Annex 2. King’s College London report

The WHO Air Quality Guideline for PM2.5 - CMAQ Modelling of future scenarios

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Acronyms

ADMS. *Atmospheric Dispersion Modelling System Model*
AQMEII. *Air quality model evaluation international initiative*
BELD3. *Biogenic Emissions Landcover Database version 3*
CMAQ. *Community Multiscale Air Quality Model*
CO. *Carbon monoxide*
CORINE. *COoRdinate INformation on the Environment*
EMEP. *European Monitoring and Evaluation Programme*
ERG. *Environmental Research Group*
IVOCs. *Intermediate Volatile Organic Compounds*
LPS. *Large Point Source*
MOZART. *e Model for Ozone and Related chemical Tracers Model*
NCAR. *National Center for Atmospheric Research*
NCEP. *National Centers for Environmental Prediction*
NH_3. *Ammonia*
NMVOC. *Non-methane Volatile Organic Compound*
NO. *Nitric Oxide*
NO_2. *Nitrogen dioxide*
NO_X. *Nitrogen oxides*
O_3. *Ozone*
OSM. *Open Street Map*
PM_{10}. *Particulate Matter with diameter less than or equal to 10 ug m-3*
$PM_{2.5}$. *Particulate Matter with diameter less than or equal 2.5 ug m-3*
POA. *Primary Organic Aerosol*
SEDAC. *the Socioeconomic Data and Applications center*
SMOKE. *Sparse Matrix Operator Kernel Emissions Model*
SNAP. *Selected Nomenclature for Air Pollution*
SO_2. *Sulphur dioxide*
SOA. *Secondary Organic Aerosol*
UK. *United Kingdom*
UNDP. *United Nations Development Programme*
USGS. *U.S. Geological Survey*
VBS. *Volatile Basis Set*
VOC. *Volatile Organic Compound*
WRF. *Weather Research and Forecasting Model*

1. Introduction

The recently published Clean Air Strategy (CAS) includes proposals to reduce exposures to $PM_{2.5}$ relative to the WHO annual mean guideline of 10 µg/m3. The wording in the CAS states '*We will set a new, ambitious, long-term target to reduce people's exposure to $PM_{2.5}$ and will publish evidence early in 2019 to examine what action would be needed to meet the WHO annual mean guideline limit of 10 µg/m3.By implementing the policies in this Strategy, we will reduce $PM_{2.5}$ concentrations across the UK, so that the number of people living in locations above the WHO guideline level of 10 µg/m3 is reduced by 50% by 2025.*' The implications of these obligations are being modelled by Imperial College, London using the UK Integrated Assessment Model (UKIAM) and parallel modelling by King's College London using an Eulerian Chemical Transport Model, CMAQ-urban, which models the dispersion, transport and atmospheric chemistry explicitly. This report describes the concentrations of $PM_{2.5}$ across the UK for a base year and two future scenarios, representing a 'business-as-usual' case (2030BC) and a scenario based on measures included in the CAS (2030Ct+).

2. Air Quality Modelling Methodology

The projections of air quality in the UK were performed using the CMAQ-Urban model, a combination of the regional scale air quality model, CMAQ (Byun and Ching, 1999), and a street scale model, ADMS-Roads (CERC, 2017). The entire CMAQ-Urban air quality modelling framework also includes the Weather Research and Forecasting (WRF) model (Skamarock, et al. 2008) for weather predictions and a range of anthropogenic and biogenic emissions processors. Chemical boundary conditions were taken from the MOZART-4 global transport model (Emmons, et al, 2010) and were used to drive CMAQ. The schematic of the entire modelling system including flows of input/output are shown in

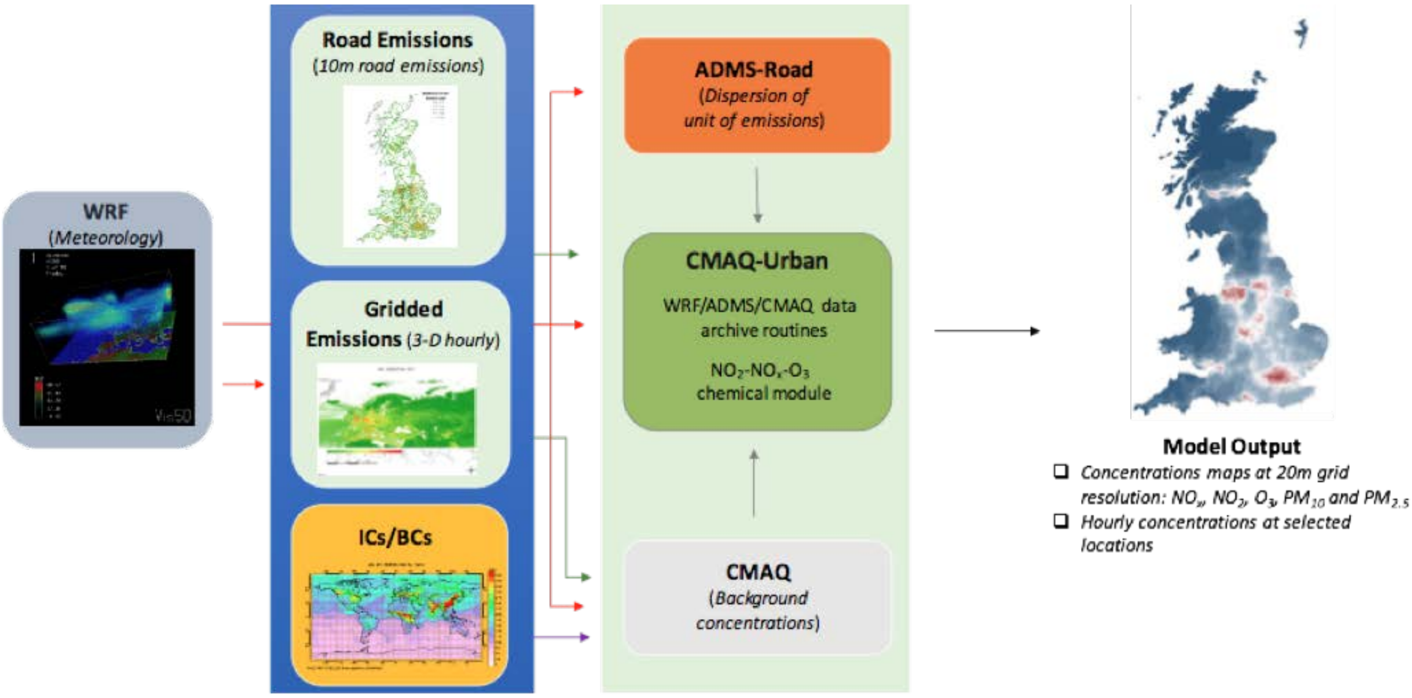


Figure 1.

Figure 1 CMAQ-Urban modelling system

2.1 Meteorological fields

The WRF version 3.6.1 was used to produce meteorological fields for 2012 with the 2030s simulations assumed to be the same. The outermost model domain covering Europe had a grid resolution of 50km and was down scaled to 10 km over the UK and 2 km over major cities (London, Birmingham, Leeds, Liverpool and Manchester, Edinburgh and Glasgow, and Cardiff and Bristol). The model domains were divided into 23 vertical layers with 7 layers within 1km of the ground and the highest being ~15 km above the ground. The height of the lowest layer was 15m.

The configurations of WRF were derived from a comprehensive model sensitivity analysis forming part the DEFRA CMAQ-UK project (https://uk-air.defra.gov.uk/research/air-quality-modelling?view=cmaq-uk) and also benchmarked for Europe as part of the AQMEII model intercomparison exercise (Solazzo, et al, 2017). The physics schemes used in WRF included RRTM long-wave radiation scheme (Mlawer, et al, 1997), Dudhia shortwave radiation scheme (Dudhia, 1989), Kain–Fritsch cumulus parameterization scheme (Kain, 2004), WSM6 microphysics (Hong and Lim, 2006), Pleim-Xiu surface layer scheme (Pleim and Xiu, 2003), RUC land surface model (Benjamin, et al. 2004), and the Asymmetric Convective Model version 2 (ACM2) for the PBL (Pleim, 2007). Grid analysis nudging of temperature, wind speed, and water vapour mixing ratio were applied within and above the planetary boundary layer (PBL). The lateral boundary conditions for WRF simulations were taken from the NCEP FNL (National Centers for Environmental Prediction Final) Operational Model Global Tropospheric Analyses having a 6-hr time interval and 1° grid resolution.

2.2 Emissions Inventories

Two sets of emissions were required for air quality modelling, including hourly 3-D gridded emissions for CMAQ and emissions rates for 10m road links for CMAQ-Urban. The CMAQ model was operated at the same grid scales as WRF model hence emissions were prepared at 50km for Europe, 10km for UK and 2km for cities. Sea salt emissions, driven by sea surface areas and meteorological conditions, were also included in the CMAQ simulations. However, these were calculated separately during the model run and therefore are not described here.

2.2.1 Emissions for CMAQ

The hourly 3-D gridded emissions of model chemical species were prepared as a summation of emissions from (i) anthropogenic area and large point sources, and (ii) biogenic sources.

i. Anthropogenic emissions

The annual anthropogenic emissions, including NO_X, CO, SO_2, NMVOC, NH_3, PM_{10} and $PM_{2.5}$, from the following UNECE SNAP (Selected Nomenclature for Air Pollution) sectors were accounted in this study:

- SNAP1: Combustion in energy and transformation industries
- SNAP2: Non-industrial combustion plants
- SNAP3: Industrial combustion
- SNAP4: Product processes
- SNAP5: Extraction and distribution of fossil fuels and geothermal energy
- SNAP6: Solvent use and other product use
- SNAP7: Road transport
- SNAP8: Other mobile sources and machinery such as shipping, aircrafts or off-road machineries
- SNAP9: Waste treatment and disposal
- SNAP10: Agriculture

In addition, emissions from cooking, residential biomass burning, and IVOCs from diesel vehicles, were included in the model simulations.

Emissions for countries outside the UK

For European countries outside the UK, the anthropogenic emissions for 2012 were obtained from the European Monitoring and Evaluation Programme (EMEP) for Europe at 0.1° grid resolution (http://www.ceip.at). The emissions for 2030 were derived from the NECD obligations for each country in the EU while for non EU countries, except international shipping, we used emissions from the ECLIPSE project for both 2030 scenarios.

The international shipping emissions for 2012 were derived from the 0.1° grid resolution EMEP data. The emissions from international shipping occurring in different European seas, e.g., North Atlantic, Baltic Sea, Black Sea, Mediterranean Sea and North Sea, were developed based on global shipping emissions from Finnish Meteorological Institute (EMEP, 2018). The scaling factors for international shipping for 2030 were assumed to be the same as those projected for the Representative Concentration Pathways 6.0 (RCP 6.0) forecast in the IIASA RCP v 2.0.5 database (https://tntcat.iiasa.ac.at/RcpDb). The RCP 6.0 represents a stabilization scenario where total radiative forcing is stabilized after

2100 without overshoot by employment of a range of technologies and strategies for reducing greenhouse gas emissions.

The $PM_{10}/_{2.5}$ emissions from cooking were estimated based on 1km global population data derived from the Oak Ridge National Laboratory (https://landscan.ornl.gov). The emission rates were assumed to be 80mg day^{-1} per capita (Fountoukis, et al., 2016) and the diurnal profiles were assumed the same as Ots, et al. (2016a).

The residential biomass emissions were calculated using average emissions factors and activity data reported to EMEP, and the resulting total emissions removed from SNAP2. The new residential biomass emissions were then scaled up by factor of 3 according findings in van der Gon, et al. (2015), and used in the final model run. The spatial distribution of biomass emissions were redistributed using the 1km global population map data from Oak Ridge National Laboratory and the Socioeconomic Data and Applications center (SEDAC) 1km global rural-urban (http://sedac.ciesin.columbia.edu/data/collection/grump-v1) data. The 1km grid population data were used to allocate emissions from residential sources. For residential biomass emissions, the spatial distribution of urban and rural population was also used to give extra weight for rural populations. The emissions from rural populations were assumed to be twice those of the emissions of urban populations following the assumption in van der Gon, et al. (2015). For residential non-biomass emissions, emissions between urban and rural are assumed equal weight.

The IVOCs emissions were assumed to be 2.3 times of road traffic NMVOC emissions. This assumption was made based on the recommendation in Ots, et al. (2016b) albeit for the UK.

The total emissions by countries for 2012 and 2030 are shown in Appendix A.

Emissions for UK

Since the CMAQ-urban modelling was based upon a 2012 year, we calculated both the 2030 Base case and Central Plus scenarios by scaling the 2012 emissions by snap sector, but including the additional categories of cooking emissions, IVOC emissions, domestic wood burning emissions and road traffic emissions, created by King's and described in Williams et al., 2018. The 2012 base year area sources and large point sources, were obtained from the NAEI 2014 (http://naei.beis.gov.uk). To get from 2012 emissions to 2030, we used a combination of scaling factors between 2016 and 2030, provided by IC (Tim Oxley personal communication) and described in Appendix C, combined with scaling factors between 2016 and 2012. The King's specific emissions were created in 2012 because at that time cooking and IVOC emissions were not included in the NAEI and domestic wood burning emissions had not included the survey by Walters, which increased UK wood use by a factor of 3 or emissions in smoke control areas. Finally, since the CMAQ-urban model uses road-by-road emissions, and again these are not available from the NAEI, King's have developed a bottom-up road transport inventory for the UK, using similar methods to that in London and including specific non-exhaust PM emission factors, based upon measurements by Harrison (see below). In London, the 2012 base model used London road traffic emissions that are more ‘specific’ to the city.

There were over 5000 large point sources (LPS) in the UK and these emissions were released into different model layers accounting for plume rise. The plume rise of each LPS was determined using the SMOKE emissions processor (https://www.cmascenter.org/smoke), and was dependent upon the stack characteristics, i.e., height, diameter, exit gas velocity and temperature, and meteorological conditions. Where stack details were missing, the sectorial average values were used.

Emissions from aircraft were also disaggregated to account for the change in height of release as aircraft take-off and land. The NAEI produces emissions up to 1000m and so as each aircraft source moves beyond the boundary of the airport site the emissions were released into different levels in the model to account for this. This ensures that unrealistic ground level concentrations are not predicted immediately around each airport.

The domestic and international shipping emissions were derived as part of the NAEI SNAP8. The missing gaps in international shipping emissions were replaced with the EMEP emissions. Further details of shipping emissions are described in Appendix D.

