Supplementary Information

Long-term exposure to outdoor air pollution and incidence of cardiovascular disease events in an English population

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eAppendix - the emission inventory, modelling and validation of models for estimating exposure to air pollutants

Introduction

AEA Technology plc are contracted by Department for Environment, Food and Rural Affairs, a government department responsible for policy and regulations on the environment in the UK. AEA Technology have developed and refined dispersion models for reporting to both the UK Government and the European Commission and for policy formulation by the UK Government. The models use the national emission inventories (NAEI) and seeks to model some of the physical and chemical processes in the atmosphere. The model represents dispersion over different terrain types using a variety of dispersion kernels for different land uses. The models provide a national scale output (across the UK) at 1x1km resolution and provide historical back-log of data for multiple pollutants and for multiple years over the last decade. These contribute to the UK Government's officially reported concentrations to the EU which are a combination of modelled concentrations and concentrations from national monitoring networks. These data have a well-established provenance within the UK air pollution community and their validity for use in epidemiology has been previously established[1,2].

Emission inventory

Emission estimates provided by the UK National Atmospheric Emission Inventory (NAEI)[3], provide the basis for the air pollution dispersion models. The Inventory is funded by the Government and provides detailed information on air pollutant emissions from a range of sources including point sources (e.g. industrial sites) and from area sources (e.g. roads, domestic combustion and smaller industrial sites) which are typically derived from a combination of activity statistics (such as fuel consumption) and known emission factors (for example, emission of a given pollutant per tonne of a given fuel burnt or kilometre travelled). Emissions from road traffic on major roads are estimated from a combination of traffic activity data (daily flows for different vehicle types on each of more than 19,000 major road links), vehicle fleet characteristics (age, relevant emission standard) and emission factors (emissions per km per vehicle). These emission estimates are then aggregated into sectors such as domestic heating, road traffic emissions and industrial emissions. The UK total emission estimates for each activity are then distributed across 1 km x 1 km squares covering the whole of the UK. The spatial patterns of emissions are derived from proxy information such as population or employment statistics for a number of activities and are fully explained in the most recent UK Emission Mapping Methodology report[4].

Air Pollution Modelling

Oxides of nitrogen

Concentrations of NO_x and NO_2 were estimated using the Pollution Climate Mapping model[5-7] .

Modelling NO_x concentrations

Annual mean NO_x concentrations were calculated by summing the estimated concentrations for the following components:

- Distant sources (characterised by the rural background concentration, interpolated from measurements at rural sites)
- Point sources (calculated using an air dispersion model)
- Local area sources (calculated using a kernel based air dispersion model)

The area source model has been calibrated using data from the national automatic monitoring networks for the relevant year.

Modelling NO_2 concentrations

To estimate NO_2 concentrations, modelled NO_x concentrations derived from the approach outlined above are converted to NO_2 using an oxidant partitioning model which describes the complex inter-relationships of NO, NO_2 and ozone as a set of chemically coupled species[8]. This approach provides additional insights into the factors controlling ambient levels of NO_2 (including the emission of primary NO_2), and how they may vary with NO_x concentration.

Particulate matter

PM_{10} and $PM_{2.5}$ concentrations were estimated using the Pollution Climate Mapping model[7,9]. Annual mean PM concentrations were calculated by summing the estimated concentrations for the following components:

- Secondary inorganic aerosol (derived by scaling measurements of PM, SO_4, NO_3)
- Point sources of primary particles (modelled using an air dispersion model and UK national emissions estimates from the National Atmospheric Emission Inventory.
- Area sources of primary particles (modelled using a dispersion kernel, which is derived using an air dispersion model and emissions estimates from the National Atmospheric Emission Inventory)

- Long-range transport primary particles (modelled with the TRACK model, a Lagrangian statistical model[10])
- Residual (assumed to be a constant value)

The area source model was calibrated using data from the national automatic monitoring networks for the relevant year.

Sulphur dioxide

SO_2 concentration estimates were estimated using the Pollution Climate Mapping model[7]. Annual mean SO_2 concentrations were calculated by summing the estimated concentrations for the following components:

- Point sources (calculated using an air dispersion model)
- Local area sources (calculated using a kernel based air dispersion model)

Point sources (such as power stations and refineries) are the dominant contributor to ground level concentrations across most of the UK. A number of major point sources are modelled using emissions information and activity profiles provided directly by power station operators.

