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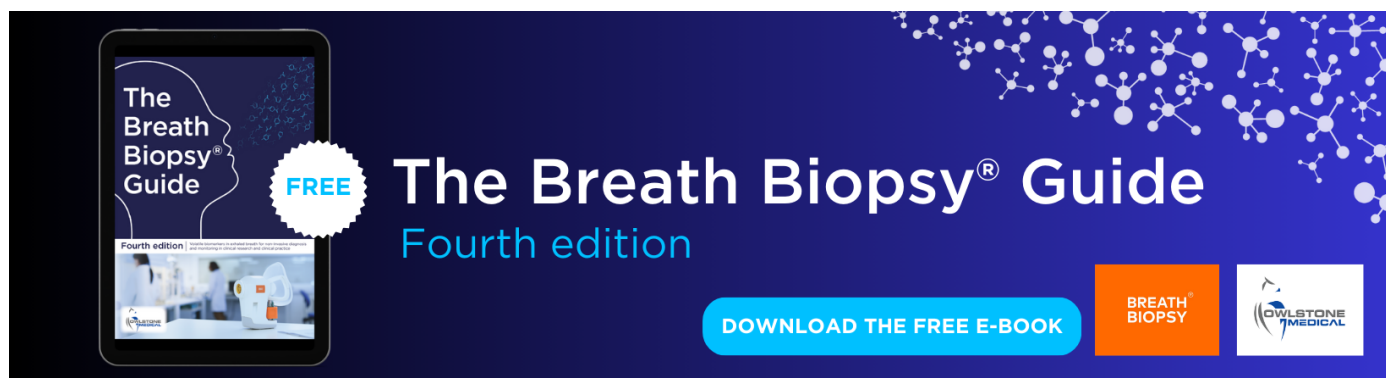
A health impact assessment of long-term exposure to particulate air pollution in Thailand

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A health impact assessment of long-term exposure to particulate
air pollution in ThailandWilliam Mueller¹ , Sotiris Vardoulakis^{1,2}, Susanne Steinle¹, Miranda Loh¹, Helinor J Johnston³,
Nopadol Precha⁴ , Wissanupong Kliengchuay⁵, Narut Sahanavin⁶, Kanchana Nakhapakorn⁵,
Rattapol Sillaparassamee⁷, Kraichat Tantrakarnapa⁵ and John W Cherrie^{1,3} ¹ Institute of Occupational Medicine, Edinburgh, United Kingdom² National Centre for Epidemiology and Population Health, Research School of Population Health, Australian National University, Canberra, Australia³ School of Engineering and Physical Sciences, Heriot Watt University, Edinburgh, United Kingdom⁴ Walailak University, Nakhon Si Thammarat, Thailand⁵ Mahidol University, Bangkok, Thailand⁶ Srinakharintarawiroj University, Bangkok, Thailand⁷ Faculty of Public Health, Valaya Alongkorn Rajabhat University, Patham Thani, ThailandE-mail: j.cherrie@hw.ac.uk**Keywords:** health impact assessment, particulate matter, air pollution, value of a statistical lifeSupplementary material for this article is available [online](#)**Abstract**

Particulate air pollution causes a spectrum of adverse health effects affecting the respiratory, cardiovascular, neurological, and metabolic systems that are hypothesised to be driven by inflammation and oxidative stress. Millions of premature deaths each year are attributed to exposure to ambient particulate matter (PM). We quantified health and economic impacts from long-term exposure to ambient PM_{2.5} in the population of Thailand for 2016. We collected data on ambient PM_{2.5} concentrations from automatic monitoring stations across Thailand over 1996–2016. We used historic exposure to PM_{2.5} to estimate the mortality in each province from lower respiratory infections (LRIs), stroke, chronic obstructive pulmonary disease, lung cancer, and ischaemic heart disease, and also assessed diabetes mortality, as well as incident cases of dementia and Parkinson's disease, in supplementary analyses. We applied risk estimates from the Global Exposure Mortality Model to calculate attributable mortality and quantify disability-adjusted life years (DALYs); we based economic costs on the value of a statistical life (VSL). We calculated 50 019 (95% confidence interval [CI]: 42 189–57 849) deaths and 508 918 (95% CI: 438 345–579 492) DALYs in 2016 attributed to long-term PM_{2.5} exposure in Thailand. Population attributable fractions ranged from 20% (95% CI: 10% to 29%) for stroke to 48% (95% CI: 27% to 63%) for LRIs. Based on the VSL, we calculated a cost of US\$ 60.9 billion (95% CI: US\$ 51.3–70.4 billion), which represents nearly 15% of Thailand's gross domestic product in 2016. While progress has been made to reduce exposure to ambient PM_{2.5} in Thailand, continued reductions based on stricter regulatory limits for PM_{2.5} and other air pollutants would help prolong life, and delay, or prevent, onset of cardiorespiratory and other diseases.

1. Background

Exposure to ambient particulate matter (PM), especially that from traffic-related sources, has consistently been linked to adverse health outcomes (Kim *et al* 2015). There is now a growing body of evidence suggesting exposure to non-traffic derived PM, including industrial emissions, natural dust and salts,

and biomass burning, can also cause harmful health effects (Hime *et al* 2018, Johnston *et al* 2019). Air pollution may damage health through a number of mechanisms, including oxidative stress and inflammation, leading to detrimental impacts on the respiratory, and cardiovascular systems, as well as a growing list of other adverse health outcomes (Münzel *et al* 2017). In addition to PM, gaseous air pollutants, such

as ozone, nitrogen dioxide, carbon monoxide, and sulphur dioxide, have been documented to cause a wide range of pathologies (Schraufnagel *et al* 2019).

The population of Thailand is exposed to PM from a range of sources, which varies spatially and temporally. In the capital, Bangkok, with a population of over 12 million, the number of cars on the road exceeds 10 million, representing a significant source of PM of size $<2.5 \mu\text{m}$ ($\text{PM}_{2.5}$) (Cheewaphongphan *et al* 2017). Emissions from biomass burning, industry, traffic, and power plants are the main contributors of PM_{10} emissions in Thailand (Vongmahadlek *et al* 2009). In the north, and the rest of the country to a lesser extent, the population is exposed to annual episodes of biomass burning of agricultural residues and forested areas, originating from within and outside Thailand, ultimately leading to very high ambient PM_{10} concentrations during January to April each year (Kliengchuay *et al* 2018, 2021, Punsompong and Chantara 2018, Mueller *et al* 2020).

