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Urban air quality modelling of Dublin

Final report

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1. Introduction

The Environmental Protection Agency (EPA) in Ireland commissioned Cambridge Environmental Research Consultants Ltd (CERC) to carry out an urban air quality assessment of the city of Dublin. The purpose of this work relates to the Irish EPA using Dublin as one of the ‘pilot exercises’ within FAIRMODE¹.

This report describes the model input data and assumptions and presents the results of the modelling. The air quality targets, with which the calculated concentrations are compared, are presented in Section 2. An overview of the area and details of measured data are given in Section 3. The emissions data are summarised in Section 4, and the detailed model set-up is summarised in Section 5. The model verification for 2015 is presented in Section 6 and evaluation of the model is presented in Section 7. The results of detailed modelling for 2015 are given in Section 8. Finally, a description of the ADMS-Urban model is given in Appendix A.

¹ <https://fairmode.jrc.ec.europa.eu/>

2. Air quality standards

The EU *Ambient Air Quality and Cleaner Air for Europe (CAFE) Directive* (2008/50/EC) sets binding limits for concentrations of air pollutants, which take into account the effects of each pollutant on the health of those who are most sensitive to air quality. The Directive was transposed into Irish legislation by the *Air Quality Standards Regulations 2011*². The limit values for nitrogen dioxide (NO₂), particulate matter (PM₁₀ and PM_{2.5}) are presented in Table 2.1.

Table 2.1: Air quality limits

	Value (µg/m ³)	Description
NO ₂	200	Hourly mean not to be exceeded more than 18 times a calendar year (modelled as 99.79 th percentile)
	40	Annual average
PM ₁₀	50	24-hour mean not to be exceeded more than 35 times a calendar year (modelled as 90.41 st percentile)
	40	Annual average
PM _{2.5}	25	Stage 1: to be attained by 2015 Annual average
	20	Stage 2: to be attained by 2020 Annual average

The short-term limits, i.e. those measured hourly or over 24 hours, are specified in terms of the number of times during a year that a concentration measured over a short period of time is permitted to exceed a specified value. For example, the concentration of NO₂ measured as the average value recorded over a one-hour period is permitted to exceed the concentration of 200 µg/m³ up to 18 times per year. Any more exceedences than this during a one-year period would represent a breach of the limit.

It is convenient to model limits of this form in terms of the equivalent percentile concentration value. A percentile is the concentration below which lie a specified percentage of concentration measurements. For example, consider the 98th percentile of one-hour concentrations over a year. Taking all of the 8760 one-hour concentration values that occur in a year, the 98th percentile value is the concentration below which 98% of those concentrations lie. Or, in other words, it is the concentration exceeded by 2% (100 – 98) of those hours, that is, 175 hours per year. Taking the NO₂ limit considered above, allowing 18 exceedences per year is equivalent to not exceeding for 8742 hours or for 99.79% of the year. This is therefore equivalent to the 99.79th percentile value. It is important to note that modelling exceedences of short term averages is generally not as accurate as modelling annual averages.

² <http://www.epa.ie/pubs/legislation/air/quality/airqualitystandardsregulations2011.html>

3. Air quality monitoring

The Environmental Protection Agency measures air pollution at a set of automatic monitors in Dublin as part of the National Ambient Air Quality Network. A nitrogen dioxide diffusion tube survey was also carried out in Dublin in 2016 and 2017. Figure 3.1 presents the locations of the automatic monitoring sites and diffusion tubes in the model area. Table 3.1 summarises the 11 automatic monitoring sites in the modelling area which measure hourly NO_2 , PM_{10} , $\text{PM}_{2.5}$ and O_3 .