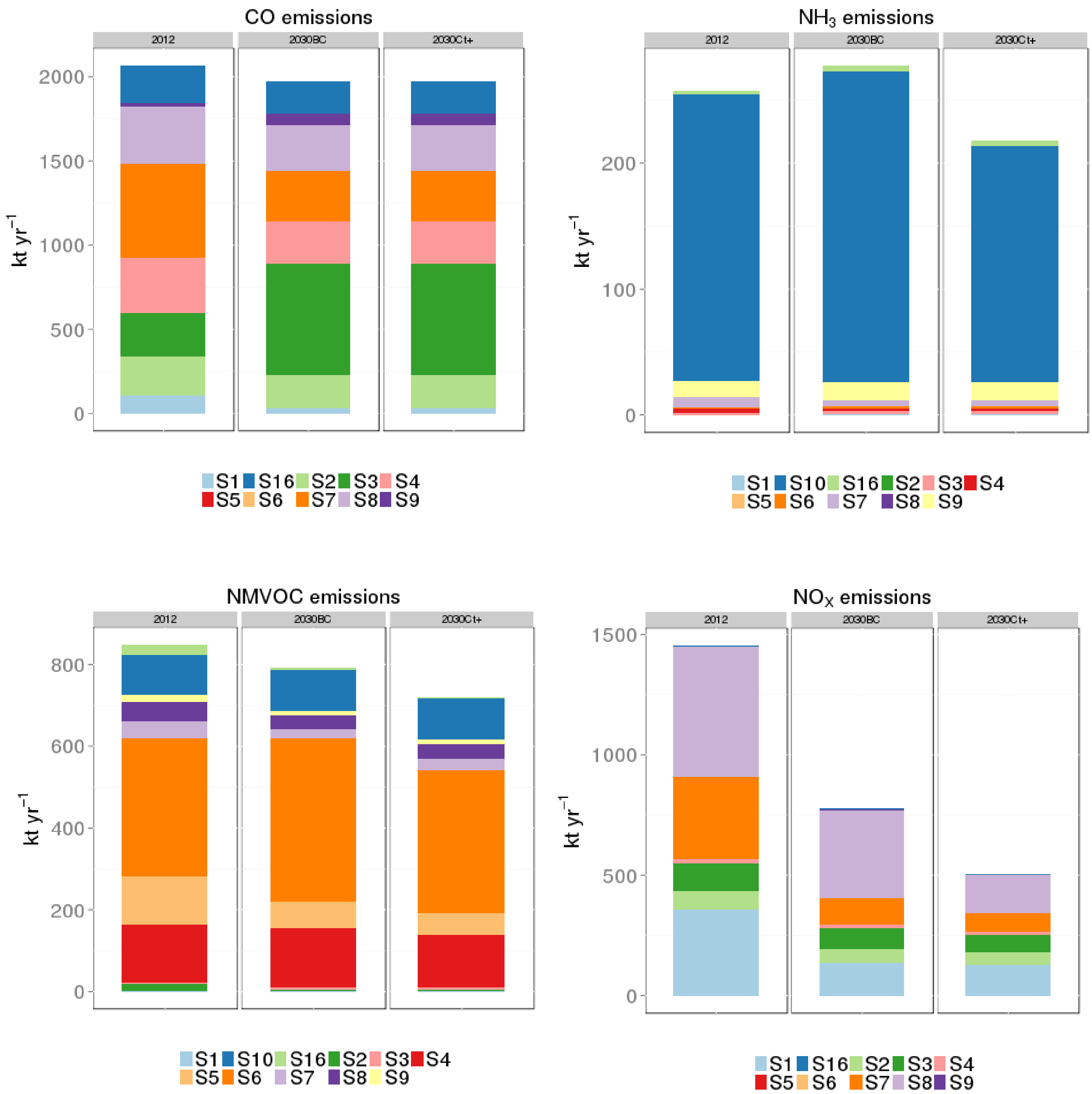
Non-exhaust emissions

The non-exhaust emissions were calculated using Tier 2 EMEP/EEA Guidebook emission factors but with the brake wear, tyre wear and resuspension emissions scaled using the measurements of Harrison et al (Env. Sci. Tech., 2012). The emission factors maintained the same speed dependence as described in the EMEP/EEA Guidebook. Non-exhaust emissions are incorporated in the SNAP 7 sector.

Table 1 UK total emissions for 20120, 2030BC and 2030Ct+ (kt yr[-1])

Pollutant	2012	2030BC	2030Ct+	%age reduction 2030BC	%age reduction 2030Ct+
CO	2067.74	1968.74	1968.74	-4.79	-4.79
HCl	14.50	7.46	7.46	-48.50	-48.50
IVOC	91.65	104.77	104.77	14.32	14.32
NH_3	257.22	277.51	218.37	7.89	-15.10
NO_X	1454.58	776.61	504.36	-46.61	-65.33
PM_{10}	164.34	133.72	96.75	-18.63	-41.13
$PM_{2.5}$	118.93	91.92	57.13	-22.71	-51.97
SO_2	559.45	179.70	124.58	-67.88	-77.73
NMVOC	848.91	791.78	720.63	-6.73	-15.11

The contribution of SNAP sectors to the total emissions of CO, NH_3, NMVOC, NO_X, PM_{10}, $PM_{2.5}$ and SO_2 are shown in Figure 2.


CO emissions
2012
2030BC
2030Ct+
kt yr−1
2000
1500
1000
500
0
S1 S16 S2 S3 S4
S5 S6 S7 S8 S9
NH3 emissions
2012
2030BC
2030Ct+
kt yr−1
200
100
0
S1 S10 S16 S2 S3 S4
S5 S6 S7 S8 S9
NMVOC emissions
2012
2030BC
2030Ct+
kt yr−1
800
600
400
200
0
S1 S10 S16 S2 S3 S4
S5 S6 S7 S8 S9
NOX emissions
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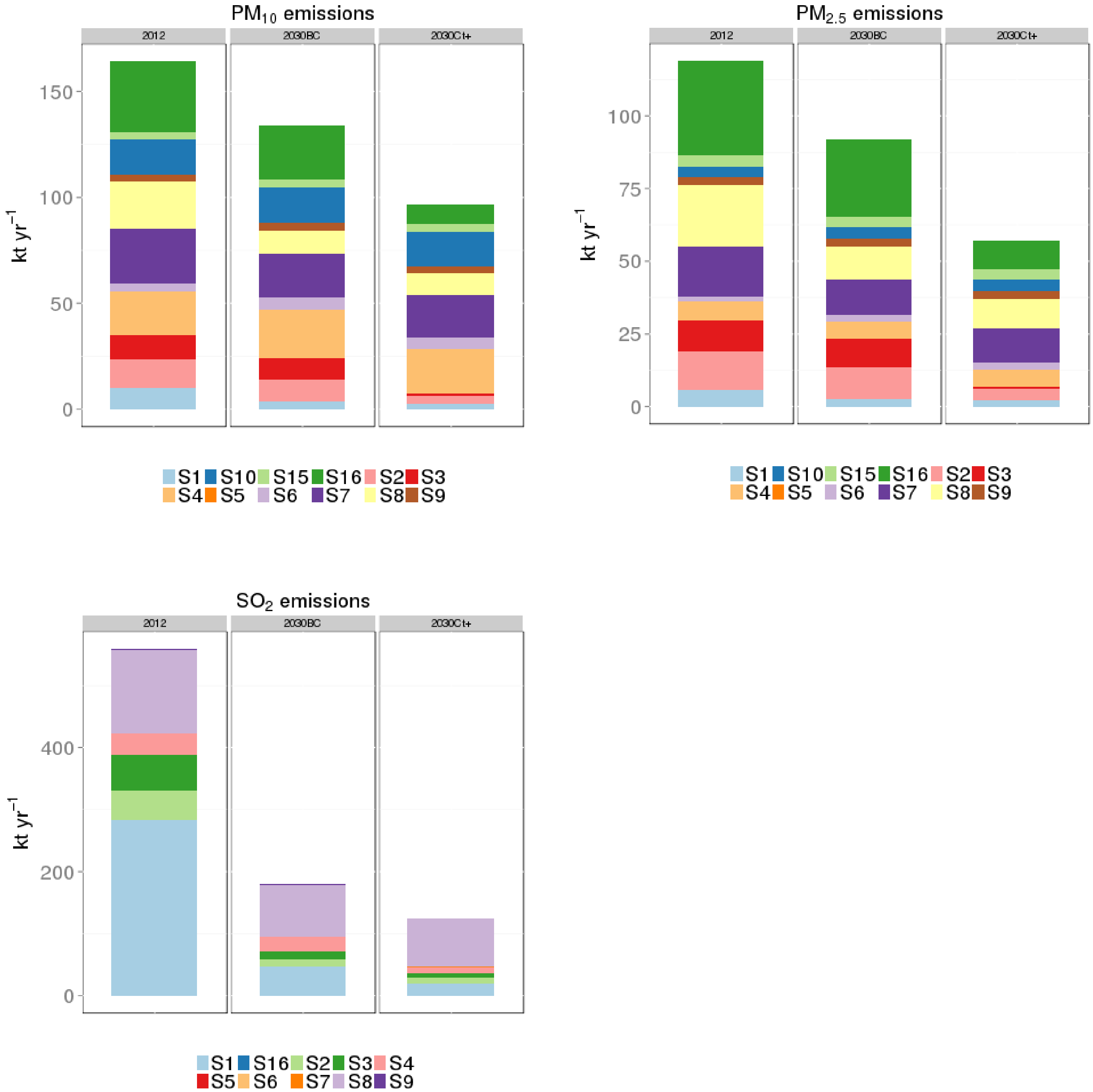


Figure 2 Contributions of source sectors to UK total emissions for 2012, 2030BC, and 2030Ct+ (15 is Cooking emissions, 16 is Residential biomass burning emissions)

The gridded anthropogenic emissions were disaggregated into hourly chemical species using the species speciation and temporal profiles from the AQMEII project (http://aqmeii.jrc.ec.europa.eu) and profiles for cooking emissions were from Ots, et al. (2016a) while the profiles for residential biomass emissions were developed at King's.

ii. Biogenic emissions

The biogenic emissions such as VOCs from vegetation and carbon monoxide (CO) and nitric oxide (NO) from microbial activities in soil were calculated using the Biogenic Emission Inventory System version 3 (BEIS3) model in SMOKE v2.6 (https://www.cmascenter.org/smoke).

The BEIS3 model determines the emissions using spatially and temporally resolved meteorological data (i.e., temperatures, solar radiation and surface pressure) from WRF, spatially resolved of vegetation, species-specific biogenic emissions factors and leaf area indices (LAI), including chemical speciation profiles. The emissions factors, including winter adjustment, were derived from the Biogenic Emissions Landcover Database version 3 (BELD3). The BELD3 land cover type does not cover Europe, therefore USGS land cover data were used. The emissions factors, including isoprene, monoterpene, NO and other VOC species, from the BELD3 database, were used with the equivalent to USGS land cover classes (http://landcover.usgs.gov).

2.2.2 Emissions rates for 10m road links for CMAQ-Urban

Emissions of NO_X, NO_2, PM_{10} and $PM_{2.5}$ were calculated for the 6.5 million 10m road links of Great Britain's major road network and were used in the 2012, 2030BC, and 2030Ct+ simulations (see Figure 3).

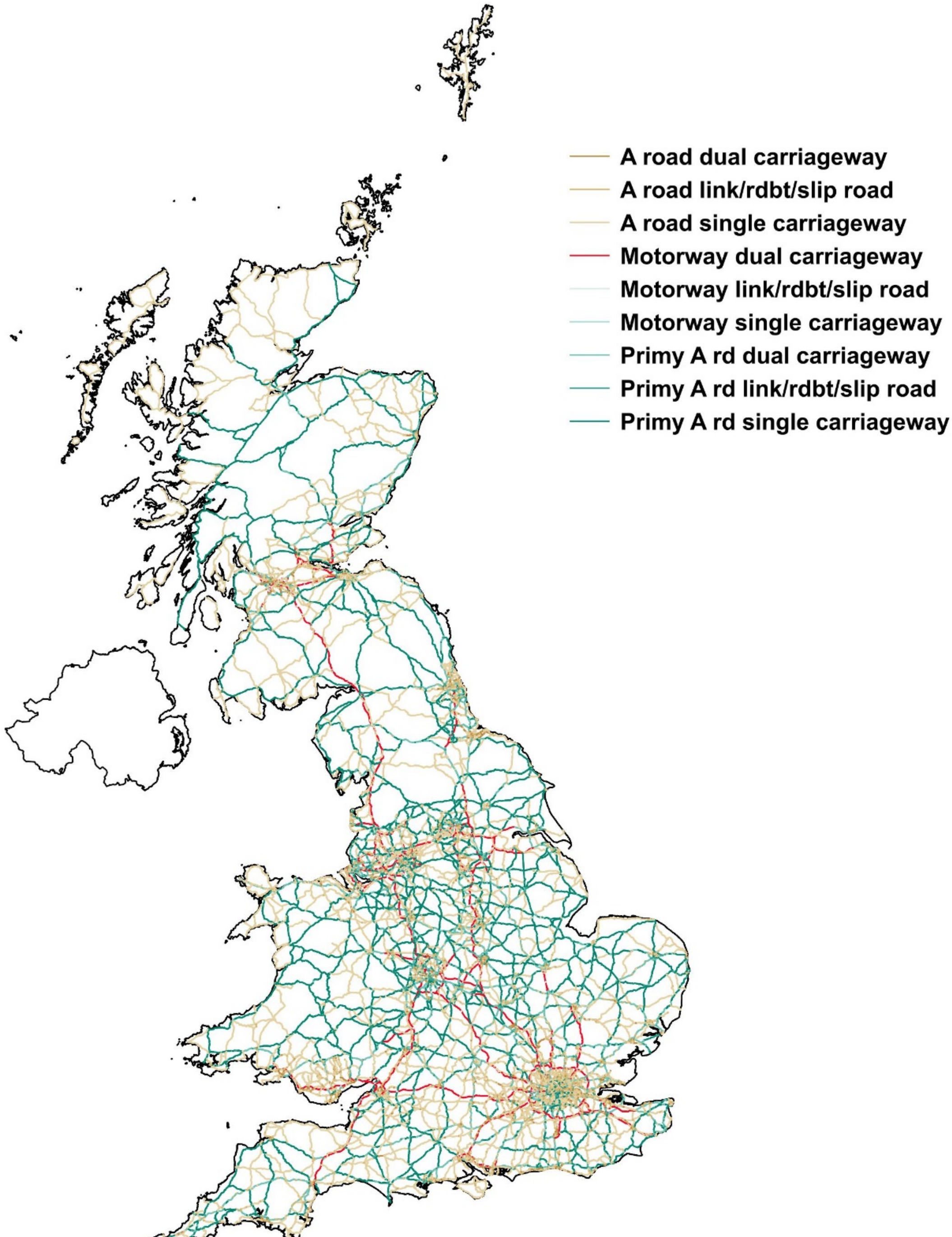


Figure 3 Major road network in Great Britain

2.3 Initial and boundary conditions for CMAQ

The chemical initial and boundary conditions were derived from the global chemical transport model MOZART-4 (Emmons, 2010) which provided key pollutant species such as CO, NO_X, O_3, OH, SO_2, HNO_3 and VOCs, sulphate, nitrate, ammonium, black carbon, POA (Primary Organic Aerosol) and SOA (Secondary Organic Aerosol), dust and sea salt.

The Mozart-4 is driven by meteorological fields from the NASA GMAO GEOS-5 model, anthropogenic emissions from ARCTAS (https://espo.nasa.gov/arctas) and fire emissions from FINN-v1 (Wiedinmyer, et al., 2011). The model outputs are available with a horizontal resolution of 1.9˚ x 2.5˚ and 56 pressure levels.

2.4 Air quality modelling

2.4.1 CMAQ simulation

The CMAQ model was used to simulate the long-range transport and background pollutant concentrations across Europe. The CMAQ model version v5.0.2, included the Volatile Basis Set scheme (VBS) for treatment of organic aerosols (Koo, et al., 2014) and was set up using the same vertical and horizontal grid structure as for WRF. Atmospheric chemistry was simulated using the CB05-TUCL gas-phase chemistry mechanism and AE6 aerosol mechanism (Whitten, et al. 2010 and Sarwar, et al., 2011). Wet and dry deposition scheme are described in Byun and Schere (2006) and Pleim and Ran (2011), respectively.

2.4.2 Street scale air quality modelling

Road dispersion simulation

The ADMS-Road model v2.3 (CERC, 2017) was used to describe the near field dispersion from roadways in CMAQ-urban, using the hourly meteorological inputs: wind speed and direction, temperature, surface sensible heat flux and planetary boundary layer height, predicted from the WRF model.

The model used six road types, including open (motorway), typical (average urban roads surrounded by low rise buildings) and 4 street canyons classified by their orientations (north-south, east-west, southwest-northeast and southeast-northwest).

CMAQ-Urban simulation

The CMAQ-Urban model combines background concentrations at 2km resolution from CMAQ, with predictions of NO_X, NO_2, PM_{10} and $PM_{2.5}$ close to roads, using the ADMS model. A simple near road NO_2-NO_x-O_3 chemistry scheme (Carslaw and Beevers, 2005) for the prediction of NO_2 and O_3 close to roads, and PM_{10} and $PM_{2.5}$ are treated as inert species. The effect of double counting of emissions are removed at model run time.

3. Air quality in 2012

The performance of the CMAQ model is shown in Appendix B where comparison plots of modelled against measured concentrations are shown, along with various statistical metrics relating to model performance. Overall the model reproduces measurements well.