Health impact assessment (HIA) is a methodology used to estimate the change in health impacts on a population level based on a given change in an exposure. In addition to predicting impacts from different policy options, HIA can also be used to quantify the overall burden of disease from a given exposure. Exposure to ambient $\text{PM}_{2.5}$ is estimated to lead to over 4 million deaths globally each year (Cohen *et al* 2017). In Thailand specifically, annual all-cause mortality has been estimated to be almost 40 000, with the percentage of deaths attributed to $\text{PM}_{2.5}$ at nearly 17% for lung cancer (Pinichka *et al* 2017).

To update and expand earlier work on the burden of disease from particulate air pollution, we undertook an HIA to quantify the health and economic impacts across Thailand from long-term exposure to ambient $\text{PM}_{2.5}$. We included health endpoints where evidence of exposure to ambient particulate air pollution is more established (i.e. respiratory and cardiovascular disease) and also investigated in supplementary analyses those still emerging (i.e. neurological and metabolic diseases). The results of this assessment could be used to provide justification for stricter air pollution regulations, both in Thailand and in other jurisdictions. This study is part of a research project to study the effects of air pollution in Thailand: Thailand Air Pollution Health Impact Assessment (TAPHIA).

2. Methods

We conducted an HIA, which necessitates identifying pollution sources, population at risk, background health data, and concentration-response functions (CRFs). The data from these inputs are combined in a health impact function to provide estimates of health impacts.

2.1. Air pollution data

We obtained from the Thai Pollution Control Department hourly averaged pollutant data from the national ground monitoring network of 63 sites. Data were available on individual pollutants, including PM_{10} , $\text{PM}_{2.5}$, carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2), and select volatile organic compounds. Air pollutant data were provided over the period 1996–2017. To measure the long-term exposure to $\text{PM}_{2.5}$, we calculated mean concentrations over the period 1996–2016 (2017 was excluded, as health data were received only up to 2016). To ensure that monitors were representative of the full period, we included only background monitors with sufficient data (i.e. those that had $<25\%$ missing PM data over 1996–2016 (Wong *et al* 2008)). This reduced the number of monitors with sufficient data to 16 sites, which were located in provinces representing 23% of the study population (see figure S1 (available online at stacks.iop.org/ERL/16/055018/mmedia)). We also performed a sensitivity analysis with two additional monitors with less than sufficient data (see supplementary material).

As the measurement of ambient $\text{PM}_{2.5}$ in Thailand did not start until 2011, we estimated concentrations during 1996–2011 based on the ratio of $\text{PM}_{2.5}:\text{PM}_{10}$ from stations where both PM size fractions were collected concurrently. We calculated regional average ratios and then applied them to PM_{10} concentrations of stations within each region (WHO 2016a) to calculate surrogate $\text{PM}_{2.5}$ concentrations. The mean $\text{PM}_{2.5}:\text{PM}_{10}$ ratios ranged from 0.50 (south) to 0.78 (northeast), which appear to be similar to published values, such as for Bangkok, Thailand (Fold *et al* 2020) and China (Gao *et al* 2015, Xu *et al* 2016) (see table S1). We calculated means for each station across 1996–2016 using these surrogate and true $\text{PM}_{2.5}$ concentrations. To convert these point estimates to average values for each province in Thailand, which could then be linked to province-level health and population data in the HIA, we used BenMAP (CE 1.5.0), a mapping software developed by the United States Environmental Protection Agency (USEPA 2018). BenMAP uses Voronoi neighbourhood averaging to interpolate air pollutant concentrations, which has been shown to produce similar results to inverse distance weighting and kriging (Yu *et al* 2018). As a comparator, we also calculated long-term mean provincial $\text{PM}_{2.5}$ values based on nearest neighbour analysis.

2.2. Population at risk

The population at risk for exposure to air pollution was the whole population of Thailand. However, as we were interested in quantifying the long-term effects of air pollution, we included only those in Thailand aged 25 years or older; mortality levels are quite low in these younger age groups, so their exclusion would not greatly alter our estimates. We

obtained population estimates by 5 year age group for each province from the Thai National Statistics Office (2020). For the year 2016, we used a total population figure of 43 831 365.

2.3. Selection of health endpoints

We included those causes of mortality with robust evidence with PM_{2.5}, namely: lower respiratory infections (LRIs), stroke, chronic obstructive pulmonary disease (COPD), lung cancer, and ischaemic heart disease (IHD) (Burnett *et al* 2018). In addition to these well-established health outcomes associated with air pollution exposure, we included in the HIA novel endpoints with compelling evidence of harm from more recent epidemiological studies. As important chronic conditions that constitute a growing global burden of disease (Naghavi *et al* 2017), we included diabetes, Alzheimer's disease and Parkinson's disease in the HIA, which have been linked to long-term PM_{2.5} exposure (Dimakakou *et al* 2018). We present in the main paper the results of the established health endpoints and include in the supplementary material additional details on the novel health outcomes.

2.4. Baseline health data

We obtained multi-year individual mortality data from the Thai Ministry of Public Health (MoPH) and included in the HIA the most recent year (2016), which included date of death, age, and province for the following health outcomes (International Classification of Disease revision 10): lung cancer (C34), COPD (J41-J44, J47), IHD (I20-I25), stroke (I60-I69), and diabetes mellitus (E10-E14). We used Stata (v15) to calculate mortality rates by 5 year age groups separately for each province for these health endpoints. For LRI (A48.1, A70, B96.0-B96.1, B97.21, B97.4-B97.6, J09-J18.2, J18.8-J18.9, J19.6-J22.9, J85.1, P23-P23.9, U04-U04.9, Z25.1), we obtained national (i.e. not provincial) average mortality rates for 2016 by 5 year age group in Thailand using data from the appendix of the Global Burden of Disease (GBD) study (Naghavi *et al* 2017).