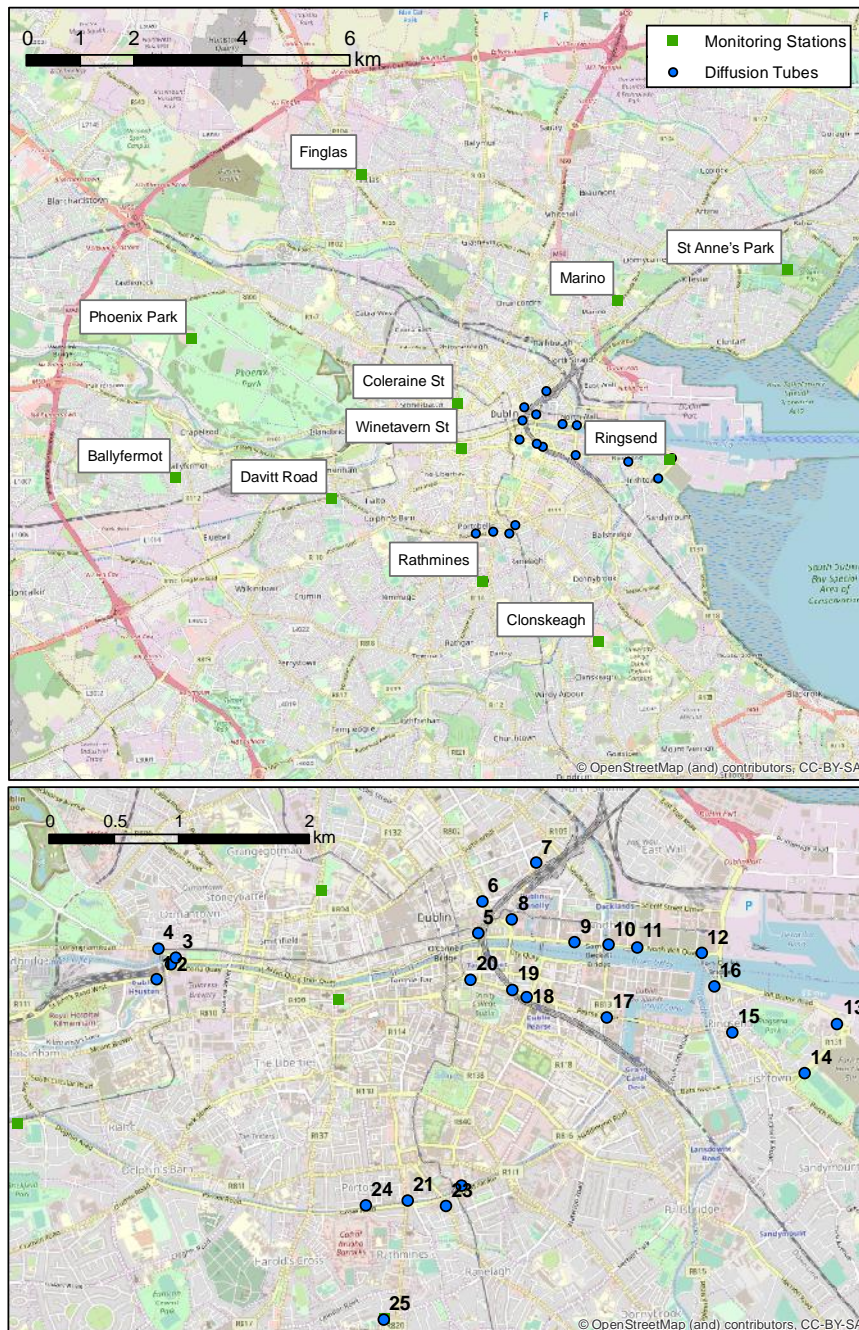


Figure 3.1: Location map of automatic monitoring sites and diffusion tubes in Dublin

Table 3.1: Summary of automatic monitoring sites

ID	Location	Type	X (m)	Y (m)	Inlet height (m)	Pollutants monitored in 2015	Pollutants monitored in 2017
CM1	Ballyfermot	Urban Background	709729	733516	1.5	NO ₂ , PM ₁₀	NO ₂
CM2	Clonskeagh	Urban Background	717576	730482	1.5	O ₃	O ₃
CM3	Coleraine St	Roadside	714965	734889	1.5	NO ₂	NO ₂
CM4	Davitt Road	Roadside	712624	733128	1.5	PM ₁₀	-
CM5	Finglas	Urban Background	713181	739147	1.5	PM _{2.5}	-
CM6	Marino	Urban Background	717947	736804	1.5	PM _{2.5}	-
CM7	Phoenix Park	Suburban	710023	736089	1.5	PM ₁₀	-
CM8	Rathmines	Urban Background	715436	731600	1.5	NO ₂ , PM ₁₀ , PM _{2.5} , O ₃	NO ₂ , PM ₁₀ , PM _{2.5} , O ₃
CM9	Ringsend	Roadside	718916	733849	1.5	-	NO ₂ , PM ₁₀
CM10	St Anne's Park	Suburban	721067	737382	1.5	NO ₂ , PM ₁₀	-
CM11	Winetavern Street	Roadside	715047	734067	1.5	NO ₂ , PM ₁₀	-

3.1. Nitrogen dioxide

Table 3.2 and Table 3.3 show, respectively, the measured annual average and 99.79th percentile of hourly average NO₂ concentrations measured by the automatic monitors.

Table 3.2: Annual average NO₂ concentrations at automatic monitors (µg/m³)

ID	Location	2015	2016	2017
CM1	Ballyfermot	16.0	17.3	16.5
CM3	Coleraine Street	25.3	27.6	25.6
CM8	Rathmines	18.3	20.0	17.1
CM9	Ringsend	-	-	21.9
CM10	St Anne's Park	13.5	-	-
CM11	Winetavern Street	31.1	36.6	-

Table 3.3: 99.79th percentile of hourly NO₂ concentrations at automatic monitors (µg/m³)

ID	Location	2015	2016	2017
CM1	Ballyfermot	94	-	110
CM3	Coleraine Street	106	-	107
CM8	Rathmines	88	-	85
CM9	Ringsend	-	-	99
CM10	St Anne's Park	67	-	-
CM11	Winetavern Street	127	-	-

Table 3.4 shows the measured annual average NO₂ concentrations measured using diffusion tubes. Exceedences of the air quality limit of 40 µg/m³ are highlighted in **bold**.

Table 3.4: Annual average NO₂ concentrations at diffusion tube sites (µg/m³)

ID	Area	Location	X (m)	Y (m)	Height (m)	2017	Capture rate (%)
DT1	Heuston Station	R148 – Dr Steevens' Hospital	713694	734222	3	53.6	100
DT2		Victoria Quay	713804	734335	3	52.3	100
DT3		Wolfe Tone Quay	713845	734386	3	48.4	100
DT4		Benburb Street	713708	734455	3	30.2	100
DT5	Busaras	Old Abbey Street	716173	734575	3	37.8	90
DT6		Gardiner Street Lower	716204	734819	3	49.8	90
DT7		Amien Street North	716620	735118	3	46.1	90
DT8		Amien Street South	716432	734681	3	45.0	100
DT9	North Wall	North Wall Quay 1	716916	734505	3	47.8	100
DT10		North Wall Quay 2	717179	734487	3	35.6	100
DT11		North Wall Quay 3	717399	734467	3	39.9	100
DT12		North Wall Quay 4	717897	734423	3	37.2	70
DT13	Ringsend	Pigeon House Road	718939	733874	3	24.3	100
DT14		Sean Moore Road	718687	733499	3	20.2	100
DT15		Ringsend Fitzwilliam Street	718130	733811	3	29.2	80
DT16		York Street	717995	734168	3	18.4	90
DT17	Pearse Street	Pearse Street 1	717163	733926	3	45.3	100
DT18		Pearse Street 2	716549	734084	3	46.0	100
DT19		Pearse Street 3	716437	734140	3	50.8	100
DT20		Pearse Street 4	716115	734218	3	64.4	100
DT21	Portobello/Rathmines	Charlemont Mall	715628	732516	3	23.8	100
DT22		Charlemont Place	716045	732630	3	21.2	70
DT23		Ranelagh Road	715924	732474	3	18.6	100
DT24		Kingsland Parade	715308	732481	3	28.9	100
DT25		Wynnefield Road	715448	731602	3	16.9	100