Ozone

The empirical mapping methods used to calculate the maps of annual mean ozone concentration have been described by Stedman and Kent[11] as a further development of the methods presented by Coyle at al[12].

Mapping ozone concentrations

The maps of annual mean concentration were calculated by interpolating monitoring data from rural monitoring sites for the well-mixed period in the afternoon (12:00 to 18:00). Two corrections were then applied: to correct for altitude and for the effect of urban environments. The altitude correction was applied to take account of the effects of topography on ozone levels[12]. Topographic effects are important for some ozone metrics, such as the annual mean, because of the disconnection of a shallow boundary layer from air aloft during the night at lowland locations. Surface ozone concentrations are lower at night in these locations due to a combination of dry deposition and titration with NO emissions. This effect is much less marked at higher altitudes and at coastal locations, where wind is generally stronger and a shallow boundary layer does not form. An urban decrement (the difference between the ozone concentration in an urban area and the regional rural value) was then calculated using the oxidant partitioning model of Jenkin[8]. Maps of regional oxidant were calculated as the sum of altitude corrected ozone and rural NO_2 as interpolated from measurements at rural sites. The partitioning of oxidant between ozone and NO_2 was then calculated as a function of local NO_x concentrations, as modelled using the approach described above. Maps of annual mean ozone concentration were calculated for all of the 1 km x 1 km squares in the UK by subtracting this urban decrement from the estimates of rural concentrations.

Model Calibration

Model calibration is achieved using national network sites applied only to the local (within ~15km) area source emissions (i.e. emissions provided by the NAEI on a 1x1 km grid). Point source emissions are modelled explicitly using a dispersion model (ADMS) which is populated using the NAEI, meteorological data purchased from the UK Met Office and stack parameters gathered from EA permits. The un-calibrated area source emissions are put through a GIS-based dispersion kernel (also generated using ADMS and Met Office data) and then the output at national network monitoring sites is compared with the measured concentrations from those sites. The measured concentrations are amended first by subtracting the modelled point source contribution (and other pollutant specific components such as long range transport primary particulate matter) at each site so that we are comparing like with like (i.e. the modelled area sources are being fairly compared with the area source component of the measured concentrations. This comparison is used to compose the calibration plot from which the calibration factor for the UK is derived. Some sites will be better represented than others because a single calibration factor is being applied to the whole map. The calibration is then applied by scaling up the un-calibrated dispersed (i.e. dispersion kernel applied) NAEI gridded emissions. This calibrated area source grid is then added to the small and large point source grids and any other pollutant specific grids (e.g. long range transport primary, secondary organic aerosol, secondary inorganic aerosol, sea salt, rural NO_X) to make the final grid of estimated ambient concentrations.

Model Validation

eTable 1 gives the model validation statistics (R^2) for a number of years at national network and verification sites. The numbers of monitors used in these assessments are also given in eTable 1. The R^2 values based upon verification sites (details of the verification sites (VS) used in the 'calibration club' are given in Stedman[13]) provide the strongest indication of the performance of the model. The data from the National Network (NN) monitoring sites are used to calibrate the model. However they do provide some indication of model performance since these data are used to provide a single, universal calibration factor (as opposed to adjusting the model to ensure good agreement specifically at the locations for which measured data are available) that is subsequently applied to all 1x1 km grids.

The R^2 statistics for SO_2 for our chosen 'exposure year' (2002) are 0.39 at the NN sites and 0 at the VS. The level of agreement varies substantially from year to year (from 0.23 to 0.45 at NN sites 0 to 0.6 at the VS sites). The R^2 statistics for NO_2 are very good for both the NN and VS sites and are consistently good year on year.R^2 statistics for PM_{10} are presented in eTable 1. Moderate agreement at NN sites and VS were obtained from the models. Due to the limited number of monitoring sites measuring $PM_{2.5}$ prior to 2008 model validation statistics for $PM_{2.5}$ for our study period were not available. However, the modelling for PM_{10} and $PM_{2.5}$ is carried out in parallel and the same general methodology is used and many of the same components so model performance for PM_{10} and $PM_{2.5}$ is similar. In 2008 separate model validation for $PM_{2.5}$ was possible and model agreement was very good (R^2 statistics of 0.9 at VS). In our study modelled ozone concentrations were verified using number of days exceeding 120 μg/m³ – the appropriate statistic for policy purposes. The performance of our models – aggregated over 2002-2004 and 2005-2007 are shown in eTable 2, demonstrating good model performance at the NN sites and moderate/reasonable performance at the VS.