It has been reported that Thailand death certificates entail a high proportion of unclassified or nonspecific deaths (Rao *et al* 2010, Naghavi *et al* 2017). Therefore, since we obtained cause-specific mortality data, we adjusted upward the rates to account for uncoded deaths. As the GBD study employed a comprehensive methodology to redistribute unclassified deaths for individual countries, we multiplied our calculated provincial- and age-specific rates by a cause-specific mortality correction factor. This adjustment assumes uncoded deaths do not vary by age or province. The correction factors ranged from 1.17 (stroke) to 2.72 (COPD) (see table S2) and were calculated with the following formula:

Mortality Correction Factor =

$$\text{GBD Mortality Count} \div \text{MoPH Mortality Count.} \quad (1)$$

2.5. Concentration response functions

For the better established health endpoints (i.e. LRI, stroke, COPD, lung cancer, and IHD), we used CRFs developed by Burnett *et al* (2018) in the Global Exposure Mortality Model (GEMM), which is based on 41 cohort studies of exposure to ambient PM concentrations in populations predominantly in Europe and North America, but also in Asia.

2.6. Calculation of health impacts

Using the above discussed inputs, we constructed an HIA model in MS Excel to calculate health impacts for the populations of every 5 year age group over 25 years (40+ years for Alzheimer's disease) in each province of Thailand. We used a burden of disease approach, meaning we calculated the cases of mortality/incidence for each health endpoint that was attributed to long-term PM_{2.5} exposure, as defined by overall mean concentrations in each province during 1996–2016. We used a counterfactual concentration of 2.4 $\mu\text{g m}^{-3}$, which implies there would be no change in risk from 0 to 2.4 $\mu\text{g m}^{-3}$ (Burnett *et al* 2018). Therefore, we subtracted 2.4 from the province-level long-term PM_{2.5} means for the purposes of health impact modelling. Upper and lower 95% confidence intervals (CIs) were calculated for health and economic impacts based on the CIs of the CRFs; 95% CIs of the aggregate impacts were based on the square root of the sum of squares of the individual standard errors (Altman & Bland 2003).

We also modelled the health and economic benefits for two scenarios: universal reductions in mean ambient PM_{2.5} concentrations to 10 $\mu\text{g m}^{-3}$ and 25 $\mu\text{g m}^{-3}$ in every province, based on the World Health Organization (WHO) and the Thai National Ambient Air Quality Standards annual limits for PM_{2.5}, respectively. We calculated the potential differences in impacts by subtracting mortality, incidence, and costs associated with the historic PM_{2.5} levels with those calculated in the two scenarios. Actual PM_{2.5} levels were retained for any provinces with levels below either of the scenario values; $n = 16$ provinces had mean PM_{2.5} concentrations below 25 $\mu\text{g m}^{-3}$.

We used the CRFs from Burnett *et al* (2018) to calculate deaths from LRI, stroke, COPD, lung cancer, and IHD. Population attributable fractions (PAFs) were calculated based on observed (O) and expected (E) deaths/cases, as in equation (2) (Mansournia and Altman 2018).

$$\text{PAF} = \frac{\sum(O - E)}{\sum O}. \quad (2)$$

We calculated years of lost life (YLL) for each individual cause of mortality by multiplying the number

of deaths by the probability of survival in each 5 year age group up to the median life expectancy of 76 years (World Bank 2019) based on a life table for Thailand (Miller and Hurley 2003, WHO 2016b). We estimated years living with disability (YLDs) for the incident neurodegenerative diseases and also for mortality from diabetes, IHD, COPD, and lung cancer. YLDs were calculated by applying disability weights to an assumed amount of time living with disability prior to death. Disability weights can take the value of 0 (good health) to 1 (death) depending on the severity and impact of a given disease. We summed YLDs and YLLs to calculate the overall disability adjusted life years (DALYs). We display in table S3 our assumptions for YLD calculations.

2.7. Calculation of economic impacts

We estimated the economic costs of the deleterious health impacts attributed to long-term PM_{2.5} exposure. This may be calculated using a value of a statistical life (VSL), which can be used to assess trade-offs between health and safety and costs. VSLs may be based on surveys of willingness-to-pay or wage compensation for riskier jobs. This metric differs from and tends to encompass much higher costs than those specifically incurred by the health care system, which we did not address. We identified a study that estimates a VSL for Thailand using data from 2012 to 2014 (Witvorapong and Komonpaisarn 2020). We adjusted this VSL to account for inflation (i.e. the general rise of prices during that period) to provide a VSL in 2016 of roughly US\$ 1.22 million, which is very similar to other estimates of the average VSL for an upper-middle income country (i.e. such as Thailand) (Viscusi and Masterman 2017). As a comparator, we adjusted the 2005 Organisation for Economic Co-operation and Development (OECD) VSL of US\$ 3 million based on purchasing power parity and using an income elasticity of 0.9 (OECD 2016) to calculate an amount of US\$ 1.65 million; this adjustment was necessary to account for the cost of living in Thailand. We multiplied each of these VSL figures by the number of deaths attributed to PM exposure.

We estimated the value of a statistical life year (VSLY), which accounts for the projected YLLs, not just mortality. This such measure is considered contentious, as it implies a lower value assigned to deaths at older ages, though we included this metric to attempt to quantify the burden of premature deaths; the VSL may overstate costs, since ultimately deaths are delayed, rather than prevented (Marteniens *et al* 2015). We calculated VSLY by dividing the VSL by the life expectancy in Thailand (76 years). This calculation provided an average cost for a life year, assuming no difference in the value given to different ages, of US\$ 16 008 and US\$ 21 682, based on the Thai and OECD adjusted VSLs, respectively. To help interpret results, we compared the overall economic costs as a

percentage to the gross domestic product (GDP) of Thailand in 2016, which was US\$ 412 billion (Country Economy 2020).