4. Scenarios results - meeting WHO guideline $PM_{2.5}$ concentrations

Significant progress is shown in Figure 4 towards attaining the 10 µg m^{-3} WHO guideline value between 2012 and the 2030 base case and central plus cases. $PM_{2.5}$ in 2012 shows widespread exceedance of the guideline value for large parts of the UK and less so for Wales, where it is limited to the southern city regions and for Scotland. In the 2030 base case scenario the cities of Birmingham and regions around London are highlighted as potentially at risk of exceeding too, only London demonstrates a similar risk in the 2030 ct+ case. This summary is based upon the 10km results from the CMAQ model run however, and it is important therefore to 'drill down' to a finer spatial scale to see what results show at region and city scale.

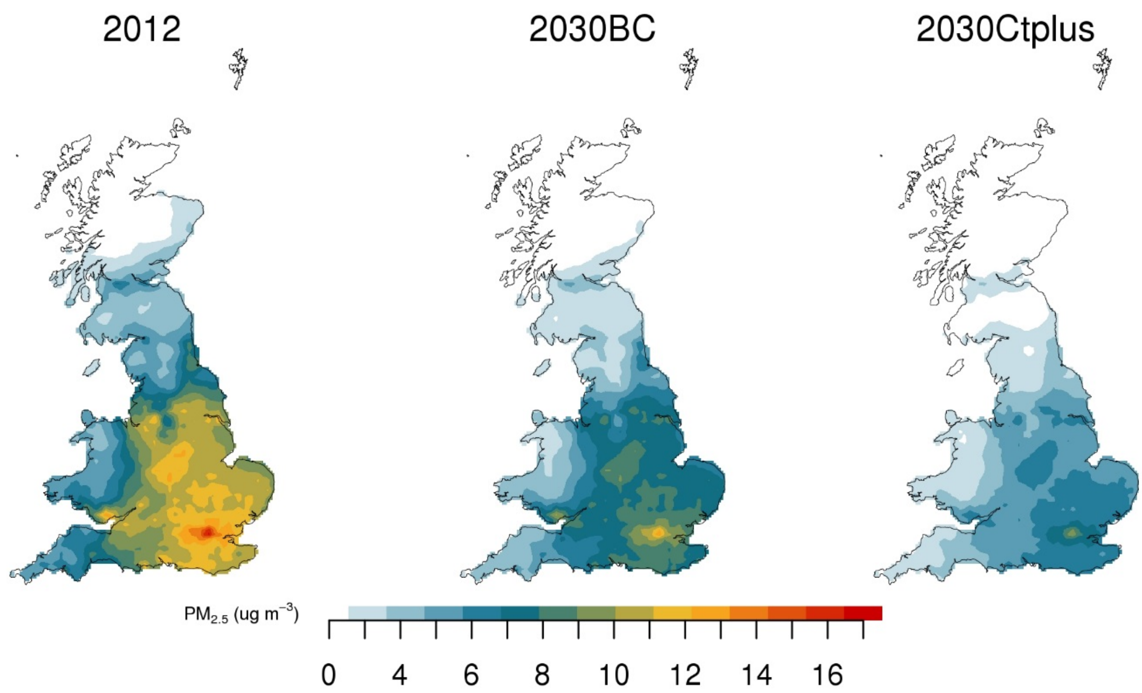
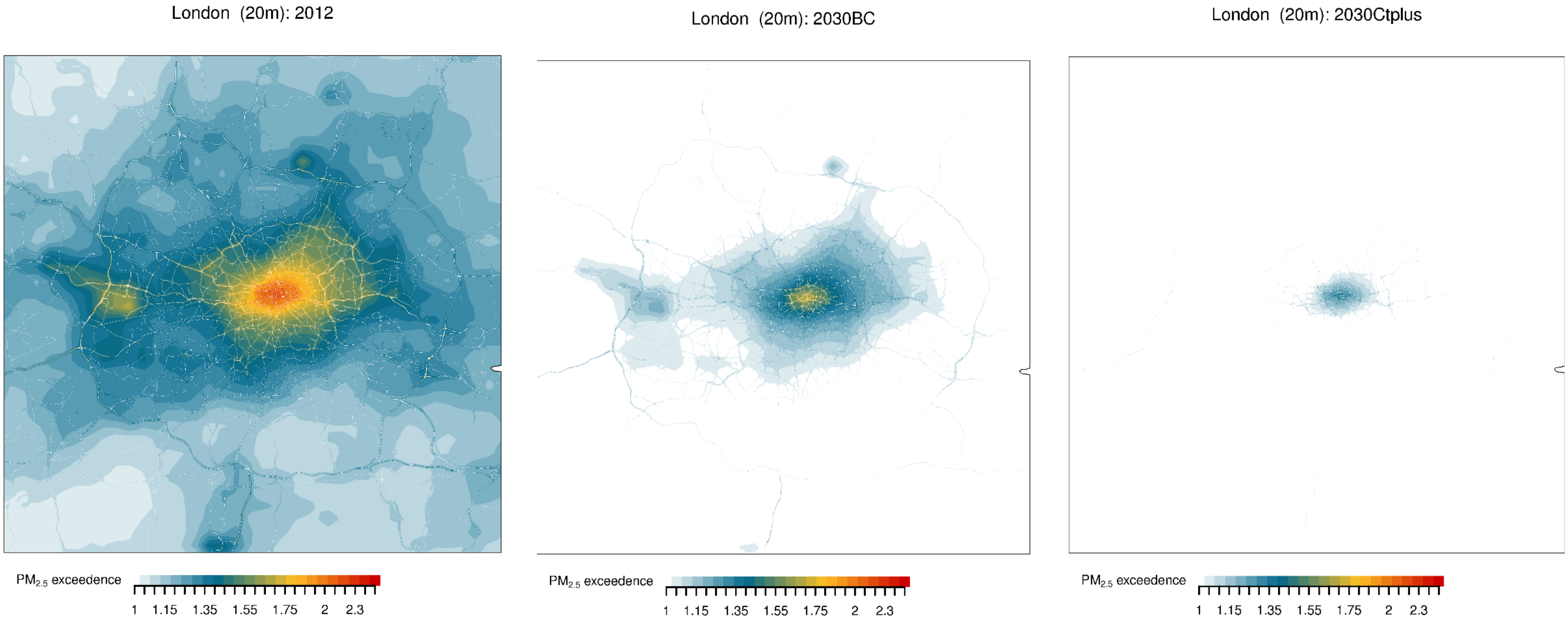
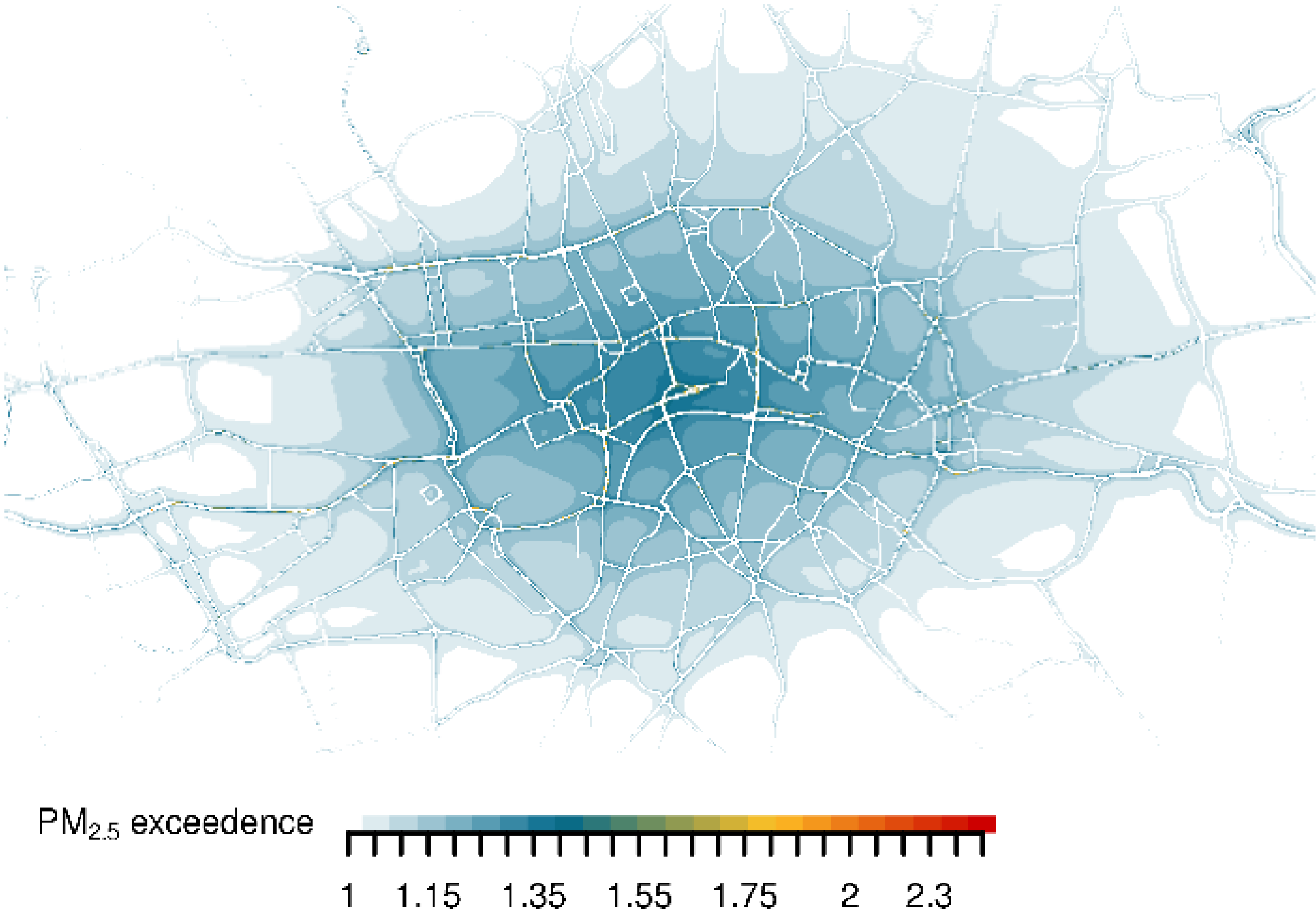


Figure 4 $PM_{2.5}$ concentrations (µg m^{-3}) in Great Britain at 10 km spatial scales for 2012, 2030BC and 2030Ct+

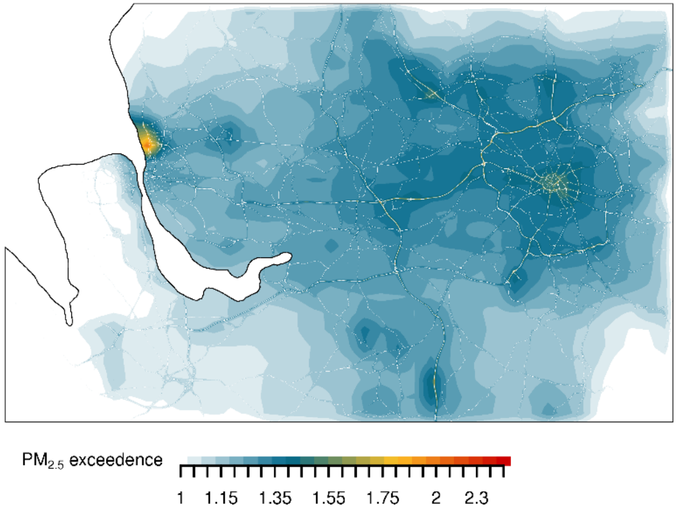
Figure 5 below shows $PM_{2.5}$ predictions in 2012 and 2030 for London, Edinburgh, Glasgow, Birmingham, Liverpool and Manchester. These are based upon the CMAQ-urban model, which produces annual average predictions every 20m. This ensures that important local sources such as road transport are correctly represented, providing a complete picture for compliance in the UK. The scale on the bottom of each plot is the ratio of the CMAQ-urban concentrations and the WHO guideline value of 10 *µg m^{-3}.* Note also that these plots have had the road centreline concentration removed as this is not admissible as a zone of exceedence for reporting purposes.


London (20m): 2012
London (20m): 2030BC
London (20m): 2030Ctplus
PM2.5 exceedence
1 1.15 1.35 1.55 1.75 2 2.3
PM2.5 exceedence
1 1.15 1.35 1.55 1.75 2 2.3
PM2.5 exceedence
1 1.15 1.35 1.55 1.75 2 2.3

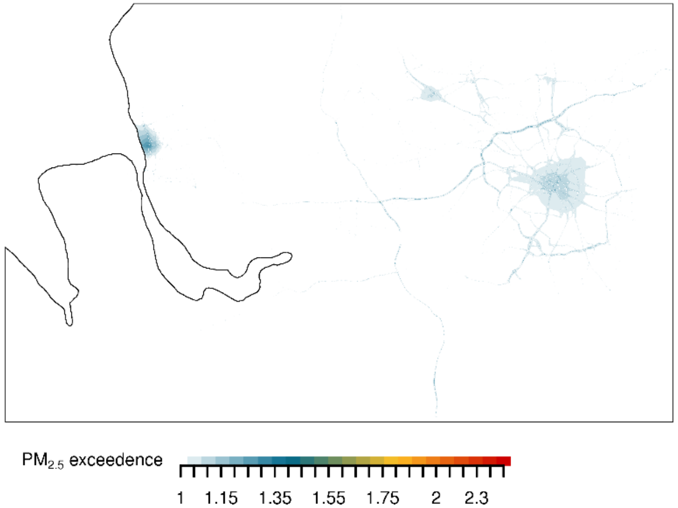
London (20m): 2030Ctplus



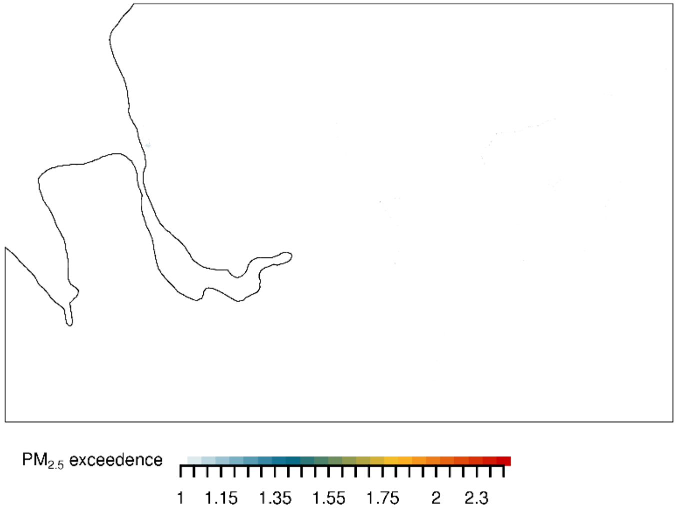
Liverpool & Manchester (20m): 2012



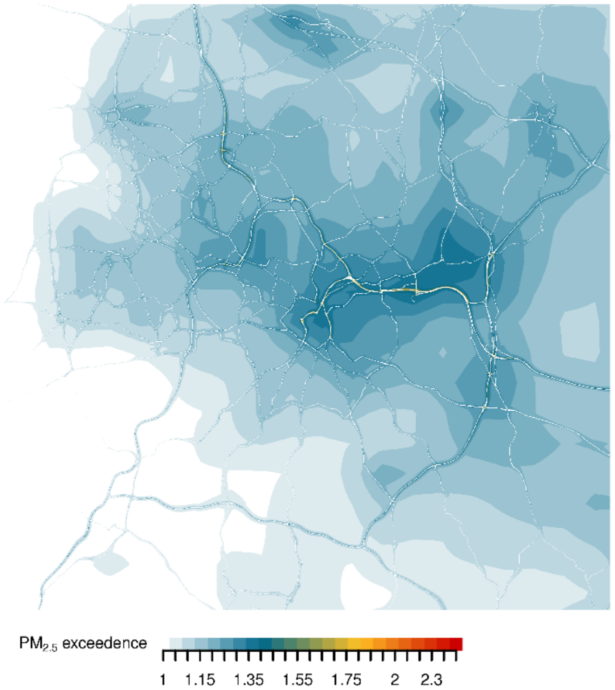
Liverpool & Manchester (20m): 2030BC



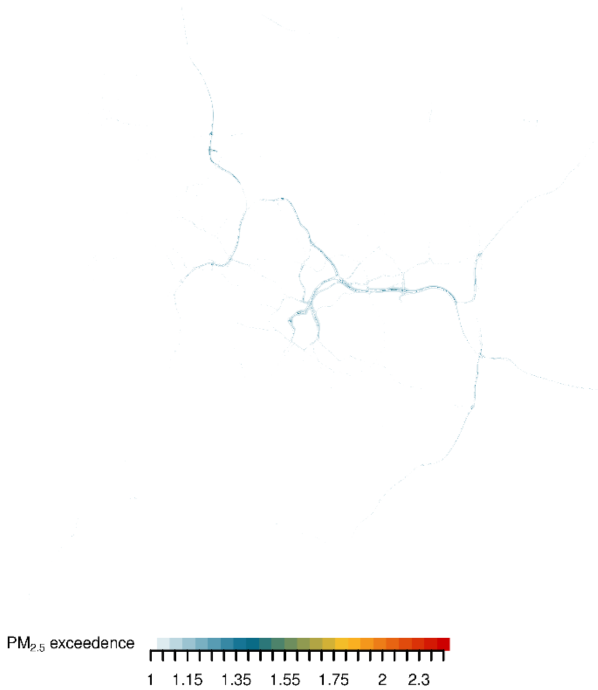
Liverpool & Manchester (20m): 2030Ctplus