eTable 1: Model validation statistics (R^2) at national network and verification sites, 2002-2007

Pollutant	Network	2002	2003	2004	2005	2006	2007
SO_2	NN	0.39	0.45	0.23	0.33	0.29	0.37
	# sites	127	108	96	100	98	66
	VS	0.00	0.56	0.14	0.00	0.04	0.59
	# sites	17	43	20	31	27	45
NO_2	NN	0.80	0.83	0.87	0.90	0.88	0.87
	# sites	62	64	69	62	74	77
	VS	0.57	0.87	0.82	0.75	0.85	0.83
	# sites	24	19	21	33	36	80
PM_{10}	NN	0.29	0.25	0.40	0.28	0.32*	0.48$
	# sites	46	47	48	50	48	31
	VS	0.46	0.37	0.11	0.13	0.34	0.36
	# sites	27	20	37	39	63	53

Notes: NN - National Network monitoring stations; VS Verification Sites; *0.62 at 6 gravimetric sites, $0.83 at 10 sites, **0.92 at 5 gravimetric sites, $$0.98 at 5 sites. Sources: Stedman et al[7,14,15], Kent et al[16,17], Grice et al[18]

eTable 2: Summary statistics for comparison between modelled and measured number of days exceeding 120 μg m⁻³ as a maximum daily 8-hour mean

	Period	Mean of measurements (days)	Mean of model estimates (days)	r^2	No. sites
National Network	2002-4	6.4	6.5	0.71	61
Verification Sites	2002-4	10.3	8.5	0.48	21
National Network	2005-7	6.1	6.0	0.76	71
Verification Sites	2005-7	8.3	7.2	0.24	17

Source: Bush et al[19], Kent et al[20]

eTable 3: Correlation coefficients between (Modified) IMD, Region & Modelled Pollution Exposure in 2002

	PM_{10}	NO_2	SO_2	O_3
All	-0.19	-0.16	-0.13	0.13
North only	-0.26	-0.20	-0.12	0.01
South (excluding London) only	0.02	0.07	0.05	0.05
London only	-0.44	-0.50	0.27	0.04

eTable 4: Summary of assigned $PM_{2.5}$ levels in 2002 for study cohort (N=836,557)

	Assigned $PM_{2.5}$ Exposure in 2002 (µg/m³)
Number of patients with linkage (%)	831,788 (99.4%)
Mean Pollution Level (sd)	12.9 (1.4)
Full Range	7.2-20.2
Inter Quartile Range	1.9
Practice Region Means (sd)	
North [50 practices]	13.0 (1.5)
South (excluding London) [72	12.5 (1.2)
London [28 practices]	14.6 (0.8)
Practice in Urban Area Means (sd)	
Yes [173 practices]	13.1 (1.4)
No [32 practices]	11.6 (1.2)
(Modified) IMD Quintile Means (sd)	
1 (Most Deprived)	13.7 (1.6)
2	13.2 (1.6)
3	12.7 (1.6)
4	12.6 (1.4)
5 (Least Deprived)	12.7 (1.0)
Correlation[a] with future years	
2003	0.68
2004	0.89
2005	0.74
2006	0.76
Correlation[a] with other pollutants	
PM_{10}	0.99
SO_2	0.53
NO_2	0.87
O_3	-0.43
Intra-class correlation by Practice	0.85

[a] - Spearman's rank correlation coefficient

eTable 5: Hazard Ratios summarising the change in risk of incident MI, Stroke, Arrhythmias and Heart Failure in 2003-7 from a 10μg/m³ change in each pollutant