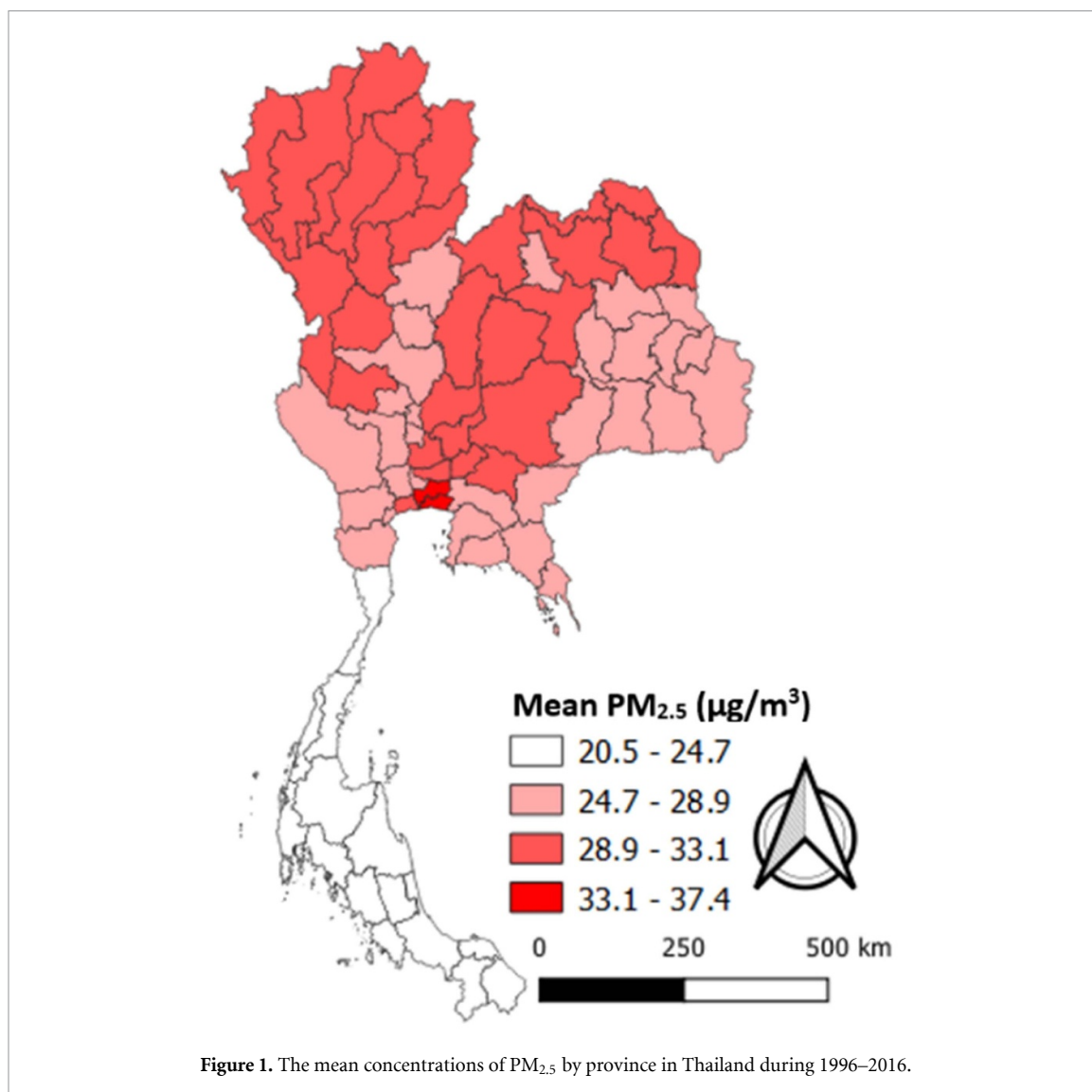
3. Results

The estimated long-term (1996–2016) mean PM_{2.5} concentrations for each province in Thailand ranged from 20.5 $\mu\text{g m}^{-3}$ to 37.4 $\mu\text{g m}^{-3}$. Ambient concentrations were lowest in the south of the country, and highest in Bangkok, as well as areas in the north (see figure 1). There was an apparent long-term decline in PM_{2.5} levels across the monitoring network, with mean annual concentrations decreasing from 41.5 $\mu\text{g m}^{-3}$ in 1996 to 24.1 $\mu\text{g m}^{-3}$ in 2016 (−41.9%). The reduction in ambient concentrations appears mostly to have occurred in the first half of the study period, with levels mainly constant in the past decade (see figure 2). Although there was good correlation between the Voronoi averaging and those values calculated using nearest neighbour ($r = 0.76$), concentrations were generally greater using the latter method (data not shown).

We calculated 50 019 (95% CI: 42 189–57 849) deaths and 508 918 (95% CI: 438 345–579 492) DALYs in 2016 attributed to long-term PM_{2.5} exposure in Thailand. We observed the most deaths for LRI (16 419 [95% CI: 9154–21 544]) and IHD (15 489 [95% CI: 14 266–16 661]). PAFs ranged from 20% (95% CI: 10% to 29%) for stroke to 48% (27% to 63%) for LRI. There were substantially more DALYs for IHD (180 008 [95% CI: 166 636–192 679]) compared to any other cause of mortality (table 1). Results of the novel (i.e. metabolic and neurodegenerative) health endpoints are presented in the supplementary material.

Using the VSL for Thailand for the total number of attributable deaths in 2016, we calculated a cost of US\$ 60.9 billion (US\$ 51.3–70.4 billion), which represents approximately 14.8% (95% CI: 12.4% to 17.1%) of Thailand's GDP. This amount was substantially reduced if economic costs were based on DALYs and the VSLY calculated for Thailand: US\$ 8.1 billion (95% CI: US\$ 7.0–9.3 billion) or 2.0% (95% CI: 1.7% to 2.2%) of GDP. If we used the adjusted OECD VSL (i.e. US\$ 1.65 million), the cost associated with the attributable deaths markedly increased to US\$ 82.4 billion (95% CI: US\$ 69.5–95.3 billion), or 20.0% (95% CI: 16.9% to 23.1%) of GDP. Likewise, when we used the adjusted OECD VSLY, the economic costs from the total DALYs grew to US\$ 11.0 billion (95% CI: US\$ 9.5–12.6 billion), or 2.7% (95% CI: 2.3% to 3.0%) of overall GDP.