Birmingham (20m): 2012

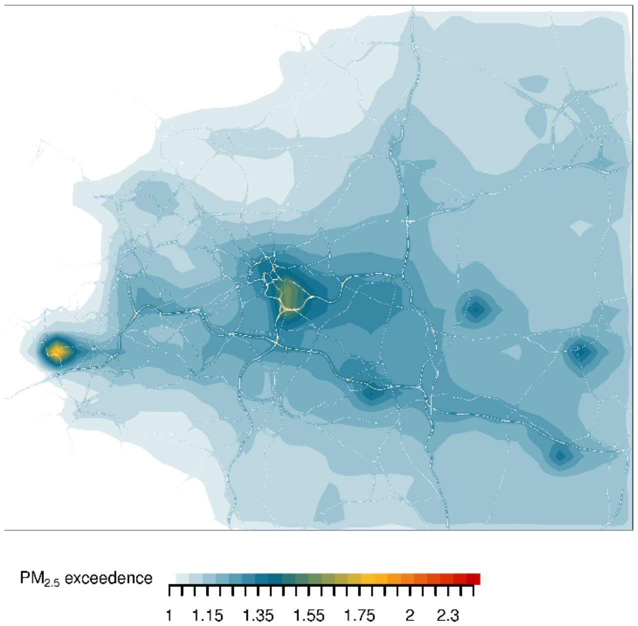


Birmingham (20m): 2030BC

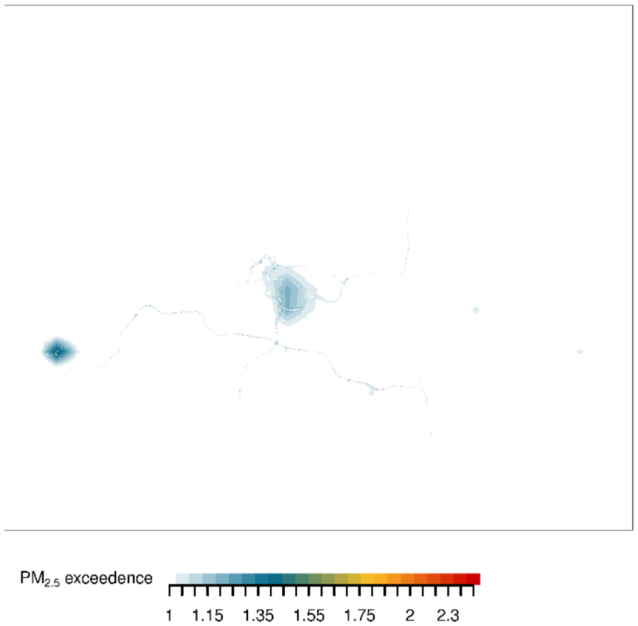


Birmingham (20m): 2030Ctplus

Leeds (20m): 2012



Leeds (20m): 2030BC



Leeds (20m): 2030Ctplus

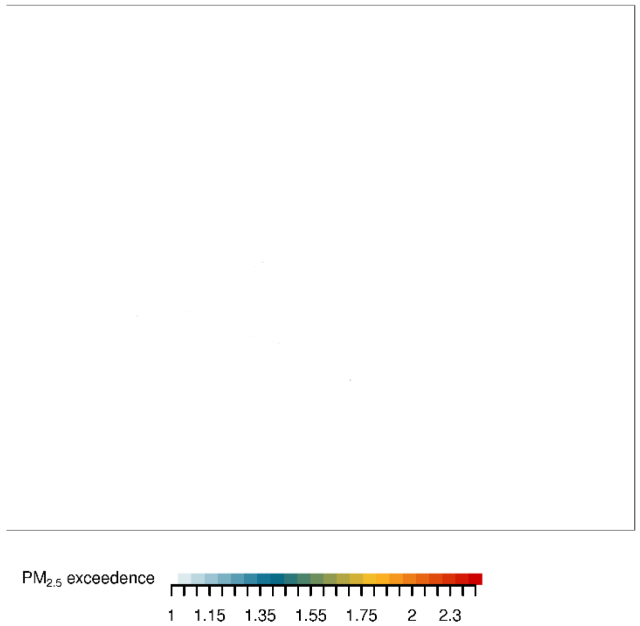
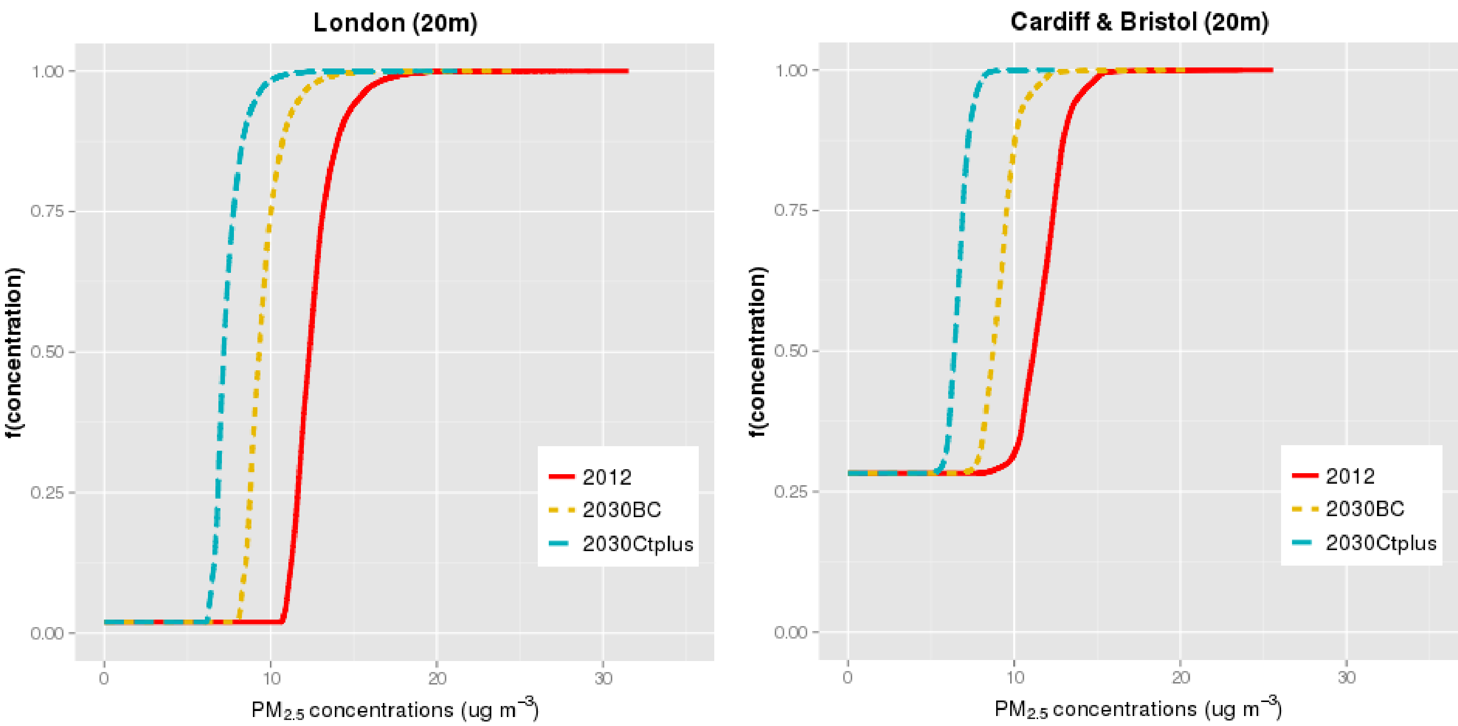


Figure 5 Exceedence ratio of the WHO Guideline value for $PM_{2.5}$ in major UK cities at 20m spatial scales for 2012, 2030BC and 2030Ct+ . A value of 1 = 10 μg m^{-3}, 0.5 = 5 μg m^{-3} and 2 = 20 μg m^{-3}

In London in 2012 there is widespread exceedence of the WHO guideline value, but in both 2030 scenarios a significant improvement in predicted concentrations is apparent with the 2030 BC only showing central London and major roads in and around London having the potential to exceed the WHO guideline. In 2030 ct+ the magnitude of this zone of exceedence is diminished further with just the very centre of London still in exceedence. Similar pictures are apparent for Liverpool/ Manchester, Birmingham and Leeds, whereby exceedences still occur in 2030 basecase albeit over very small areas in the centre of the cities and in the 2030 ct+ case no exceedences of guideline value. Other cites, Cardiff/Bristol, are not shown but have similar results and finally Edinburgh and Glasgow is not predicted to exceed the guideline value in 2012.

In addition to the city maps in Figure 5, we have made a comparison of all 20m results as a frequency plot to better describe the actual range of $PM_{2.5}$ concentrations for 2012, 2030 BC and 2030 Ct+, again without the inclusion of road centreline concentrations (Figure 6). Also note that the frequency plots do not reduce to zero and that is because all the predictions over the sea have been removed, hence in the example of Cardiff and Bristol over 25% of the 20m model domain is in the Bristol Channel. In London, the frequency plot confirms that in 2012 everywhere exceeds 10 μg m^{-3}, that in the 2030 BC only the top 25% of points exceed and in the 2030 Ct+ case the top 2-3% of locations exceed. For Cardiff and Bristol again, PM2.5 exceeds virtually everywhere in 2012, about 12% of the domain in 2030 BC and a handful of points in the 2030 Ct+ scenario.



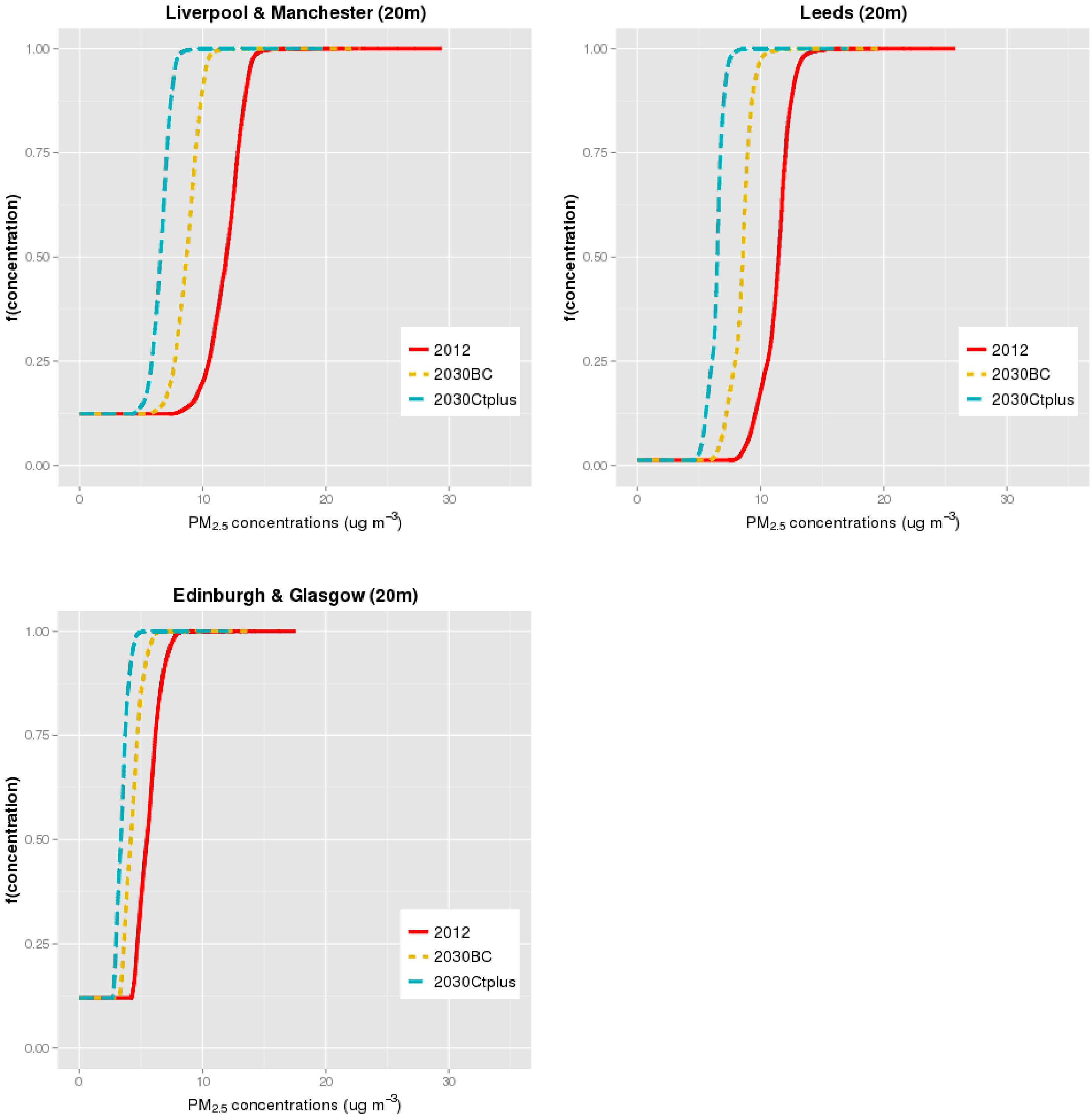


Figure 6 The frequency of $PM_{2.5}$ concentration (μg m^{-3}) for every 20m prediction in major UK cities for 2012, 2030BC and 2030Ct+

Table 2 The area of $PM_{2.5}$ exceedence (%) in 2012, 2030BC and 2030Ct+

Exceeds WHO guideline?	2012	2030 BC	2030 Ct+
London	100%	25%	~2%
Cardiff - Bristol	98%	10%	<1%
Leeds	75%	2%	<1%
Liverpool - Manchester	95%	2%	<1%
Edinburgh - Glasgow	<1%	<1%	<1%

Table 2 summarises each city giving an estimate of the area of the model domain over which exceedence of the WHO guideline value occurs. All of the results show a considerable improvement in concentrations in 2030, with the Ct+ scenario resulting in exceedences of <2% of the city in all cases.

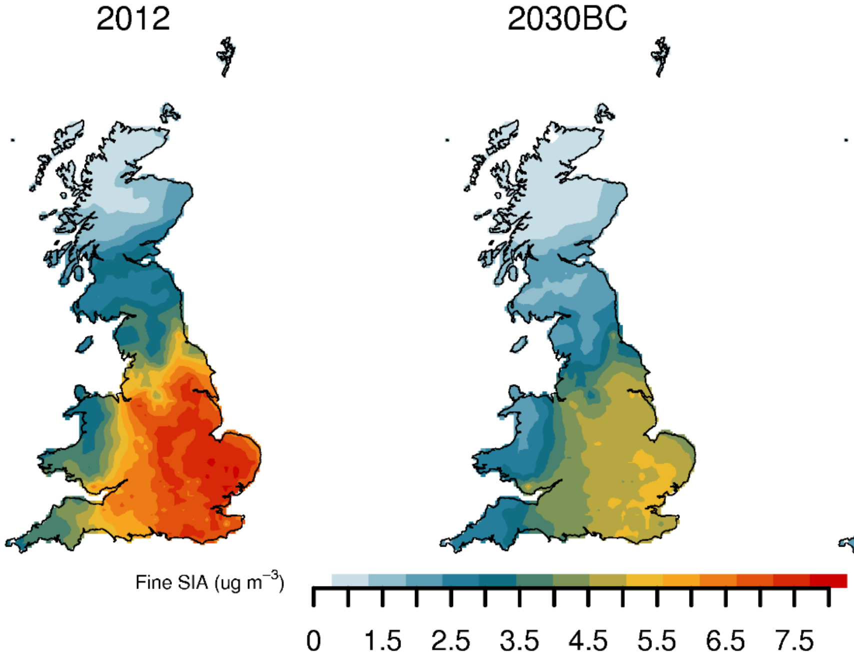
What PM components and sources are responsible for the $PM_{2.5}$ reduction?