Pollutant	Baseline Variables	Myocardial Inf. (n=810,686)		Stroke (n=819,370)		Arrhythmias (n=790,751)		Heart Failure (n=810,188)	
		HR	95 % CI	**HR**	95 % CI	**HR**	95 % CI	**HR**	95 % CI
PM_{10}	Adjusted for age & sex	**1.10**	0.95-1.27	**1.06**	0.95-1.18	**1.00**	0.89-1.11	**1.41**	1.20-1.66
	Further adj. for smoking, BMI & co-morbs	**1.05**	0.92-1.19	**1.03**	0.93-1.14	**0.99**	0.90-1.09	**1.34**	1.16-1.55
	Further adjusted for (modified) IMD	**0.92**	0.82-1.05	**0.92**	0.83-1.02	**0.97**	0.89-1.07	**1.21**	1.05-1.39
NO_2	Adjusted for age & sex	**1.04**	0.99-1.09	**1.04**	1.00-1.08	**1.00**	0.97-1.03	**1.11**	1.06-1.16
	Further adj. for smoking, BMI & co-morbs	**1.02**	0.98-1.07	**1.03**	0.99-1.06	**1.00**	0.97-1.03	**1.09**	1.05-1.14
	Further adjusted for (modified) IMD	**0.98**	0.94-1.03	**0.99**	0.96-1.03	**0.99**	0.96-1.02	**1.06**	1.01-1.11
SO_2	Adjusted for age & sex	**1.45**	1.35-1.56	**1.27**	1.17-1.37	**1.12**	1.06-1.20	**1.44**	1.33-1.55
	Further adj. for smoking, BMI & co-morbs	**1.36**	1.21-1.53	**1.21**	1.09-1.35	**1.09**	0.99-1.20	**1.34**	1.15-1.55
	Further adjusted for (modified) IMD	**1.23**	1.11-1.38	**1.11**	1.00-1.23	**1.08**	0.98-1.19	**1.21**	1.05-1.40
O_3	Adjusted for age & sex	**0.78**	0.70-0.88	**0.91**	0.81-1.03	**1.04**	0.93-1.16	**0.72**	0.62-0.84
	Further adj. for smoking, BMI & co-morbs	**0.82**	0.73-0.91	**0.95**	0.84-1.06	**1.05**	0.94-1.17	**0.75**	0.65-0.86
	Further adjusted for (modified) IMD	**0.88**	0.79-0.98	**1.01**	0.90-1.13	**1.06**	0.95-1.18	**0.81**	0.70-0.92

Hazard ratios refer to a 10μg/m³ change in each pollutant.

eTable 6: Hazard Ratios summarising the change in risk of incident MI, Stroke, Arrhythmias and Heart Failure in 2003-7 from an inter-quartile change and 10μg/m³ change in $PM_{2.5}$

Pollutant	Baseline Variables	Myocardial Inf. (n=810,686)		Stroke (n=819,370)		Arrhythmias (n=790,751)		Heart Failure (n=810,188)	
		HR	95 % CI	**HR**	95 % CI	**HR**	95 % CI	**HR**	95 % CI
$PM_{2.5}$ (1.9μg/m³ change)	Adjusted for age & sex	**1.04**	1.00-1.08	**1.03**	0.99-1.06	**1.01**	0.97-1.04	**1.12**	1.06-1.17
	Further adj. for smoking, BMI & co-morbs	**1.02**	0.98-1.06	**1.02**	0.98-1.05	**1.00**	0.97-1.03	**1.10**	1.05-1.14
	Further adjusted for (modified) IMD	**0.98**	0.94-1.02	**0.98**	0.95-1.01	**1.00**	0.97-1.03	**1.06**	1.01-1.11
$PM_{2.5}$ (10μg/m³ change)	Adjusted for age & sex	**1.22**	0.98-1.52	**1.15**	0.97-1.37	**1.02**	0.86-1.21	**1.76**	1.37-2.26
	Further adj. for smoking, BMI & co-morbs	**1.12**	0.92-1.36	**1.08**	0.92-1.27	**1.01**	0.87-1.17	**1.62**	1.30-2.02
	Further adjusted for (modified) IMD	**0.90**	0.74-1.10	**0.90**	0.77-1.06	**0.98**	0.85-1.14	**1.35**	1.08-1.68

eTable 7: Hazard Ratios summarising the change in risk of incident Coronary Heart Disease and Cerebrovascular Disease in 2003-7 from an inter-quartile change in each pollutant