We also analysed the health benefits from hypothetical PM_{2.5} reductions to 10 $\mu\text{g m}^{-3}$ and 25 $\mu\text{g m}^{-3}$ in each province over the life course of the exposed population. This reduction in ambient PM_{2.5} levels is estimated to have an effect of 28 681 (95% CI: 24 382–32 980) and 4741 (95% CI: 4222–5260)



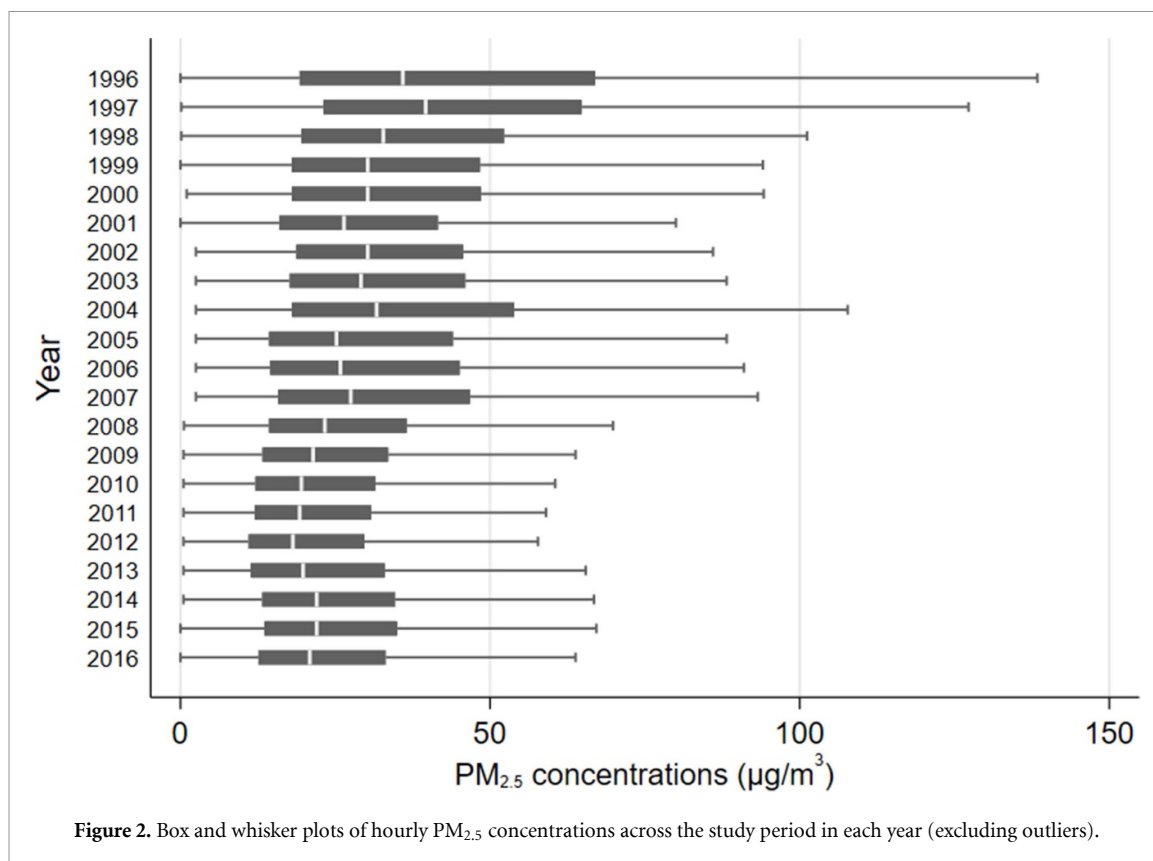
fewer deaths, and 284 212 (95% CI: 245 072–323 353) and 48 522 (95% CI: 42 811–54 232) fewer DALYs in the 10 µg m⁻³ and 25 µg m⁻³ scenarios, respectively. The overall PAFs associated with the 10 µg m⁻³ and 25 µg m⁻³ scenarios were 13% (95% CI: 9% to 17%) and 28% (95% CI: 19% to 36%), respectively. The associated savings using the Thai VSL would be US\$ 34.9 billion (95% CI: US\$ 29.7–40.1 billion) and US\$ 5.8 billion (95% CI: US\$ 5.1–6.4 billion) based on deaths, and US\$ 4.6 billion (95% CI: US\$ 3.9–5.2 billion) and US\$ 0.78 billion (95% CI: US\$ 0.69 billion to 0.87 billion) savings from the cost of DALYs in the 10 µg m⁻³ and 25 µg m⁻³ scenarios, respectively.

4. Discussion

We undertook an HIA for long-term exposure (1996–2016) to PM_{2.5} for the population of Thailand aged over 25 years in 2016. We calculated 50 019 deaths and over 508 918 DALYs from LRI, stroke, COPD, lung cancer, and IHD. In modelling a nation-wide

reduction to 10 µg m⁻³ of PM_{2.5}, we identified decreases in the overall PAF of 18 percentage points.

Our HIA in Thailand from air pollution mortality estimates were somewhat smaller than those calculated for the year 2015 by Burnett *et al* (2018) using the GEMM estimates, ranging from 1% (COPD) to 39% (LRI) lower. These differences can largely be explained by disparities in the baseline mortality data. We consolidated individual deaths by province and corrected for uncoded deaths using national rates from the GBD study (Naghavi *et al* 2017), whereas the GEMM study made use of the Global Health Data Exchange, which combines numerous different global data sources; to illustrate the differences, the baseline LRI mortality counts was 72% higher in the latter study. We believe our study provides reliable provincial baseline mortality rates for 2016. Pinichka *et al* (2017) calculated 38 410 deaths for all-causes in Thailand in those over 30 years of age in 2009. Our estimates, based on specific causes of diseases are 30% in excess of this figure, likely due to a number of factors, including the application of greater estimates of risk



(i.e. GEMM) across larger overall reductions in PM_{2.5}. The PAFs calculated from exposure to fine PM in our study were substantial, with values for individual causes of mortality ranging from 20% to 48%. For those endpoints for which we relied on GEMM risk estimates, our PAF values are in line with those projected for the observed magnitude of exposure levels (Burnett and Cohen 2020).

We modelled two hypothetical scenarios in which there were consistent PM_{2.5} reductions in each province to 25 and 10 $\mu\text{g m}^{-3}$. Although these might be challenging reductions to achieve, particularly in the higher PM_{2.5} settings, for example, in Bangkok, a study reported a decrease of 21.8% in mean PM_{2.5} concentrations in an urban area in Thailand during March 2020 due to COVID-19 mitigation measures, compared to the preceding time period (Stratoulias and Nuthammachot 2020); other such studies in Southeast Asia also have found reductions in PM_{2.5} and other air pollutants (Kanniah *et al* 2020). It is encouraging that such reductions are possible even though the measures needed to bring them about have been drastic; it remains to be seen whether these reductions are temporary, or whether there will be a priority on sustaining them as societies get accustomed to, and overcome, COVID-19. While even more modest reductions of ambient PM_{2.5} levels will be beneficial, any potential decreases in attributable deaths in the future may be offset to some extent by a growing and ageing population (Butt *et al* 2017).