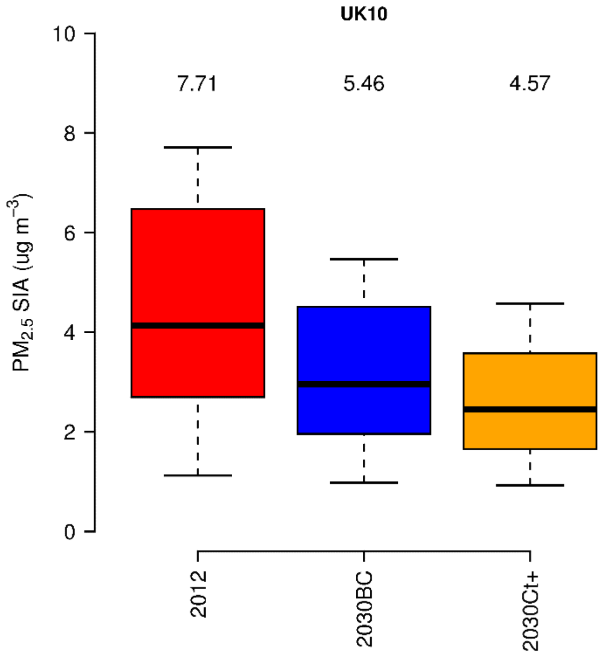
From the median concentrations of $PM_{2.5}$ components (Table 3) it is apparent that all are predicted to decrease between 2012 and the two 2030 scenarios. For convenience these are added in order of importance hence SIA is the most influential with a change in concentration of between 1.18 to 1.69 μgm^{-3}, followed by organic aerosol (0.17-0.34$\mu g\ m^{-3}$), elemental carbon (0.09-0.15 μgm^{-3}), Other (0.05-0.22 μgm^{-3}), and seasalt (0.05-0.07 μgm^{-3}). In this case the 'other' contribution includes: unclassified PM components such as metals and mineral dust. It is clear from these results that the main driver for change in $PM_{2.5}$ is SIA and that this prioritises the need for real reductions in NOx, ammonia and of less significance SO_2 emissions.

Table 3 The median value of $PM_{2.5}$ components ($\mu g\ m^{-3}$) in 2012, 2030BC and 2030Ct+ across GB

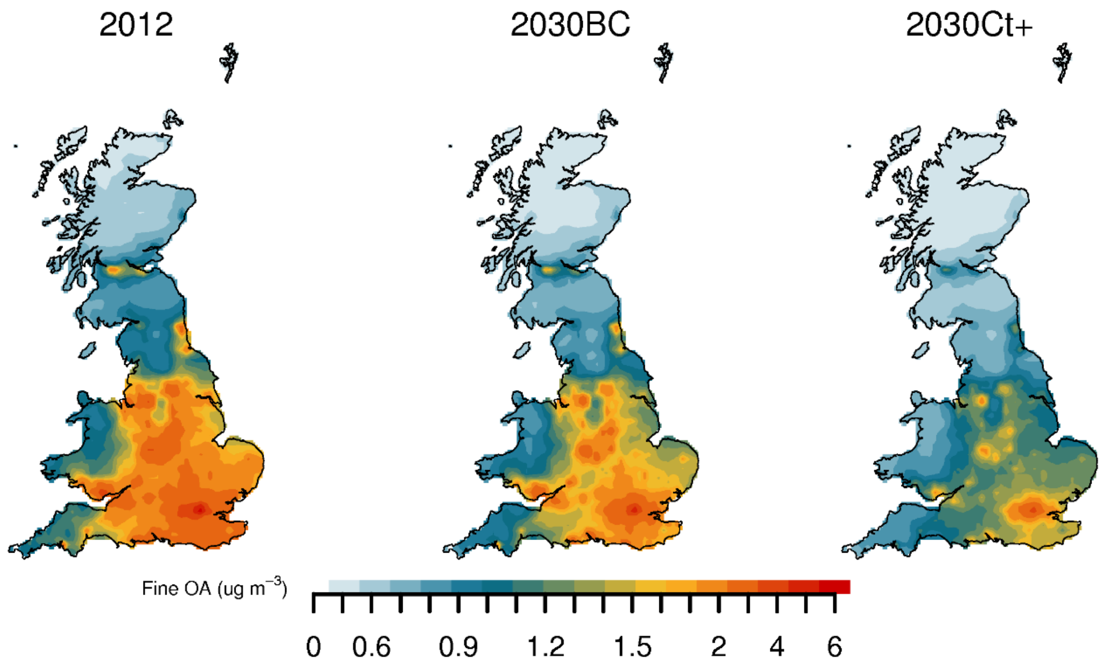
Pollutant	2012	2030 BC	2030 Ct+	Change
$PM_{2.5}$ - Secondary Inorganic Aerosol	4.13	2.95	2.44	1.18 - 1.69
$PM_{2.5}$ - Organic aerosol	1.21	1.04	0.87	0.17 - 0.34
$PM_{2.5}$ - Elemental Carbon	0.30	0.21	0.15	0.09 - 0.15
$PM_{2.5}$ - Other	0.49	0.44	0.26	0.05 - 0.22
$PM_{2.5}$ - Seasalt	0.26	0.2	0.18	0.05 - 0.07

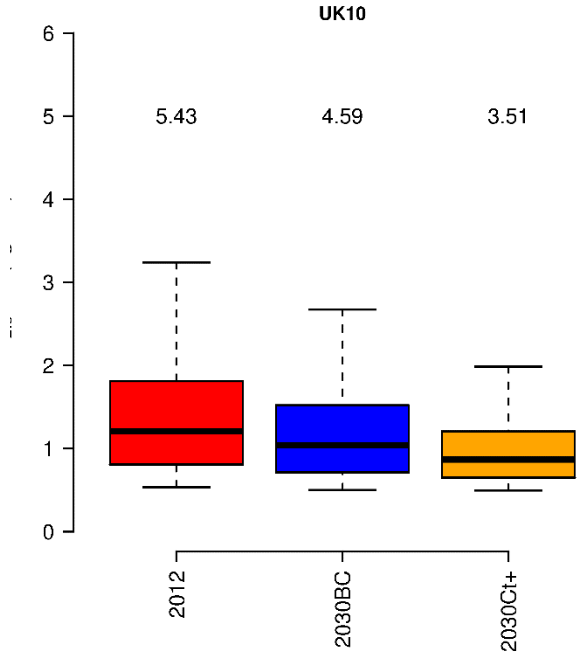
PM2.5 - Secondary Inorganic Aerosol



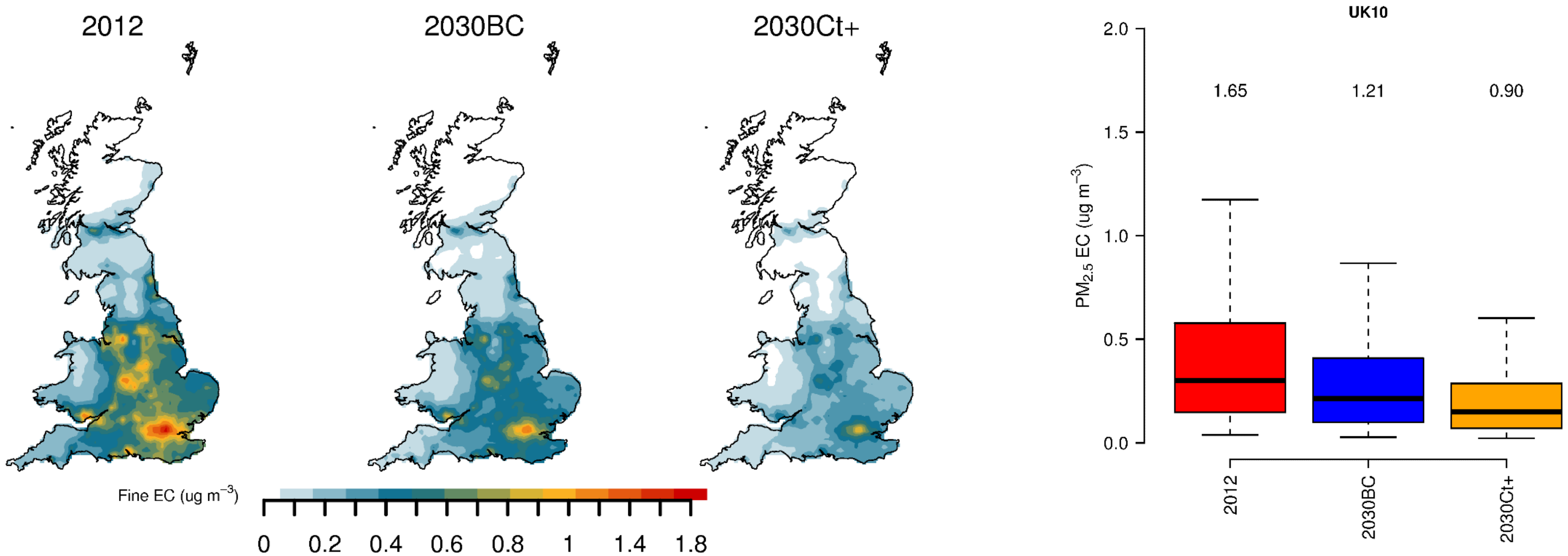


PM$_{2.5}$ - Organic aerosol

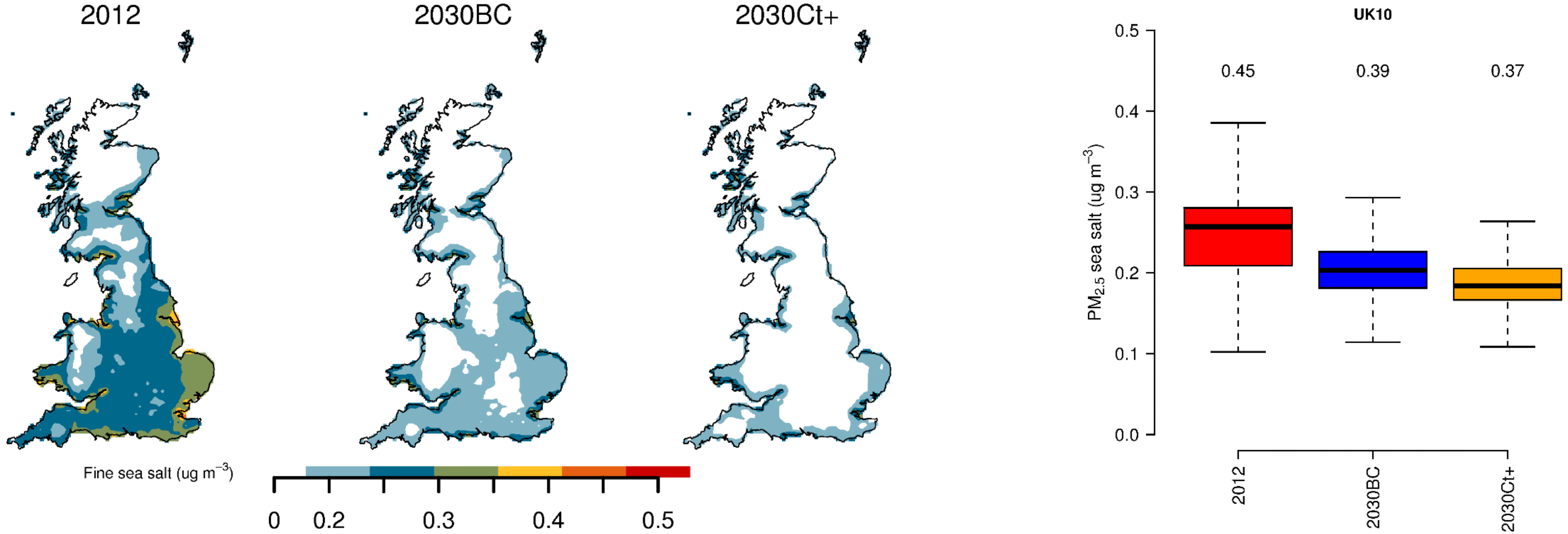




$PM_{2.5}$ - Elemental Carbon



$PM_{2.5}$ - Seasalt



PM$_{2.5}$ - Other

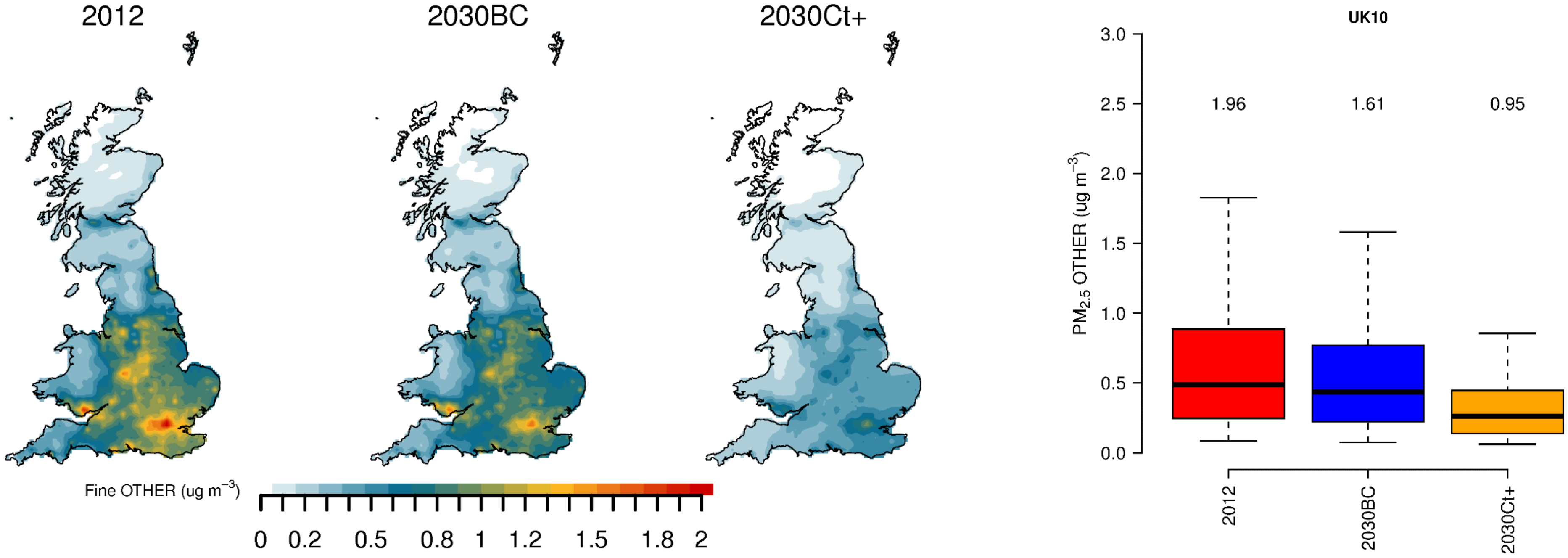


Figure 7 The trend in PM$_{2.5}$ concentration (µg m^{-3}) across Great Britain from 2012 to 2030BC and 2030Ct+

The source apportionment in Central London, exemplified by the CMAQ results for the City of London site is shown in Figure 8 and Table 4.