3.2. PM₁₀

Table 3.5 shows the measured annual average PM₁₀ concentrations at the automatic monitors. Table 3.6 and Table 3.7 show, respectively, the number of measured daily average PM₁₀ concentrations which exceeded 50 µg/m³ and the 90.41st percentile of daily average PM₁₀ concentrations.

Table 3.5: Annual average PM₁₀ concentrations at automatic monitors (µg/m³)

ID	Location	2015	2016	2017
CM1	Ballyfermot	11.7	10.7	-
CM4	Davitt Road	13.2	13.5	-
CM7	Phoenix Park	11.6	10.5	-
CM8	Rathmines	15.2	14.8	11.5
CM9	Ringsend	-	-	12.9
CM10	St Anne's Park	15.2	-	-
CM11	Winetavern Street	13.8	14.0	-

Table 3.6: Number of days with PM₁₀ > 50 µg/m³ at automatic monitors

ID	Location	2015	2016	2017
CM1	Ballyfermot	3	0	-
CM4	Davitt Road	6	2	-
CM7	Phoenix Park	2	0	-
CM8	Rathmines	5	3	4
CM9	Ringsend	-	-	0
CM10	St Anne's Park	3	-	-
CM11	Winetavern Street	4	2	-

Table 3.7: 90.41st percentile of daily average PM₁₀ concentrations at automatic monitors

ID	Location	2015	2016	2017
CM1	Ballyfermot	21.8	n/a	-
CM4	Davitt Road	25.4	n/a	-
CM7	Phoenix Park	20.4	n/a	-
CM8	Rathmines	28.9	n/a	19.4
CM9	Ringsend	-	-	18.9
CM10	St Anne's Park	22.3	-	-
CM11	Winetavern Street	24.5	n/a	-

3.3. PM_{2.5}

Table 3.8 shows the measured annual average PM_{2.5} concentrations. There were no measured exceedences of the air quality limit of 25 µg/m³ for the years 2015 to 2017.

Table 3.8: Annual average PM_{2.5} concentrations at automatic monitors (µg/m³)

ID	Location	2015	2016	2017
CM3	Coleraine Street	9.4	9.0	-
CM5	Finglas	8.1	8.5	-
CM6	Marino	7.8	7.0	-
CM9	Rathmines	9.9	10.0	8.5

4. Emissions data

Emissions inventories were compiled for Dublin and the surrounding area for 2015 using CERC's emissions inventory toolkit (EMIT), version 3.6.0.

4.1. Major road traffic emissions

Traffic data were provided by Dublin City Council for the majority of the city area. The data comprised hourly traffic counts, speeds and percentage HGV for each road. The traffic counts were taken from the City's SCATS traffic management system. The light/heavy vehicle split was derived from the City's annual Cordon Count, which counts the traffic entering the inner city over all bridges on the Grand and Royal Canals. Figure 4.1 shows the annual average daily total (AADT) traffic flows for the city.