HIAs in other jurisdictions have estimated economic costs of ill health attributed to air pollution. Due to the wide range of valuation that can be used in an HIA, particularly given the economic disparities between jurisdictions, it is difficult to compare monetary impacts on health. Trejo-Gonzalez *et al* (2019) estimated the number of deaths and costs that would have been prevented if PM_{2.5} levels in Mexico were reduced to 10 $\mu\text{g m}^{-3}$, which equated to 14 666 deaths (all-cause) and US\$ 64 billion, based on the OECD VSL (US\$ 3 million) and adjusted for purchasing power in Mexico. In Japan, Seposo *et al* (2018) calculated nearly 25 000 attributable deaths (all-cause), at a cost of nearly US\$ 80 billion with a VSL of US\$ 3.2 million. These cost estimates from particulate air pollution are within the range of those calculated in the present study using the Thai and adjusted OECD VSL (i.e. US\$ 60.9–82.4 billion).

We included PM_{2.5} as the main exposure in this HIA, since research has indicated this pollutant entails the most widespread health impacts (Cohen *et al* 2017). Studies demonstrate that other air pollutants have also been linked to ill health, but often air pollutants are correlated and are believed to act on similar pathways (e.g. PM_{2.5} and NO₂), so including multiple pollutants in an HIA would likely overestimate health impacts. Using unadjusted CRFs for PM_{2.5} in HIAs also accounts to some extent for health impacts caused by other pollutants from common sources (COMEAP 2018).

Table 1. The overall results (95% confidence interval) of the main HIA analysis of the burden of disease in Thailand from long-term exposure to PM_{2.5}.

Outcome	Health			Economic (\$US millions) ^a	
	Deaths	DALYs	Attributable fractions	Deaths	DALYs
Ischaemic heart disease	15 489 (14 266–16 661)	180 008 (166 636–192 679)	33% (30% to 35%)	18 844 (17 357–20 270)	2882 (2668–3084)
COPD	4999 (2480–7166)	31 090 (15 420–44 575)	24% (12% to 35%)	6082 (3017–8719)	498 (247–714)
Stroke	7411 (3731–10 628)	95 158 (48 805–134 129)	20% (10% to 29%)	9016 (4540–12 931)	1523 (781–2147)
Lower respiratory infections	16 419 (9154–21 544)	105 221 (58 680–138 032)	48% (27% to 63%)	19 976 (11 137–26 212)	1684 (939–2210)
Lung cancer	5701 (3537–7596)	97 440 (60 443–129 850)	27% (17% to 36%)	6936 (4303–9242)	1560 (968–2079)
Total	50 019 (42 189–57 849)	508 918 (438 345–579 492)	31% (21% to 40%)	60 855 (51 328–70 382)	8147 (7017–9277)
% of Thailand GDP	—	—	—	14.8% (12.4% to 17.1%)	2.0% (1.7% to 2.2%)

^a Based on the Thai VSL of US\$ 1.22 million.

There were important sources of uncertainty with the various inputs to our calculations, which is typical in HIA studies. Previous work indicates much of the uncertainty with mortality estimates may be due to the PM_{2.5} estimates and the CRFs, rather than baseline mortality rates (Giani *et al* 2020), despite the differences in the latter between ours and other studies. We estimated mortality from exposure to PM_{2.5} based on mean concentrations of long-term periods (21 years). This is a longer exposure period than that included in other HIAs, which have based mortality from 1 (Pinichka *et al* 2017) to 5 (Cohen *et al* 2017) years. The GEMM risk estimates are based on cohort studies of multi-year follow-up, meaning a multi-year exposure period would be most appropriate, though the optimal period length is unclear. Given the relatively lower recent ambient concentrations in Thailand, had we based exposures on a shorter and more recent period, attributable mortality in general would have been reduced, depending on the specific period and duration. By contrast, if we had explicitly accounted for those outcomes with longer latencies or pre-clinical periods (e.g. lung cancer), such as more heavily weighting or only using the more historic (higher) exposure period, the calculated health impacts would have been greater. Quantification of mortality in a single year based on multiple years of exposure would not capture deaths from earlier years and thus would underestimate the true impact. Likewise, long-term annual averages would to some degree mask seasonal peaks in ambient concentrations, for which there would likely be short-term increases in mortality, for example, the seasonal biomass burning in northern Thailand (Pothirat *et al* 2019). PM_{2.5} estimates based on nearest neighbour methods were found to be higher in our study, although such methods have been shown previously to overestimate concentrations (Xie *et al* 2017). In addition, as we only

included the subset of population older than 25 years, our mortality figures are necessarily an underestimate of the impacts from air pollution, though the contribution from younger ages is small by comparison (Lelieveld *et al* 2018).

Our study raises a number of important considerations to be addressed in future research and HIA studies. We included a broader suite of health endpoints in the supplementary analyses, which produced important findings, as the second highest DALYs were from Alzheimer's disease and dementia. As the evidence base becomes more firm and precise, these and other health outcomes should be considered for quantifying the overall burden of disease and estimating impacts related to ambient air pollution control policies. The duration of exposure data will depend on the specific period of interest, but should be aligned with risk estimates from research with a comparable study period. HIAs should be undertaken to assess health and economic impacts from short and long-term changes as a result of policy measures and large-scale behaviour changes possibly related to COVID-19.