Pollutant	Baseline Variables	Coronary Heart Disase (n=754,067)		Cerebrovascular Disease (n=800,896)	
		HR	95 % CI	**HR**	95 % CI
PM_{10}	Adjusted for age & sex	**1.04**	1.00-1.08	**1.02**	0.99-1.05
	Further adj. for smoking, BMI & co-morbs	**1.03**	1.00-1.06	**1.01**	0.98-1.04
	Further adjusted for (modified) IMD	**1.00**	0.97-1.03	**0.99**	0.96-1.02
NO_2	Adjusted for age & sex	**1.05**	1.01-1.10	**1.05**	1.01-1.09
	Further adj. for smoking, BMI & co-morbs	**1.04**	1.00-1.08	**1.04**	1.00-1.07
	Further adjusted for (modified) IMD	**1.00**	0.97-1.04	**1.01**	0.98-1.05
SO_2	Adjusted for age & sex	**1.08**	1.07-1.09	**1.07**	1.05-1.08
	Further adj. for smoking, BMI & co-morbs	**1.07**	1.04-1.10	**1.06**	1.03-1.08
	Further adjusted for (modified) IMD	**1.05**	1.02-1.07	**1.04**	1.02-1.06
O_3	Adjusted for age & sex	**0.93**	0.91-0.96	**0.96**	0.93-0.99
	Further adj. for smoking, BMI & co-morbs	**0.94**	0.91-0.97	**0.97**	0.94-1.00
	Further adjusted for (modified) IMD	**0.96**	0.94-0.99	**0.98**	0.95-1.01

Hazard ratios refer to an IQR change in each pollutant (PM_{10}=3.0μg/m^3, SO_2=2.2 μg/m^3, NO_2=10.7μg/m^3, O_3=3.0 μg/m^3).

eTable 8: Multi-pollutant models showing hazard Ratios summarising the change in risk of incident MI, Stroke, Arrhythmias and Heart Failure in 2003-7 from an inter-quartile change in each pollutant

Pollutant	Adjusted for	Myocardial Infarct. (n=810,686)		Stroke (n=819,370)		Arrhythmias (n=790,751)		Heart Failure (n=810,188)	
		HR	95 % CI	**HR**	95 % CI	**HR**	95 % CI	**HR**	95 % CI
PM_{10}	**+ O_3**	**0.96**	0.92-0.98	**0.97**	0.94-1.00	**0.99**	0.97-1.02	**1.04**	0.99-1.08
PM_{10}	**+ SO_2**	**0.94**	0.90-0.98	**0.95**	0.92-0.98	**0.98**	0.95-1.01	**1.05**	1.00-1.10
NO_2	**+ O_3**	**0.96**	0.91-1.00	**0.99**	0.95-1.03	**1.00**	0.96-1.03	**1.03**	0.98-1.08
NO_2	**+ SO_2**	**0.95**	0.91-1.00	**0.97**	0.93-1.01	**0.98**	0.95-1.02	**1.05**	1.00-1.10
SO_2	**+ PM_{10}**	**1.07**	1.04-1.10	**1.04**	1.02-1.07	**1.02**	1.00-1.05	**1.03**	0.99-1.06
SO_2	**+ NO_2**	**1.06**	1.03-1.09	**1.03**	1.01-1.06	**1.02**	1.00-1.05	**1.03**	1.00-1.07
SO_2	**+ O_3**	**1.04**	1.01-1.07	**1.03**	1.00-1.05	**1.02**	1.00-1.05	**1.02**	0.99-1.06
O_3	**+ PM_{10}**	**0.95**	0.92-0.98	**0.99**	0.96-1.03	**1.02**	0.98-1.05	**0.95**	0.91-0.99
O_3	**+ NO_2**	**0.95**	0.92-0.98	**1.00**	0.96-1.03	**1.02**	0.98-1.05	**0.95**	0.91-0.99
O_3	**+ SO_2**	**0.98**	0.95-1.02	**1.01**	0.98-1.05	**1.03**	1.00-1.06	**0.95**	0.91-0.99

Hazard ratios refer to an IQR change in each pollutant (PM_{10}=3.0μg/m^3, SO_2=2.2 μg/m^3, NO_2=10.7μg/m^3, O_3=3.0 μg/m^3). All models adjusted for age, sex, smoking, modified IMD, BMI & co-morbidities

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