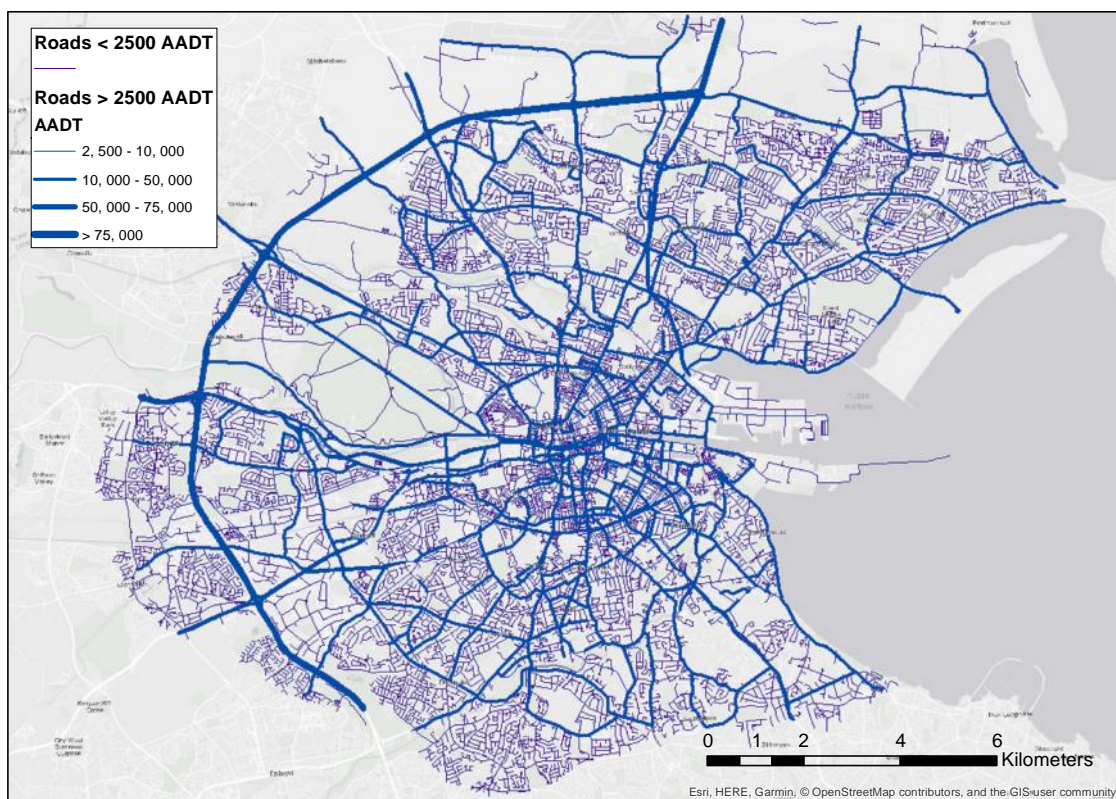


Figure 4.1: Daily traffic flows for modelled roads in Dublin

Some anomalies were identified in the traffic data during the data processing; changes were made, where possible, based on the traffic flow on neighbouring roads and local knowledge.

This version of the report includes updates to traffic flows on two minor and three major roads. Flows for minor roads Pembroke Lane and Wellington Road were provided by the Council and flows for major roads M2, N3 and M50 were taken from TII's traffic count website³.

³ [https://www.nrtraffdata.ie/c2/gmapbasic.asp?sgid=ZvyVmXU8jBt9PJE\\$c7UXt6](https://www.nrtraffdata.ie/c2/gmapbasic.asp?sgid=ZvyVmXU8jBt9PJE$c7UXt6)

4.1.1. Emission factors

Traffic emissions of NO_x, NO₂, PM₁₀ and PM_{2.5} were calculated from traffic flows using emission factors from the Emission Factor Toolkit (EFT) version 8.0 published by the UK Department for the Environment Food and Rural Affairs (Defra). This dataset includes factors for different vehicle types based on their Euro vehicle emissions category, fuel type, engine size and technology based on the COPERT 5⁴ emission factors.

Note that there is large uncertainty surrounding the current emissions estimates of NO_x from all vehicle types, in particular diesel vehicles, in these factors; refer to for example an AQEG report from 2007⁵ and a Defra report from 2011⁶. In order to address this discrepancy, the NO_x emission factors were modified based on recently published Remote Sensing Data (RSD)⁷ for vehicle NO_x emissions in London. Scaling factors were applied to each vehicle category and Euro standard.

Concentrations of PM₁₀ and PM_{2.5} at roadside locations are affected by brake, tyre and road-wear, and concentrations of PM₁₀ are also affected by resuspension. With the exception of resuspension, these non-exhaust road traffic emissions were calculated using EFT v8.0 emission factors. Resuspension emission factors were taken from a report produced by TRL Limited on behalf of Defra⁸.

4.1.2. Vehicle fleet composition

The vehicle-specific emission factors described above were applied to the traffic flows using city-wide fleet composition data. These data represent the proportion of each vehicle type with each combination of Euro engine, engine size, fuel type and technology. The fleet composition for Dublin was calculated from vehicle population and distance data split by vehicle type for Ireland.

4.1.3. Traffic speed

Traffic speed limits were provided for each road. The average vehicle speed was taken to be half of the speed limit, to reflect the congested nature of Dublin's streets.

⁴<http://www.emisia.com/copert/General.html>

⁵ *Trends in primary nitrogen dioxide in the UK*, Air Quality Expert Group, 2007
<https://uk-air.defra.gov.uk/assets/documents/reports/ageg/primary-no-trends.pdf>

⁶ *Trends in NO_x and NO₂ emissions and ambient measurements in the UK*, Prepared for Defra by King's College London, Leeds University and AEA, 3rd March 2011 https://uk-air.defra.gov.uk/assets/documents/reports/cat05/1103041401_110303_Draft_NOx_NO2_trends_report.pdf

⁷ Carslaw, D and Rhys-Tyler, G 2013: New insights from comprehensive on-road measurements of NO_x, NO₂ and NH₃ from vehicle emission remote sensing in London, UK. *Atmos. Env.* **81** pp 339–347.

⁸ Stocker, J. and Carruthers, D., 2007. Road vehicle non-exhaust particulate matter: Initial air quality model development and application, model uncertainty analysis and further model improvements. *PUBLISHED PROJECT REPORT PPR224*.

4.1.4. Major and minor roads

All major roads with an AADT greater than 2,500 were included in the model as road sources. Emissions from all other roads were modelled as aggregated 1-km resolution grid sources.

4.1.5. Daily traffic variation

The variation of traffic flow during the day was taken into account by applying a set of hourly profiles to the road emissions. Hourly traffic data for the M50, N31, R108 and N32 published by TII (Transport Infrastructure Ireland) for Saturday, Sunday and workdays were used to calculate a profile, as shown in Figure 4.2⁹. These profiles were applied to all major roads in the modelling area and grid sources, representing emissions of minor roads, and other emissions, aggregated on 1-km square basis, described in Section 4.3.