4.1. Strengths and limitations

We attempted to use the best available data for all inputs to provide accurate estimates of the potential health impacts in Thailand from long-term exposure to PM_{2.5}. Unlike previous HIAs, we included provincial level exposure and corrected health data to help refine our estimates, as well as incorporated recent evidence on novel health endpoints. In addition, we extended mortality impacts to include DALYs and economic impacts, and we examined effects of PM_{2.5} reductions in two scenarios based on national regulatory and WHO limits. The extended period of air pollutant monitoring data (21 years) that we included would have more represented cumulative

lifetime exposure. Nevertheless, there were limitations in our calculations. We acknowledge that the network of air quality monitors is not completely spatially representative of Thailand. However, the long-term averages between the different sites were within $20 \mu\text{g m}^{-3}$, so it is not anticipated that using data from additional monitors in less populated (i.e. more rural) areas would have a significant effect on the calculated population level health impacts. Still, interpretation of our results likely will be more reliable at the national level, as potential differences in PM concentrations and sources may impact findings for a given province. We did not have $\text{PM}_{2.5}$ concentrations for the entire exposure period and had to extrapolate using levels of PM_{10} . We excluded effects from concentrations below $2.4 \mu\text{g m}^{-3}$, for which concentration response curves are not known, but may also entail adverse health. We corrected as much as the data would allow for uncoded mortality and adjusted for age-related rates; the correction factors we applied were based on national averages, which may have attenuated any differences between provinces. We did not account for mortality from exposure to ambient ozone, which is often less correlated with $\text{PM}_{2.5}$; however, less than 10% of global deaths from ambient air pollution have been attributed to ozone, so this exclusion is not likely to substantially increase our estimates (Cohen *et al* 2017). Further, a meta-analysis found little evidence of increased mortality with long-term exposure to ozone (Atkinson *et al* 2016).

5. Conclusions

We have completed an HIA indicating that long-term exposure to $\text{PM}_{2.5}$ has resulted in approximately 50 000 annual deaths in Thailand. Overall costs of this excess mortality is equivalent to nearly 15% of Thailand's GDP in 2016, based on the value of a statistical life. Our study benefitted from a lengthy longitudinal dataset of ambient air quality, mostly province-specific health data, and established and emerging risk estimates of mortality and incidence. While progress has been made to reduce exposure to ambient $\text{PM}_{2.5}$ in Thailand, continued reductions based on stricter regulatory limits for $\text{PM}_{2.5}$ and other air pollutants would help prolong life, and delay, or prevent, onset of cardiorespiratory and other diseases.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

- Altman D G and Bland J M 2003 Interaction revisited: the difference between two estimates *BMJ* **326** 219
- Atkinson R W *et al* 2016 Long-term exposure to ambient ozone and mortality: a quantitative systematic review and meta-analysis of evidence from cohort studies *BMJ Open* **6** e009493
- Burnett R *et al* 2018 Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter *Proc. Natl Acad. Sci.* **115** 9592–7
- Burnett R and Cohen A 2020 Relative risk functions for estimating excess mortality attributable to outdoor $\text{PM}_{2.5}$ air pollution: evolution and state-of-the-art *Atmosphere* **11** 589
- Butt E W, Turnock S T, Rigby R, Reddington C L, Yoshioka M, Johnson J S, Regayre L A, Pringle K J, Mann G W and Spracklen D V 2017 Global and regional trends in particulate air pollution and attributable health burden over the past 50 years *Environ. Res. Lett.* **12** 104017
- Cheewaphongphan P, Junpen A, Garivait S and Chatani S 2017 Emission inventory of on-road transport in Bangkok metropolitan region (BMR) development during 2007–2015 using the GAINS model *Atmosphere* **8** 167
- Cohen A J *et al* 2017 Estimates and 25 year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the global burden of diseases study 2015 *Lancet* **389** 1907–18
- Committee on the Medical Effects of Air Pollutants (COMEAP) 2018 Associations of long term average concentrations of nitrogen dioxide with mortality
- Country Economy 2020 Thailand GDP—gross domestic product (available at: <https://countryeconomy.com/gdp/thailand?year=2016>) (Accessed 22 May 2020)
- Dimakakou E, Johnston H J, Strefataris G and Cherrie J W 2018 Exposure to environmental and occupational particulate air pollution as a potential contributor to neurodegeneration and diabetes: a systematic review of epidemiological research *Int. J. Environ. Res. Public Health* **15** 1704
- Fold N R, Allison M R, Wood B C, Thao P T, Bonnet S, Garivait S, Kamens R and Pengjan S 2020 An assessment of annual mortality attributable to ambient $\text{PM}_{2.5}$ in Bangkok, Thailand *Int. J. Environ. Res. Public Health* **17** 7298
- Gao J *et al* 2015 The variation of chemical characteristics of $\text{PM}_{2.5}$ and PM_{10} and formation causes during two haze pollution events in urban Beijing, China *Atmos. Environ.* **107** 1–8
- Giani P, Anav A, De Marco A, Zhaozhong F and Crippa P 2020 Exploring sources of uncertainty in premature mortality estimates from fine particulate matter: the case of China *Environ. Res. Lett.* **15** 064027
- Hime N J, Marks G B and Cowie C T 2018 A comparison of the health effects of ambient particulate matter air pollution