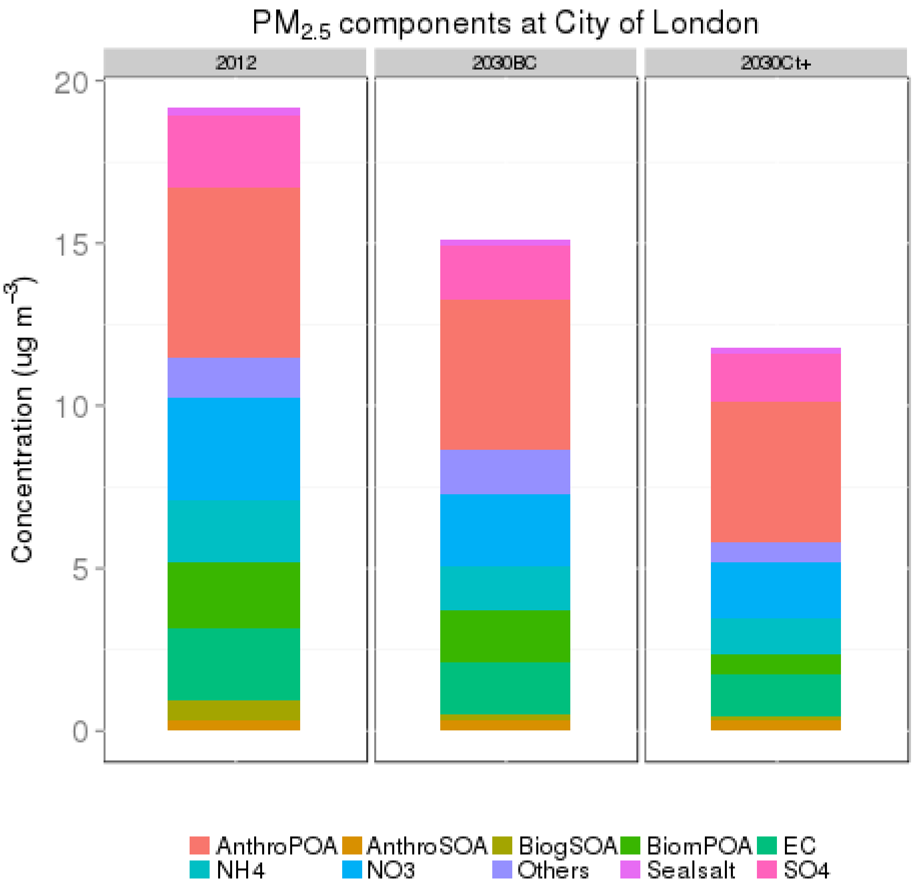


Figure 8. PM2.5 components in µg/m3.

Table 4. $PM_{2.5}$ components as percentages of total PM2.5 mass at the City of London site.

Case	SO_4^{2+}	NO_3^-	NH_4^+	EC	Sea salt	Anthro. POA	Anthro. SOA	Biomass POA	Biog. SOA	Others
2012	10.9	15.3	9.4	10.9	1.3	25.7	1.5	9.9	3.2	11.9
2030BC	10.2	13.8	8.4	10.0	1.3	28.6	1.9	9.8	3.8	12.2
2030Ct+	11.9	13.5	8.8	9.9	1.4	33.6	2.4	5.1	4.5	8.9

5. Summary and Discussion

- Projections show significant reduction of $PM_{2.5}$ between 2012 and 2030
- In urban areas, emissions in the 2030BC scenario result in concentrations which almost comply with the WHO guideline while the 2030Ct+ case complies everywhere except central London.
- The changes are driven largely by SIA and organic aerosols.
- Source apportionment suggests that the main source of exceedances remaining in London in the 2030Ct+ scenario is anthropogenic POA.
- Sources of anthropogenic POA of concern include road traffic, domestic commercial. combustion, SNAP8 (shipping, mobile machinery and aircraft) and biomass burning.
- Consideration should also be given to reduction of ammonia emissions.
- The non-linearity of PM concentration changes, due to reductions in emissions, are difficult to represent using the existing models runs, with further model runs needed.

Future work. Through an analysis of recent measurements in and around London, it is clear that the inter annual variability of regional $PM_{2.5}$ varies, both up and down, by as much as 2 μg m^{-3}. This is important, since the inter annual change is as large as the predicted changes between 2012 and 2030 (see Table 3). The implications are that the base year from which you forecast future $PM_{2.5}$ is critical in determining whether the WHO guideline value is meet in 2030. This also presents an opportunity to understand the mechanisms that drive large $PM_{2.5}$ changes year on year, and how this may inform future policy towards reducing future UK concentrations.

It is recommended therefore that a $PM_{2.5}$ modelling exercise be undertaken for a number of recent high and low years, to establish: the reasons for the large interannual variability of $PM_{2.5}$ concentrations, and to recommend future actions that will reduce $PM_{2.5}$ most in the UK.

Further modelling could incorporate more ambitious measures beyond the 2030 Ct+ scenario. Further improvements in air quality could potentially be delivered by climate policies which move towards a ‘net-zero’ carbon future for the UK following the Paris Agreement. Further work will be needed to explore these possibilities.

Acknowledgement

We would like to acknowledge the DEFRA for funding the study. Thanks also go to the US EPA for CMAQ model, the NCEP/NCAR for WRF model, EMEP for European emissions. TNO (AQMEII) for point source emissions, EEA for ground-based measurements, NCEP/NCAR for MOZART-4 and finally AQMEII for species and temporal profiles.

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Appendix A: European Emissions

The total anthropogenic emissions, excluding cooking emissions, for European countries outside the UK for 2012 and 2030 are shown in Table 4. The emissions for 2030 are based on the NECD obligations for each country in the EU. The scaling factors were derived from ECLIPSE project for other countries in model domain (http://www.iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv5.html).

The emissions for the rest of Europe are attributed to Albania, Bosnia and Herzegovina, Belarus, Switzerland, Georgia, Iceland, Liechtenstein, Moldova, Macedonia, North Africa, Norway, Russia, Turkey, Ukraine, Yugoslavia, remaining Asian areas in EMEP domain, including international shipping emissions from European seas (i.e., North Atlantic, Baltic Sea, Black Sea, Mediterranean Sea and North Sea)

Table 5 Total emissions for European countries outside the UK for 2012 and 2030 (kt yr^{-1})

Country	SO_2		NO_X		$PM_{2.5}$		NH_3		NMVOC	
	2012	2030	2012	2030	2012	2030	2012	2030	2012	2030
Austria	17.4	16.0	164.6	71.0	18.7	11.0	66.7	58.0	132.6	93.0
Belgium	47.5	49.0	216.1	125.0	32.2	23.0	63.4	60.0	140.6	94.0
Bulgaria	328.7	93.0	139.6	75.0	31.0	22.0	37.9	35.0	92.3	74.0
Cyprus	16.3	3.0	21.3	10.0	1.2	1.0	5.0	5.0	7.8	6.0
Czech Rep	150.1	70.0	189.9	100.0	26.3	15.0	68.0	66.0	138.9	104.0
Germany	416.7	198.0	1270.2	501.0	113.8	72.0	654.9	477.0	1136.1	833.0
Denmark	12.9	11.0	128.1	57.0	22.5	12.0	77.1	58.0	115.7	70.0
Spain	384.9	153.0	853.6	558.0	70.1	68.0	365.1	420.0	555.4	487.0

Estonia	40.6	24.0	32.1	28.0	17.2	9.0	11.3	10.0	34.1	21.0
Finland	51.4	46.0	146.5	97.0	37.5	24.0	37.3	31.0	104.8	66.0
France	235.5	103.0	1007.6	428.0	181.1	112.0	721.7	655.0	772.5	578.0
Greece	205.0	65.0	266.2	181.0	41.7	30.0	53.2	52.0	186.2	100.0
Croatia	24.8	10.0	55.5	34.0	16.4	19.0	38.7	29.0	48.6	50.0
Hungary	30.9	11.0	124.1	53.0	30.1	19.0	76.9	54.0	117.3	51.0
Ireland	25.2	11.0	78.5	43.0	15.3	11.0	105.9	98.0	88.2	46.0
Italy	174.9	119.0	863.4	417.0	121.1	101.0	414.7	364.0	862.2	651.0
Lithuania	20.0	12.0	47.7	25.0	20.8	13.0	41.5	30.0	68.1	37.0
Luxembourg	1.5	1.0	34.6	10.0	2.1	2.0	4.5	5.0	7.9	7.0

Latvia	2.0	5.0	34.2	27.0	26.4	13.0	15.0	17.0	89.2	29.0
Malta	4.6	1.0	8.0	2.0	0.8	0.0	1.5	1.0	3.2	3.0
Netherlands	34.1	30.0	247.5	140.0	13.2	12.0	135.6	120.0	153.7	149.0
Poland	858.6	351.0	819.2	478.0	144.8	104.0	262.5	260.0	630.3	434.0
Portugal	43.3	30.0	162.3	91.0	45.8	27.0	49.3	45.0	168.2	122.0
Romania	294.3	73.0	216.9	133.0	122.2	57.0	167.0	145.0	309.5	191.0
Slovakia	58.4	17.0	81.0	44.0	28.6	20.0	25.3	23.0	61.5	51.0
Slovenia	10.5	3.0	45.9	18.0	12.4	5.0	18.1	17.0	35.4	20.0
Sweden	28.3	28.0	131.5	66.0	22.7	25.0	51.2	53.0	179.4	129.0
Rest of EU domain	9650.5	9921.5	8597.5	7823.8	2372.5	2900.5	2459.2	2800.3	5027.7	4545.6

Appendix B: Evaluation of modelled air pollution

The modelled annual average concentrations of NO_2, NO_X, $PM_{2.5}$ and PM_{10} for 2012 were assessed prior to their use in the study. The predictions were compared against the ground-based measurements across Great Britain. The measurements (*Figure 9*) were obtained from the Automatic Urban and Rural Network (AURN) and London Air Quality Network (LAQN) which include rural (16), urban background (81), roadside (49), kerbside (8), and industrial (4) sites.

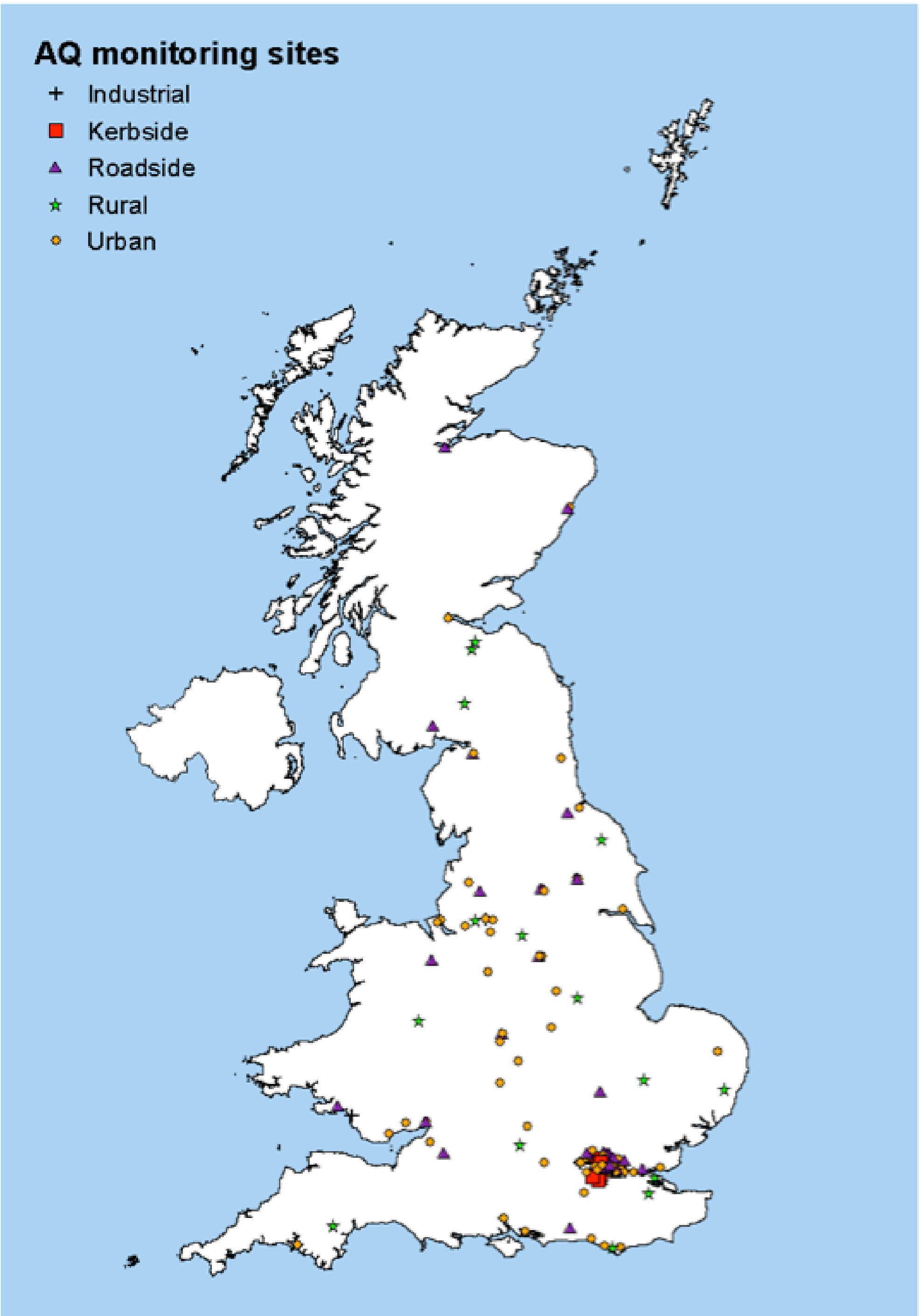


Figure 9. Air quality monitoring stations in Great Britain

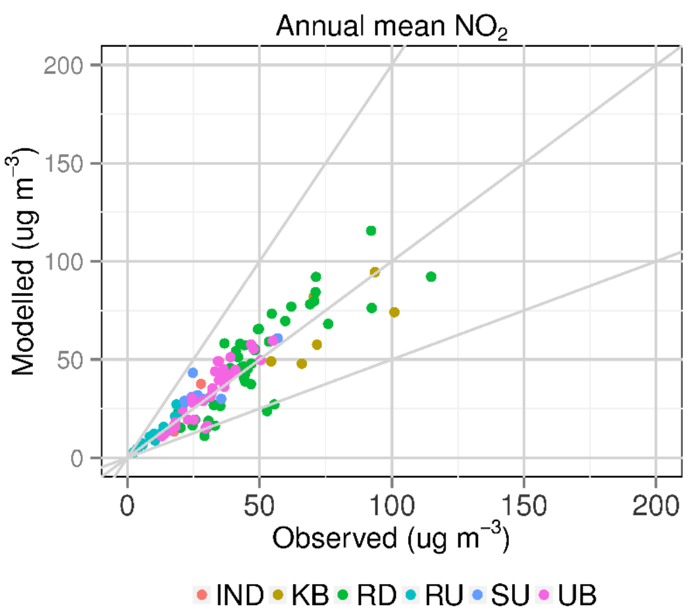
The performance statistics (*Table 6*) show good percentages of predictions within a factor of two of the measurements (FAC2 × 100), i.e., 94% for NO_2, 96% for NO_X, and 100% for $PM_{2.5}$ and PM_{10}. The model slightly underestimates NO_X (6.47 µg m^{-3} or 8%) and $PM_{2.5}$ (0.41 µg m^{-3} or 3%) while marginally overestimates NO_2 (1.14 µg m^{-3} or 3%) and PM_{10} (0.46 µg m^{-3} or 2%). The RMSE and r reveal that the spatial variations of the predicted NO_2 (RMSE=10.32 µg m^{-3}, r=0.90) and NO_X (RMSE=30.52 µg m^{-3}, r=0.89) are reasonably accurate although slightly less so for PM10 (RMSE=4.14 µg m^{-3}, r=0.77) and $PM_{2.5}$ (RMSE=2.80 µg m^{-3}, r=0.66).

Table 6 Performance statistics of CMAQ-Urban for 2012

Pollutant	Number of data	Observed mean (µg m ^{3})	Modelled mean (µg m ^{3})	FAC2	MB (µg m ^{3})	NMB	RMSE (µg m ^{3})	r
NO_2	109	37.75	38.90	0.96	1.14	0.03	10.32	0.90
$PM_{2.5}$	86	13.03	12.62	1	-0.41	-0.03	2.80	0.66

Note: FAC2, fraction of predictions within a factor of two; MB, mean bias; NMB, normalised mean bias; RMSE, root mean squared error; r, correlation coefficient.