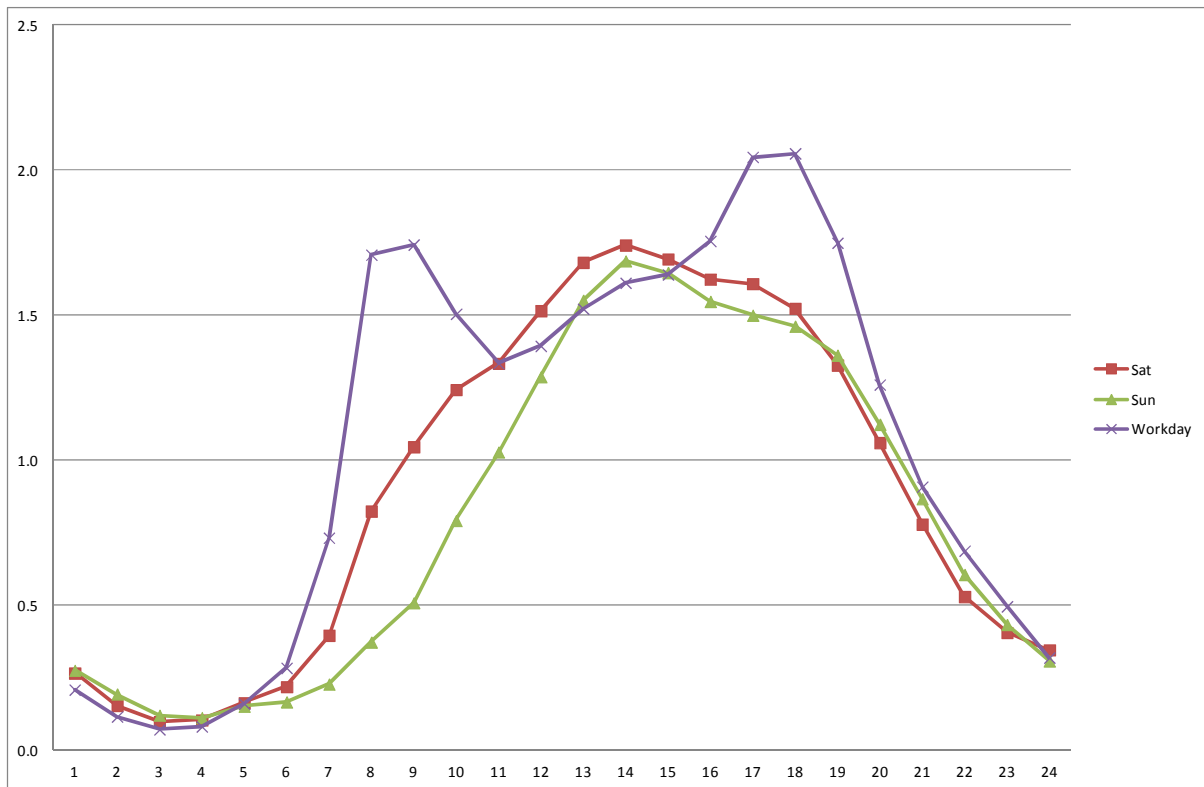


Figure 4.2: Diurnal profiles for road traffic emissions

⁹ [https://www.nrtrafficaidata.ie/c2/gmapbasic.asp?sgid=ZvyVmXU8jBt9PJE\\$c7UXt6](https://www.nrtrafficaidata.ie/c2/gmapbasic.asp?sgid=ZvyVmXU8jBt9PJE$c7UXt6)

4.2. Industrial sources

Industrial sources were included in the modelling. Fourteen large point sources were modelled explicitly using data including emission rates, stack height and diameter, emission temperature and velocity. These sources are summarised in Table 4.1 and their locations are shown in Figure 4.3. Emissions from smaller industrial sources were modelled as aggregated 1-km grid sources.