- from five emission sources *Int. J. Environ. Res. Public Health* **15** 1206
- Johnston H J, Mueller W, Steinle S, Vardoulakis S, Tantrakarnapa K, Loh M and Cherrie J W 2019 How harmful is particulate matter emitted from biomass burning? A Thailand perspective *Curr. Pollut. Rep.* **5** 353–77
- Kanniah K D, Zaman N A F K, Kaskaoutis D G and Latif M T 2020 COVID-19's impact on the atmospheric environment in the Southeast Asia region *Sci. Total Environ.* **736** 139658
- Kim K H, Kabir E and Kabir S 2015 A review on the human health impact of airborne particulate matter *Environ. Int.* **74** 136–43
- Kliengchuay W, Cooper Meeyai A, Worakhunpiset S and Tantrakarnapa K 2018 Relationships between meteorological parameters and particulate matter in Mae Hong Son province, Thailand *Int. J. Environ. Res. Public Health* **15** 2801
- Kliengchuay W, Worakhunpiset S, Limpanont Y, Meeyai A C and Tantrakarnapa K 2021 Influence of the meteorological conditions and some pollutants on PM 10 concentrations in Lamphun, Thailand *J. Environ. Health Sci. Eng.* **1**–13
- Lelieveld J, Haines A and Pozzer A 2018 Age-dependent health risk from ambient air pollution: a modelling and data analysis of childhood mortality in middle-income and low-income countries *Lancet Planet. Health* **2** e292–e300
- Mansournia M A and Altman D G 2018 Population attributable fraction *BMJ* **360** k757
- Martenies S E, Wilkins D and Batterman S A 2015 Health impact metrics for air pollution management strategies *Environ. Int.* **85** 84–95
- Miller B G and Hurley J F 2003 Life table methods for quantitative impact assessments in chronic mortality *J. Epidemiol. Community Health* **57** 200–6
- Mueller W, Loh M, Vardoulakis S, Johnston H J, Steinle S, Precha N, Kliengchuay W, Tantrakarnapa K and Cherrie J W 2020 Ambient particulate matter and biomass burning: an ecological time series study of respiratory and cardiovascular hospital visits in northern Thailand *Environ. Health* **19** 1–12
- Münzel T, Sørensen M, Gori T, Schmidt F P, Rao X, Brook F R, Chen L C, Brook R D and Rajagopalan S 2017 Environmental stressors and cardio-metabolic disease: part II—mechanistic insights *Eur. Heart J.* **38** 557–64
- Naghavi M et al 2017 Global, regional, and national age-sex specific mortality for 264 causes of death, 1980–2016: a systematic analysis for the global burden of disease study 2016 *Lancet* **390** 1151–210
- National Statistics Office 2020 Demography, housing and population branch (available at: <http://statbi.nso.go.th/staticreport/page/sector/en/01.aspx>) (Accessed 20 May 2020)
- Organisation for Economic Cooperation and Development (OECD) 2016 *The Economic Consequences of Outdoor Air Pollution* (Paris: OECD Publishing) (<https://doi.org/10.1787/9789264257474-en>)
- Pinichka C, Makka N, Sukkumnoed D, Chariyalertsak S, Inchai P and Bundhamcharoen K 2017 Burden of disease attributed to ambient air pollution in Thailand: a GIS-based approach *PLoS One* **12** e0189909
- Pothirat C, Chaiwong W, Liwsrisakun C, Bumroongkit C, Deesomchok A, Theerakittikul T, Limsukon A, Tajarernmuang P and Phetsuk N 2019 The short-term associations of particular matters on non-accidental mortality and causes of death in Chiang Mai, Thailand: a time series analysis study between 2016–2018 *Int. J. Environ. Health Res.* **1**–10
- Punsompong P and Chantara S 2018 Identification of potential sources of PM10 pollution from biomass burning in northern Thailand using statistical analysis of trajectories *Atmos. Pollut. Res.* **9** 1038–51
- Rao C, Porapakkhom Y, Pattaraarchachai J, Polprasert W, Swampunyalert N and Lopez A D 2010 Verifying causes of death in Thailand: rationale and methods for empirical investigation *Popul. Health Metrics* **8** 11
- Schraufnagel D E et al 2019 Air pollution and noncommunicable diseases: a review by the forum of international respiratory societies' environmental committee, part 2: air pollution and organ systems *Chest* **155** 417–26
- Seposo X, Kondo M, Ueda K, Honda Y, Michikawa T, Yamazaki S and Nitta H 2018 Health impact assessment of PM2.5-related mitigation scenarios using local risk coefficient estimates in 9 Japanese cities *Environ. Int.* **120** 525–34
- Stratoulis D and Nuthammachot N 2020 Air quality development during the COVID-19 pandemic over a medium-sized urban area in Thailand *Sci. Total Environ.* **746** 141320
- Trejo-González A G, Riojas-Rodríguez H, Texcalac-Sangrador J L, Guerrero-López C M, Cervantes-Martínez K, Hurtado-Díaz M, De La Sierra-de L A and Zuñiga-Bello P E 2019 Quantifying health impacts and economic costs of PM 2.5 exposure in Mexican cities of the national urban system *Int. J. Public Health* **64** 561–72
- U.S. Environmental Protection Agency (USEPA) 2018 Environmental benefits mapping and analysis program—community edition (BenMAP-CE) (available at: www.epa.gov/benmap/) (Accessed 20 May 2020)
- Viscusi W K and Masterman C J 2017 Income elasticities and global values of a statistical life *J. Benefit Cost Anal.* **8** 226–50
- Vongmahadlek C, Bich Thao P T, Satayopas B and Thongboonchoo N 2009 A compilation and development of spatial and temporal profiles of high-resolution emissions inventory over Thailand *J. Air Waste Manage. Assoc.* **59** 845–56
- Witvorapong N and Komonpaisarn T 2020 The value of a statistical life in Thailand: evidence from the labour market *J. Consum. Policy* **43** 491–518
- Wong C M, Vichit-Vadakan N, Kan H and Qian Z 2008 Public health and air pollution in Asia (PAPA): a multicity study of short-term effects of air pollution on mortality *Environ. Health Perspect.* **116** 1195–202
- World Bank 2019 Life expectancy at birth, total (years) (available at: <https://data.worldbank.org/indicator/SP.DYN.LE00.IN>) (Accessed 22 May 2020)
- World Health Organization (WHO) 2016a *Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease* (available at: www.eea.europa.eu/publications/air-quality-in-europe-2017/at_download/filehttp://europa.eu/rapid/press-release_IP-17-4604_en.pdfhttp://eur-lex.europa.eu/legal-content/LT/TXT/PDF/?uri=CELEX:52013SC0532&from=LT) (Accessed 5 October 2020)
- World Health Organization (WHO) 2016b Life tables by country; Thailand (available at: <https://apps.who.int/gho/data/view.main.61640?lang=en>) (Accessed 5 October 2020)
- Xie X, Semanjski I, Gautama S, Tsiligianni E, Deligiannis N, Rajan R T, Pasveer F and Philips W 2017 A review of urban air pollution monitoring and exposure assessment methods *ISPRS Int. J. Geo-Inf.* **6** 389
- Xu G, Jiao L, Zhang B, Zhao S, Yuan M, Gu Y, Liu J and Tang X 2016 Spatial and temporal variability of the PM2.5/PM10 ratio in Wuhan, Central China *Aerosol Air Qual. Res.* **17** 741–51
- Yu H, Russell A, Mulholland J, Odman T, Hu Y, Chang H H and Kumar N 2018 Cross-comparison and evaluation of air pollution field estimation methods *Atmos. Environ.* **179** 49–60