Further investigation (Figures 10 and 11) has revealed that the prediction bias is largest at industrial and kerside locations where emissions estimates are highly uncertain. Tackling uncertainties in emissions would further enhance the model performance.



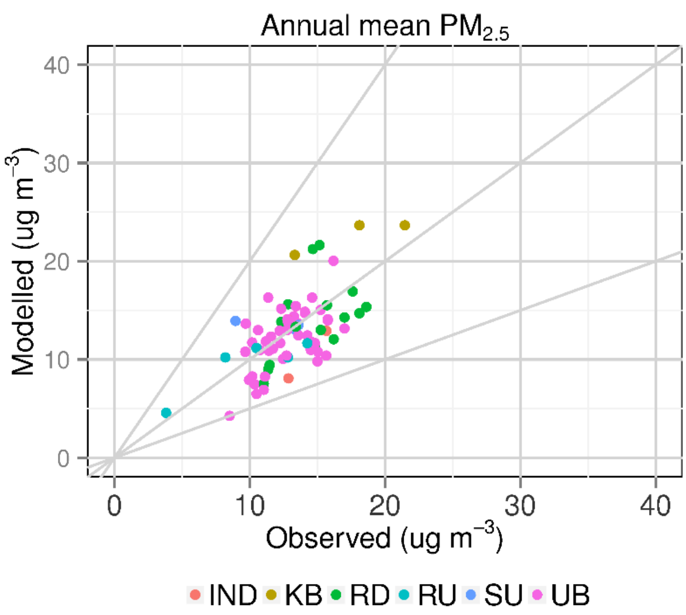
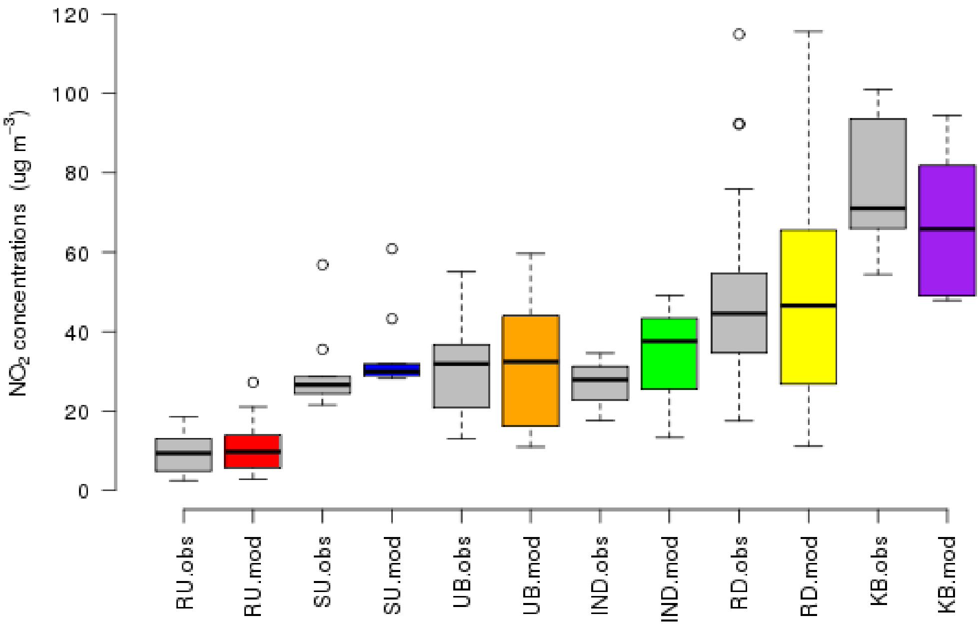


Figure 10 Scatter plots of modelled and observed NO_2 and $PM_{2.5}$ for 2012 (IND = industrial sites, KB = kerbside sites, RD = roadside site, RU = rural sites, SU = suburban sites, UB = urban background sites)



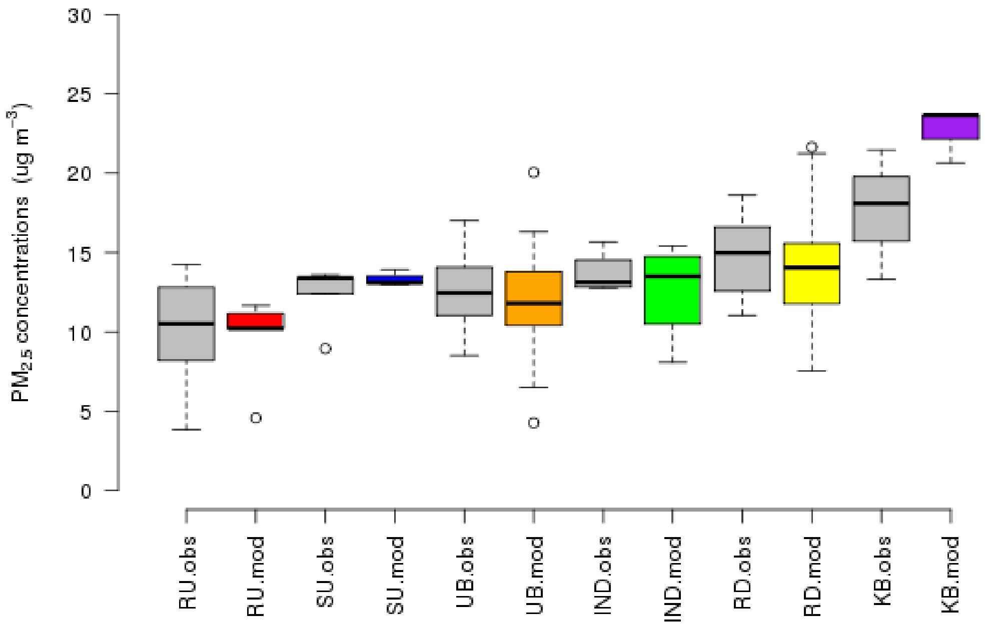


Figure 11 Spatial gradients of modelled and observed exposure to NO_2 and $PM_{2.5}$ (RU = rural sites, SU = suburban sites, UB = urban background sites, IND = industrial sites, RD = roadside site, KB = kerbside sites)

The modelled PMs components from the UK 10km grid domain were compared against the measurements from Clearflo project (http://www.clearflo.ac.uk). Only data from North Kensington were available for comparison and results is shown in Figure 12. Overall, the model predicts SIA and organic components well although slightly higher than the measurements. The underprediction of PM2.5 suggests small underprediction of other components.

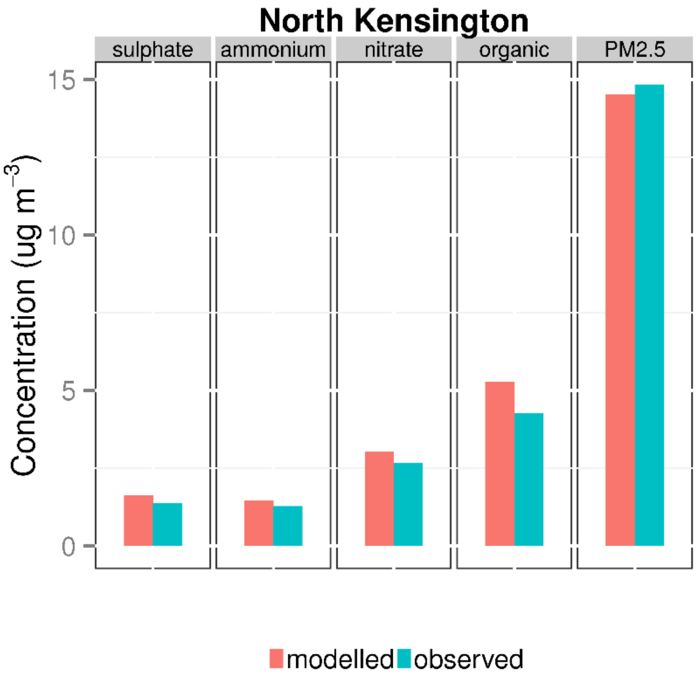


Figure 12 Comparison of $PM_{2.5}$, sulphate, ammonium, nitrate, and organic aerosol at North Kensington (UK 10km domain).

Appendix C: UK emissions scaling between 2016 and 2030 base case and 2030 central plus

Table 7 Scaling factors between 2016 and 2030BC nd 2030Ct+

Pollutant	SNAP	Base year	Prediction year	Factor 2030BC	Factor 2030Ct+
NH_3	1	2016	2030	1.38150052	1.38150052
NH_3	2	2016	2030	1.19892324	1.19892324
NH_3	3	2016	2030	1.22985619	1.22985619
NH_3	4	2016	2030	1.03599581	1.03599581
NH_3	5	2016	2030	1	1
NH_3	6	2016	2030	1.1363048	1.1363048
NH_3	7	2016	2030	1.111085	1.111085
NH_3	8	2016	2030	1.12037296	1.12037296
NH_3	9	2016	2030	1.01729734	1.01729734
NH_3	10	2016	2030	0.97923463	0.74467768
NH_3	11	2016	2030	1.05782154	1.05782154
SO_2	1	2016	2030	0.69960002	0.2856511
SO_2	2	2016	2030	0.25674083	0.1868161
SO_2	3	2016	2030	0.40211124	0.28001693

SO_2	4	2016	2030	0.84552364	0.32322275
SO_2	5	2016	2030	0.78855371	0.78855371
SO_2	6	2016	2030	1	1
SO_2	7	2016	2030	1.00440371	1.00440371
SO_2	8	2016	2030	0.84241971	0.78206179
SO_2	9	2016	2030	1.02776684	1.02776684
SO_2	10	2016	2030	1	1
SO_2	11	2016	2030	1.1610269	1.1610269
NO_X	1	2016	2030	0.70552194	0.65852868
NO_X	2	2016	2030	0.76634853	0.70254003
NO_X	3	2016	2030	0.8278438	0.67947682
NO_X	4	2016	2030	0.91884647	0.91884647
NO_X	5	2016	2030	0.74923842	0.74923842
NO_X	6	2016	2030	1	1
NO_X	7	2016	2030	0.35662063	0.25310977
NO_X	8	2016	2030	0.7158865	0.30442728

NO_X	9	2016	2030	1.03376605	1.03376605
NO_X	10	2016	2030	1	1
NO_X	11	2016	2030	0.98360895	0.98360895
PM_{10}	1	2016	2030	0.76022553	0.56361689
PM_{10}	2	2016	2030	0.76508176	0.27997294
PM_{10}	3	2016	2030	0.7904192	0.0752883
PM_{10}	4	2016	2030	0.90290636	0.82870377
PM_{10}	5	2016	2030	0.79447355	0.79447355
PM_{10}	6	2016	2030	1.25018692	1.25018692
PM_{10}	7	2016	2030	0.82326678	0.8082831
PM_{10}	8	2016	2030	0.66354795	0.59095694
PM_{10}	9	2016	2030	1.00133388	1.00133388
PM_{10}	10	2016	2030	1.00416581	0.96477849
PM_{10}	11	2016	2030	1.00539729	1.00539729
$PM_{2.5}$	1	2016	2030	0.72100223	0.60375146
$PM_{2.5}$	2	2016	2030	0.83560176	0.30831949

$PM_{2.5}$	3	2016	2030	0.79244142	0.07162625
$PM_{2.5}$	4	2016	2030	0.89523338	0.8112101
$PM_{2.5}$	5	2016	2030	0.79447355	0.79447355
$PM_{2.5}$	6	2016	2030	1.22753708	1.22753708
$PM_{2.5}$	7	2016	2030	0.82326678	0.8082831
$PM_{2.5}$	8	2016	2030	0.693293	0.64063385
$PM_{2.5}$	9	2016	2030	1.00123893	1.00123893
$PM_{2.5}$	10	2016	2030	1.00650743	0.96711096
$PM_{2.5}$	11	2016	2030	1.00539729	1.00539729
NMVOC	1	2016	2030	0.7452886	0.7452712
NMVOC	2	2016	2030	0.17096829	0.15201202
NMVOC	3	2016	2030	1.06040771	1.06040771
NMVOC	4	2016	2030	1.00990726	0.89874198
NMVOC	5	2016	2030	0.75723567	0.63093911
NMVOC	6	2016	2030	1.17282768	1.02423905
NMVOC	7	2016	2030	0.80543206	1.07993346

NMVOC	8	2016	2030	0.86104717	0.86104717
NMVOC	9	2016	2030	0.835495	0.835495
NMVOC	10	2016	2030	0.99028314	0.99028314
NMVOC	11	2016	2030	1.00003937	1.00003937
CO	1	2016	2030	0.45003832	0.45003832
CO	2	2016	2030	0.82342591	0.82342591
CO	3	2016	2030	3.08442371	3.08442371
CO	4	2016	2030	0.79099777	0.79099777
CO	5	2016	2030	0.00421092	0.00421092
CO	6	2016	2030	1	1
CO	7	2016	2030	1	1
CO	8	2016	2030	0.7396244	0.7396244
CO	9	2016	2030	3.25545238	3.25545238
CO	11	2016	2030	1.6980426	1.6980426

Appendix D: UK shipping emissions

UK domestic and international shipping emissions are included in NAEI SNAP8 mapping. Table 8 shows total emissions of SNAP8 and the percentages of international shipping and other shippings.

Table 8 UK total emissions for SNAP8 (kt yr^{-1}) and percentages of international and other shipping

Pollutant	2012	2030BC	2030Ct+	%ages of other shipping	%ages of international shipping
CO	343.14	278.07	278.07	10.3%	3.3%
NH_3	0.025	0.027	0.027	5.4%	10.0%
NO_X	540.99	367.59	156.32	22.8%	51.3%
PM_{10}	22.02	11.15	9.93	16.4%	41.9%
$PM_{2.5}$	21.46	11.34	10.48	16.2%	41.0%
SO_2	133.8	83.12	77.16	23.9%	74.5%
NMVOC	48.4	35.66	35.66	18.5%	18.9%

Figure 13 shows the NAEI NOx emissions map for SNAP8 at its original 1km grid resolution before being aggregated into model grids. The EMEP emissions were used to fill in missing gaps outside the UK mainland. Figure 14 shows the aggregated emissions at 10km grid resolution. The figure on the left includes only NAEI emission and figure on the right include both NAEI and EMEP emissions.