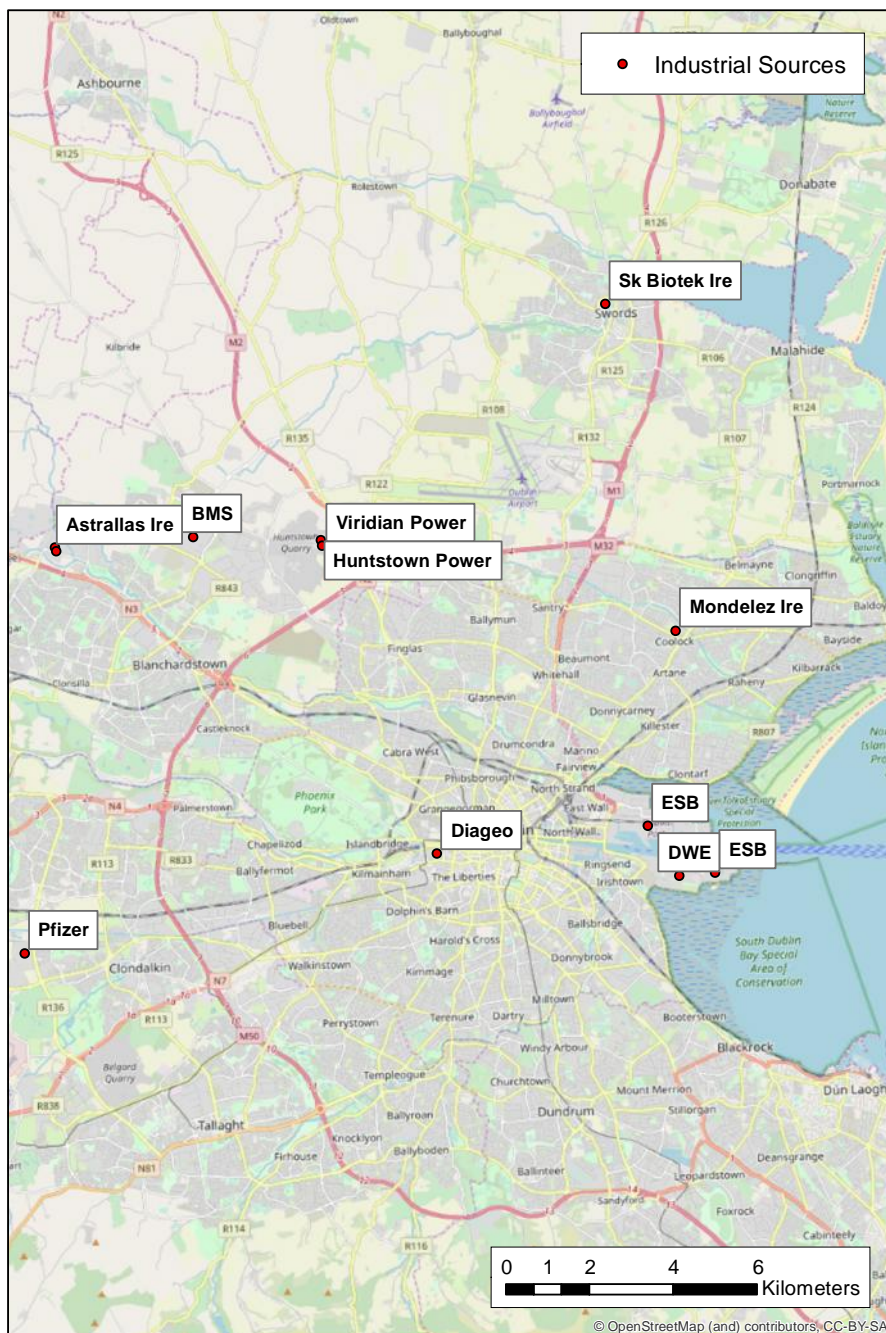


Figure 4.3: Explicitly modelled industrial sources

Table 4.1: Explicitly modelled industrial sources

ID	Name	Location		Height (m)	Diameter (m)	Exit velocity (m/s)	Temperature (°C)	NO _x (t/yr)	PM ₁₀ (t/yr)
		X (m)	Y (m)						
1	Pfizer	704208.5	731734.9	45	1.4	15	200	10.73	0.3785
2a	Diageo	714055.2	734120.4	46	2.0	15	200	45.68	-
2b		714055.2	734120.4	25	1.0	15	200	-	0.1325
3	ESB	719095.2	734778.4	65	1.0	15	200	26.71	-
4	DWE	719844.5	733594.9	105	1.0	15	200	230.79	-
5	ESB	720702.3	733661.1	30	2.0	15	200	70.19	-
6	Mondelez Ire	719750.1	739448.3	9.7	1.0	15	200	2.29	-
7	Sk Biotek Ire	718071.5	747254.9	15	1.0	15	200	1.60	0.4353
8	Huntstown Power	711274.7	741613.2	34.5	1.0	15	200	153.42	-
9	Viridian Power	711311.3	741469.3	34.5	1.0	15	200	283.96	-
10a	BMS	707861.0	741690.2	25	1.0	15	200	0.67	-
10b		708226.8	741687.4	35	1.0	15	200	6.78	0.0004
11a	Astrallas Ire	704927.3	741424.0	14.9	1.0	15	200	0.29	-
11b		704962.3	741346.9	19.7	1.4	15	200	0.87	0.0420

4.3. Other emissions

Emission rates for all other sources were taken from the output of the national emission mapping model ‘MapEIre’, which uses emissions from the national emission inventory and its output on a spatial resolution of 1 km x 1 km for Ireland¹⁰. Gridded emissions from the national inventory are split into the fifteen groups as described in Table 4.2.

Table 4.2: Categories of gridded emissions in the national emission inventory¹⁰

Group	Description
A_Public Power	Emissions from plants producing electricity and/or heat for the public grid
B_Industry	Emissions from combustion and processes in industry
C_OtherStationaryComb	Emissions from small combustion sectors, e.g. commercial, institutional, residential and agricultural
D_Fugitive	Fugitive emissions associated with production, refining, transport and storage of fuels.
E_Solvents	Emissions from the use of solvents
F_RoadTransport	Emissions from road transport
G_Shipping	Emissions from domestic navigation, i.e. navigation between two domestic ports. Fishing is included under “I_Offroad”
H_Aviation	Emissions from landing and take-off (LTO) both for domestic and international flights
I_Offroad	Emissions from machinery used in industry, households, agriculture as well as from railways and fishing vessels
J_Waste	Emissions associated with waste handling. Waste incineration with energy recovery is included under “A_PublicPower” or “B_Industry”
K_AgriLivestock	Emissions associated with animal husbandry and manure management
L_AgriOther	All other agricultural emissions, e.g. from application of mineral or organic fertilizer, crops and field operations
O_AviCruise	Emissions from the cruise phase of both domestic and international flights
P_IntShipping	Emissions from international navigation
Q_LULUCF	Emissions from land use, land use change and forestry

Where explicit emissions data were available, the emissions have been subtracted from the appropriate gridded emissions category. This includes all Public Power emissions and a proportion of the Industry emissions. All Road Transport emissions were removed where traffic data were available; grid Road Transport emissions were retained for the outskirts of Dublin, where traffic data were unavailable.

¹⁰ <http://projects.au.dk/mapeire/project-results/download/>

4.4. Total emissions

Table 4.3 shows the total annual NO_x, NO₂, PM₁₀ and PM_{2.5} emissions for the modelled area.

Table 4.3: Total annual emissions for the modelled area (tonnes/year)

Emissions Group	NO ₂	NO _x	PM ₁₀	PM _{2.5}	Modelled explicitly	Modelled as gridded emissions
Modelled Roads > 2500 AADT	1036	4149	223	140	✓	
Modelled Roads < 2500 AADT	121	394	23	15		✓
Industrial Sources	41	834	1	0	✓	
B_Industry	59	1183	224	218		✓
C_OtherStationaryComb	102	2041	503	471		✓
D_Fugitive	0	0	0	0		✓
E_Solvents	0	0	0	0		✓
F_RoadTransport*	109	2172	167	122		✓
G_Shipping	2	40	0.8	0.7		✓
H_Aviation	41	820	15	15		✓
I_Offroad	10	195	6	5		✓
J_Waste	0.3	7	0.2	0.1		✓
K_AgriLivestock	0	0	17	6		✓
L_AgriOther	0	0	197	10		✓
O_AviCruise	0.4	8	0.3	0.3		✓
P_IntShipping	0.3	6	0.1	0.1		✓
Q_LULUCF	0	0	0	0		✓

*Gridded road transport emissions outside domain of traffic data

5. Model set-up

Modelling was carried out using the ADMS-Urban¹¹ model (version 4.2.2). The model uses the detailed emissions data described in Section 4, together with a range of other input data, to calculate the dispersion of pollutants. This section summarises the data and assumptions used in the modelling.

