017. *Sci Total Environ* 2020; **744:** 140925.

30 Rupakheti D, Yin X, Rupakheti M, et al. Spatio-temporal characteristics of air pollutants over Xinjiang, northwestern China. *Environ Pollut* 2021; **268:** 115907.

31 Ma Z, Liu R, Liu Y, Bi J. Effects of air pollution control policies on $PM_{2.5}$ pollution improvement in China from 2005 to 2017: a satellite-based perspective. *Atmos Chem Phys* 2019; **19:** 6861–77.

32 Li F, Liang W, Chandio AA, Zang D, Duan Y. Household clean energy consumption and health: Theoretical and empirical analysis. *Front Public Health* 2022; **10:** 945846.

33 Shen G, Xiong R, Tian Y, et al. Substantial transition to clean household energy mix in rural China. *Natl Sci Rev* 2022; **9:** nwac050.

34 Chen Y, Shen H, Smith KR, et al. Estimating household air pollution exposures and health impacts from space heating in rural China. *Environ Int* 2018; **119:** 117–24.

35 Mohajeri N, Hsu SC, Milner J, et al. Urban-rural disparity in global estimation of $PM_{2.5}$ household air pollution and its attributable health burden. *Lancet Planet Health* 2023; **7:** e660–72.

36 Liu C, Chen R, Sera F, et al. Interactive effects of ambient fine particulate matter and ozone on daily mortality in 372 cities: two stage time series analysis. *BMJ* 2023; **383:** e075203.

37 Guo J, Zhou J, Han R, et al. Association of short-term co-exposure to particulate matter and ozone with mortality risk. *Environ Sci Technol* 2023; **57:** 15825–34.