Figure 13. 2012 NAEI NOX emissions for SNAP8, including domestic and international shipping, at 1km grid resolution

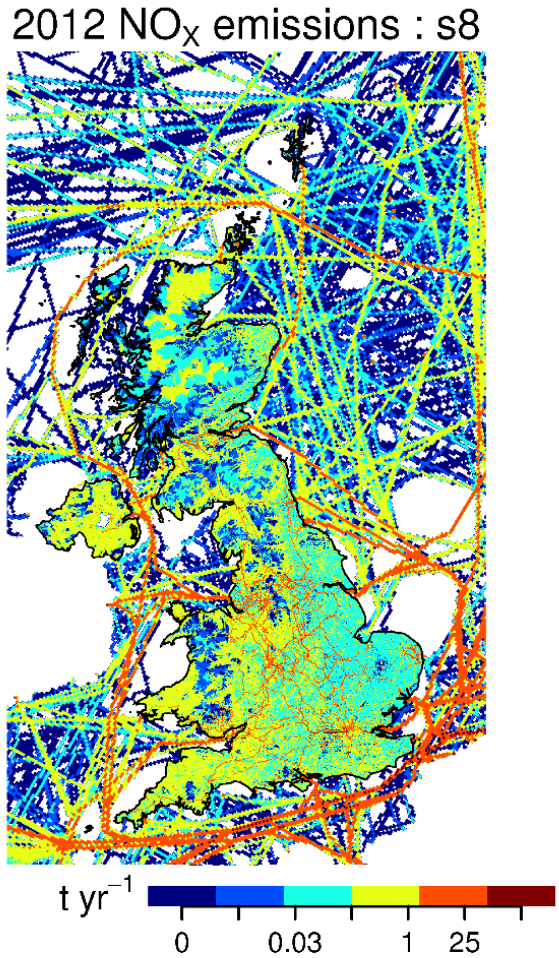
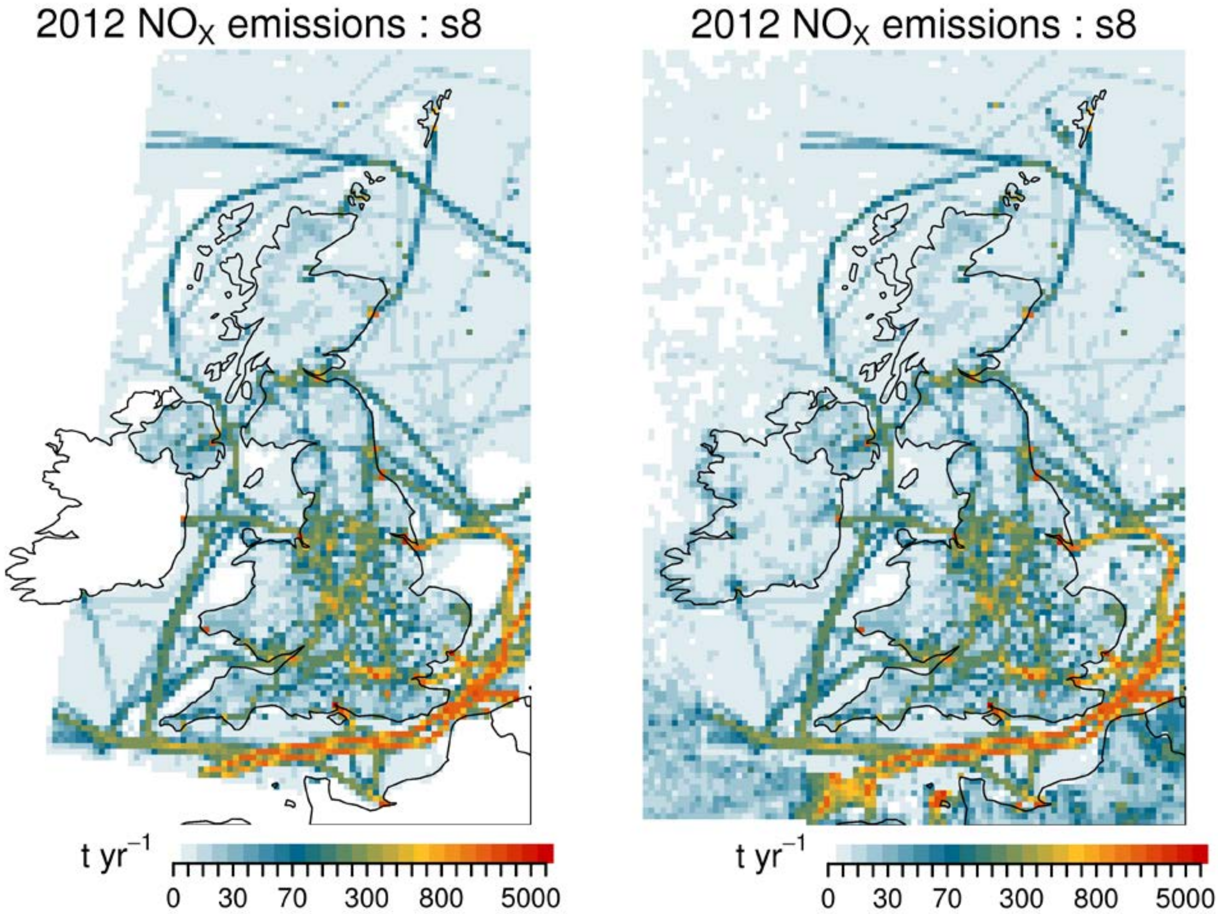


Figure 14. 2012 NAEI NOX emissions of SNAP8, including domestic and international shipping, at 10km grid resolution (left: only NAEI, right: NAEI and EMEP



Appendix E: PM components at AGANet sites

PM components at the AGANet sites for 2012, 2030BC and 2030Ct+ are shown in Table 9, Table 10, and Table 10, respectively.

Table 9 PM components at AGANet sites for 2012

Site	SO_4^{2}	NO_3	NH_4^+	EC	Sea salt	Anthro. SOA	Biog. SOA	Anthro. POA	Biomass POA	Others
Strathvaich	0.88	0.19	0.22	0.05	0.13	0.06	0.45	0.05	0.04	0.15
Lagganlia	0.90	0.27	0.32	0.06	0.12	0.06	0.46	0.06	0.04	0.18
Forsinard	0.95	0.14	0.21	0.05	0.14	0.06	0.44	0.05	0.04	0.16
Halladale	0.95	0.14	0.21	0.05	0.14	0.06	0.44	0.05	0.04	0.16
Polloch	0.98	0.27	0.27	0.06	0.19	0.07	0.46	0.06	0.05	0.19
Lerwick	0.99	0.11	0.14	0.05	0.24	0.05	0.42	0.04	0.03	0.17
Rum	1.05	0.27	0.23	0.05	0.25	0.07	0.46	0.06	0.05	0.18

Glensaugh	1.07	0.71	0.59	0.10	0.20	0.07	0.46	0.11	0.07	0.26
Eskdalemuir	1.13	0.93	0.67	0.16	0.18	0.09	0.51	0.16	0.10	0.33
Carradale	1.17	0.68	0.52	0.11	0.23	0.07	0.47	0.11	0.09	0.29
Lough Navar	1.18	0.72	0.61	0.16	0.21	0.08	0.48	0.15	0.15	0.41
Auchencorth Moss	1.20	1.03	0.77	0.21	0.23	0.09	0.49	0.22	0.15	0.42
Barcombe Mills	1.20	1.03	0.77	0.21	0.23	0.09	0.49	0.22	0.15	0.42
Plas Y Brenin	1.22	1.10	0.77	0.19	0.18	0.11	0.48	0.19	0.20	0.43
Edinburgh St Leonards	1.22	0.99	0.71	0.39	0.25	0.08	0.47	0.37	0.25	0.59
Moorhouse	1.23	1.27	0.87	0.17	0.20	0.11	0.48	0.20	0.13	0.37
Cwmystwyth	1.27	1.19	0.84	0.19	0.19	0.12	0.51	0.20	0.20	0.42

Bush Estate	1.28	1.11	0.82	0.48	0.25	0.10	0.50	0.50	0.35	0.72
Hillsborough	1.40	1.19	0.90	0.52	0.24	0.10	0.51	0.31	0.79	1.13
High Muffles	1.46	2.24	1.33	0.31	0.25	0.11	0.48	0.32	0.20	0.60
Yarner Wood	1.47	1.66	1.08	0.28	0.23	0.15	0.53	0.27	0.31	0.60
Narberth	1.48	1.38	0.97	0.25	0.34	0.12	0.49	0.25	0.22	0.54
Goonhilly	1.49	1.12	0.84	0.21	0.27	0.13	0.47	0.20	0.19	0.47
Rosemaund	1.59	2.49	1.48	0.45	0.26	0.16	0.56	0.53	0.36	0.88
Stoke Ferry	1.71	3.69	1.98	0.50	0.30	0.19	0.55	0.53	0.41	0.96
Ladybower	1.76	2.04	1.35	0.38	0.21	0.14	0.51	0.38	0.34	0.77
Harwell	1.80	3.03	1.75	0.61	0.26	0.20	0.56	0.60	0.60	1.05

Chilbolton Observatory	1.83	2.95	1.74	0.56	0.28	0.20	0.57	0.54	0.58	1.05
Caenby	1.83	3.31	1.87	0.54	0.29	0.15	0.52	0.56	0.35	0.94
Rothamsted	1.87	3.22	1.85	0.80	0.26	0.21	0.57	0.78	0.81	1.27
Lullington Heath	1.90	2.74	1.55	0.61	0.30	0.22	0.61	0.53	0.74	1.14
Detling	1.92	3.17	1.83	0.84	0.33	0.23	0.60	0.85	0.89	1.38
Sutton Bonnington	2.06	3.23	1.93	0.99	0.27	0.17	0.55	1.01	0.69	1.41
London Cromwell Road	2.09	2.94	1.81	1.58	0.25	0.26	0.62	2.27	1.65	2.05

Table 10 PM components at AGANet sites for 2030BC

Site	SO_4^{2}	NO_3	NH_4^+	EC	Sea salt	Anthro. SOA	Biog. SOA	Anthro. POA	Biomass POA	Others
Lerwick	0.87	0.09	0.11	0.04	0.25	0.04	0.42	0.03	0.02	0.15
Forsinard RSPB	0.82	0.10	0.15	0.03	0.14	0.05	0.43	0.04	0.03	0.13
Halladale	0.82	0.10	0.15	0.03	0.14	0.05	0.43	0.04	0.03	0.13
Strathvaich	0.75	0.13	0.16	0.03	0.12	0.05	0.44	0.04	0.03	0.13
Lagganlia	0.74	0.19	0.24	0.04	0.11	0.05	0.45	0.05	0.03	0.16
Polloch	0.83	0.19	0.19	0.04	0.19	0.06	0.45	0.05	0.04	0.16
Rum	0.91	0.19	0.16	0.04	0.25	0.06	0.45	0.04	0.03	0.16
Carradale	0.94	0.46	0.36	0.08	0.22	0.06	0.46	0.08	0.07	0.25

Glensaugh	0.86	0.47	0.42	0.07	0.17	0.06	0.45	0.08	0.05	0.22
Lough Navar	0.97	0.44	0.42	0.12	0.19	0.07	0.47	0.11	0.11	0.34
Eskdalemuir	0.90	0.61	0.47	0.09	0.16	0.08	0.49	0.11	0.07	0.31
Edinburgh St Leonards	0.96	0.68	0.49	0.27	0.23	0.07	0.46	0.27	0.19	0.50
Auchencorth Moss	0.93	0.64	0.51	0.14	0.19	0.08	0.47	0.17	0.12	0.36
Barcombe Mills	0.93	0.64	0.51	0.14	0.19	0.08	0.47	0.17	0.12	0.36
Plas Y Brenin	0.97	0.74	0.54	0.14	0.15	0.10	0.47	0.15	0.15	0.36
Bush Estate	0.97	0.70	0.53	0.34	0.21	0.08	0.48	0.38	0.27	0.60
Goonhilly	1.23	0.72	0.59	0.15	0.23	0.11	0.45	0.15	0.13	0.38
Cwmystwyth	1.02	0.80	0.60	0.14	0.17	0.11	0.49	0.15	0.14	0.37

Hillsborough	1.05	0.76	0.59	0.40	0.21	0.08	0.49	0.24	0.62	0.95
Moorhouse	0.95	0.85	0.60	0.12	0.17	0.09	0.47	0.15	0.09	0.33
Narberth	1.19	0.92	0.68	0.18	0.30	0.10	0.47	0.19	0.16	0.47
Yarner Wood	1.18	1.09	0.75	0.20	0.18	0.13	0.50	0.21	0.23	0.48
Ladybower	1.25	1.45	0.93	0.27	0.17	0.13	0.49	0.29	0.26	0.67
High Muffles	1.11	1.58	0.92	0.20	0.20	0.10	0.47	0.24	0.15	0.55
Rosemaund	1.22	1.67	1.01	0.33	0.21	0.15	0.54	0.42	0.27	0.75
Lullington Heath	1.46	1.96	1.10	0.43	0.26	0.20	0.57	0.40	0.53	0.88
London Cromwell Road	1.57	2.16	1.30	1.16	0.20	0.27	0.58	1.89	1.27	1.66
Chilbolton Observatory	1.35	1.99	1.17	0.41	0.22	0.19	0.54	0.42	0.44	0.86

Harwell	1.33	2.09	1.20	0.44	0.20	0.19	0.53	0.46	0.45	0.86
Detling	1.44	2.24	1.28	0.60	0.26	0.22	0.57	0.66	0.66	1.11
Rothamsted	1.35	2.23	1.25	0.57	0.20	0.21	0.54	0.60	0.62	1.03
Sutton Bonnington	1.36	2.27	1.28	0.67	0.20	0.17	0.52	0.74	0.53	1.17
Caenby	1.33	2.25	1.25	0.35	0.22	0.14	0.50	0.41	0.27	0.88
Stoke Ferry	1.25	2.41	1.29	0.35	0.21	0.18	0.52	0.41	0.30	0.79

Table 11 PM components at AGANet sites for 2030Ct+

Site	SO_4^{2}	NO_3	NH_4^+	EC	Sea salt	Anthro. SOA	Biog. SOA	Anthro. POA	Biomass POA	Others
Lerwick	0.86	0.07	0.09	0.03	0.25	0.04	0.42	0.03	0.02	0.14
Forsinard RSPB	0.80	0.07	0.13	0.03	0.13	0.05	0.43	0.03	0.02	0.12
Halladale	0.80	0.07	0.13	0.03	0.13	0.05	0.43	0.03	0.02	0.12
Strathvaich	0.73	0.09	0.14	0.03	0.12	0.05	0.44	0.03	0.02	0.11
Lagganlia	0.71	0.14	0.20	0.03	0.11	0.05	0.44	0.04	0.02	0.12
Polloch	0.80	0.14	0.16	0.03	0.19	0.05	0.44	0.04	0.02	0.13
Rum	0.89	0.14	0.13	0.03	0.25	0.05	0.44	0.04	0.02	0.14
Carradale	0.90	0.33	0.29	0.05	0.21	0.06	0.45	0.06	0.04	0.18

Glensaugh	0.82	0.34	0.34	0.05	0.16	0.06	0.44	0.07	0.03	0.16
Lough Navar	0.93	0.34	0.37	0.08	0.18	0.06	0.45	0.09	0.05	0.23
Eskdalemuir	0.85	0.43	0.38	0.07	0.15	0.07	0.48	0.08	0.05	0.19
Edinburgh St Leonards	0.90	0.47	0.39	0.20	0.22	0.07	0.45	0.23	0.08	0.32
Auchencorth Moss	0.88	0.45	0.41	0.10	0.17	0.07	0.46	0.14	0.06	0.24
Barcombe Mills	0.88	0.45	0.41	0.10	0.17	0.07	0.46	0.14	0.06	0.24
Plas Y Brenin	0.91	0.53	0.44	0.09	0.14	0.09	0.45	0.11	0.08	0.24
Bush Estate	0.91	0.50	0.43	0.25	0.20	0.08	0.47	0.32	0.11	0.37
Goonhilly	1.20	0.54	0.49	0.11	0.21	0.10	0.45	0.12	0.09	0.28
Cwmystwyth	0.96	0.58	0.49	0.10	0.15	0.10	0.47	0.12	0.09	0.26

Hillsborough	0.98	0.56	0.49	0.21	0.19	0.08	0.45	0.17	0.21	0.45
Moorhouse	0.89	0.62	0.49	0.08	0.16	0.09	0.46	0.11	0.06	0.22
Narberth	1.12	0.66	0.55	0.13	0.28	0.10	0.46	0.14	0.09	0.34
Yarner Wood	1.13	0.80	0.61	0.14	0.17	0.12	0.48	0.16	0.14	0.33
Ladybower	1.10	1.06	0.73	0.18	0.16	0.12	0.47	0.23	0.12	0.39
High Muffles	1.00	1.17	0.72	0.15	0.18	0.10	0.45	0.19	0.08	0.35
Rosemaund	1.10	1.22	0.79	0.22	0.19	0.14	0.51	0.31	0.14	0.47
Lullington Heath	1.41	1.55	0.92	0.32	0.24	0.20	0.55	0.34	0.35	0.64
London Cromwell Road	1.46	1.66	1.08	0.87	0.18	0.27	0.55	1.70	0.53	1.03
Chilbolton Observatory	1.24	1.45	0.92	0.28	0.19	0.18	0.51	0.33	0.22	0.53

Harwell	1.22	1.54	0.95	0.31	0.18	0.19	0.50	0.37	0.22	0.54
Detling	1.35	1.72	1.04	0.44	0.24	0.21	0.54	0.55	0.36	0.73
Rothamsted	1.23	1.65	0.99	0.41	0.18	0.20	0.51	0.50	0.28	0.64
Sutton Bonnington	1.19	1.68	0.99	0.49	0.18	0.16	0.49	0.60	0.23	0.72
Caenby	1.15	1.65	0.96	0.25	0.19	0.13	0.48	0.33	0.14	0.57
Stoke Ferry	1.15	1.78	1.01	0.26	0.19	0.17	0.50	0.32	0.18	0.51