5.1. Meteorological data

Modelling was carried out using hourly sequential meteorological data measured at Dublin Airport and Casement Airport for the years 2015 and 2017. Dublin Airport is located approximately 8 km north of Dublin city centre and Casement Airport is located approximately 13 km south west of Dublin city centre.

To take account of the different surface characteristics at Dublin and Casement Airports compared to the city, a surface roughness of 0.1 m was used for both meteorological sites.

The hours of meteorological data used in the analysis exclude hours of calm, hours of variable wind direction and unavailable data, for example due to issues with the instrumentation. A summary of the data used is given in Table 5.1 and Table 5.2. The ADMS meteorological pre-processor, written by the Met Office, uses the data provided to calculate the parameters required by the program.

Figure 5.1 shows wind roses for the sites, giving the frequency of occurrence of wind from different directions for a number of wind speed ranges, for the years 2015 and 2017.

Table 5.1: Summary of meteorological data at Dublin Airport

Year	Percentage Used	Parameter	Minimum	Maximum	Mean
2015	100%	Temperature (°C)	-7.7	24.2	9.5
		Wind speed (m/s)	0.5	19	5.9
		Cloud cover (oktas)	0	8	5.6
2017	99.9%	Temperature (°C)	-4.4	26.1	10.1
		Wind speed (m/s)	0	22.6	5.6
		Cloud cover (oktas)	0	8	5.7

Table 5.2: Summary of meteorological data at Casement Airport

Year	Percentage Used	Parameter	Minimum	Maximum	Mean
2015	99.6%	Temperature (°C)	-7.2	24.8	9.6
		Wind speed (m/s)	0	19	5.4
		Cloud cover (oktas)	0	8	5.5
2017	99.9%	Temperature (°C)	-6.2	26.6	10.2
		Wind speed (m/s)	0	20.6	5.1
		Cloud cover (oktas)	0	8	5.8

¹¹ <http://www.cerc.co.uk/environmental-software/ADMS-Urban-model.html>

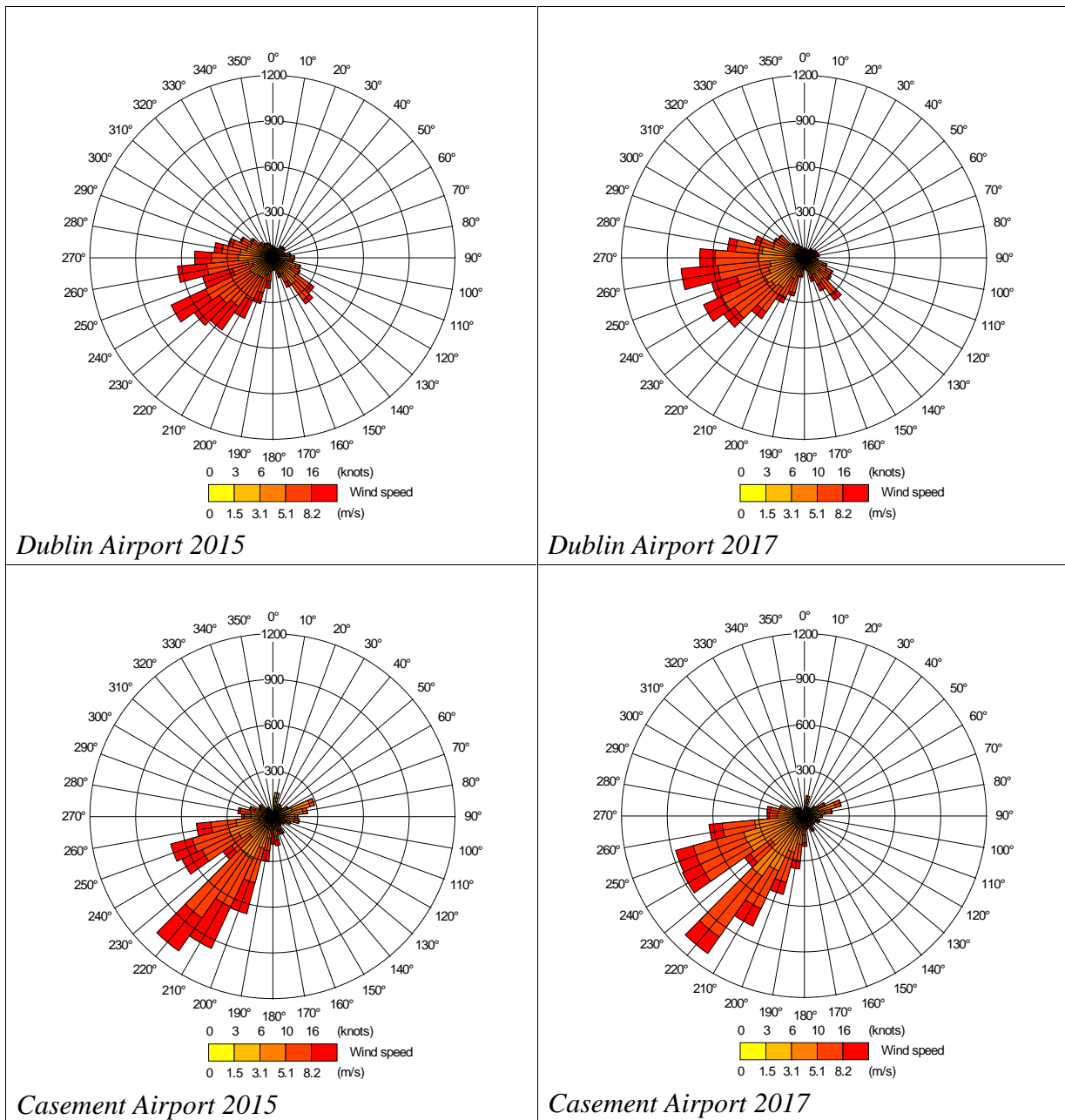


Figure 5.1: Wind roses for Dublin Airport and Casement Airport for 2015 and 2017

5.2. Surface roughness

A length scale parameter called the surface roughness length is used in the model to characterise the study area in terms of the effects it will have on wind speed and turbulence, which are key factors in the modelling. A value of 0.5 m was used to represent the modelled area, however, additional effects of the buildings in the city on wind speeds and turbulence was taken into account using the ADMS-Urban urban canopy option.

5.3. Urban canopy flow

The ADMS-Urban spatially varying urban canopy flow option calculates changes in the vertical profiles of velocity and turbulence caused by the presence of buildings in an urban area, allowing the flow field within urban areas to be characterised on a neighbourhood-by-neighbourhood basis. The velocity and turbulence profiles are displaced by the building height, and flow within the building canopy is slowed by the buildings.

Urban canopy data were calculated from GIS building data and associated building heights calculated from LIDAR surface and terrain height data.

5.4. Monin-Obukhov length

In urban and suburban areas a significant amount of heat is emitted by buildings and traffic, which warms the air within and above a city. This is known as the urban heat island and its effect is to prevent the atmosphere from becoming very stable. In general, the larger the urban area the more heat is generated and the stronger the effect becomes.

In the ADMS-Urban model, the stability of the atmosphere is represented by the Monin-Obukhov parameter, which has the dimension of length. In very stable conditions it has a positive value of between 2 metres and 20 metres. In near neutral conditions its magnitude is very large, and it has either a positive or negative value depending on whether the surface is being heated or cooled by the air above it. In very convective conditions it is negative with a magnitude of typically less than 20 metres.

The effect of the urban heat island is that, in stable conditions, the Monin-Obukhov length will never fall below some minimum value; the larger the city, the larger the minimum value. A value of 50 metres was used for the city and 10 metres for the meteorological sites.

5.5. Street canyons

The modelling used the advanced street canyon modelling option in ADMS-Urban. This option allows better treatment of tall canyons, and also allows for improved treatment of canyon porosity, pavements, and asymmetric canyons (both with respect to traffic lane positions and building heights on either side of the road) within the modelling.

The advanced street canyon modelling option in ADMS-Urban modifies the dispersion of pollutants from a road source according to the presence and properties of canyon walls on one or both sides of the road.

Street canyon data were calculated from GIS building data and associated building heights calculated from LIDAR surface and terrain height data.

5.6. Background data

Background concentrations of nitrogen dioxide (NO₂), ozone (O₃), particulates (PM₁₀ and PM_{2.5}) and sulphur dioxide (SO₂) for years 2015 and 2017 were obtained from rural air quality monitoring locations in Ireland, provided by the Environmental Protection Agency.

Nitrogen dioxide (NO₂) results from direct emissions from combustion sources together with chemical reactions in the atmosphere involving NO₂, nitric oxide (NO) and O₃. The combination of NO and NO₂ is referred to as nitrogen oxides (NO_x).

The chemical reactions taking place in the atmosphere were taken into account in the modelling using the Generic Reaction Set (GRS) of equations. These use hourly average background concentrations of NO_x, NO₂ and O₃, together with meteorological and modelled emissions data to calculate the NO₂ concentration at a given point.

NO_x, NO₂, O₃ and PM₁₀ concentration data were taken from the Kilkitt monitoring site, approximately 90 km north west of Dublin. PM_{2.5} is not measured at Kilkitt; PM_{2.5} concentration data were taken from the Claremorris monitoring site, approximately 180 km west of Dublin.

Table 5.3 and Table 5.4 summarise the annual statistics of the resulting background concentrations used in the modelling for 2015 and 2017.

Table 5.3: Summary of background data from Kilkitt rural monitoring station used in the modelling (µg/m³)

Site	Location (X,Y)	Year	Statistic	NO _x	NO ₂	O ₃	PM ₁₀	SO ₂
Monaghan Kilkitt Waterworks	Kilkitt, Monaghan (672851,815334)	2015	Annual average	2.7	2.2	59.6	8.8	2.2
			Maximum	289	96.5	136.8	53.1	15.2
		2017	Annual average	2.7	2.3	57.7	8.2	1.6
			Maximum	110.2	25.4	125	41.5	6.1

Table 5.4: PM_{2.5} background data from Claremorris rural monitoring station used in the modelling (µg/m³)

Site	Location (X, Y)	Year	Statistic	PM _{2.5}
Claremorris Waste Water Treatment Plant	Claremorris, Mayo (533110, 771322)	2015	Annual average	5.7
			Maximum	24.3
		2017	Annual average	-
			Maximum	-

6. Model verification

The first stage of a modelling study is to verify that the input data and model set-up are representative of the area. Initial modelling verification using Dublin Airport and Casement Airport meteorological data showed that the significantly better agreement was achieved using Casement Airport meteorological data; Casement Airport was therefore used for the remainder of the modelling.

The model verification was carried out by comparing the measured and modelled concentrations of NO_2 , PM_{10} and $\text{PM}_{2.5}$ at the monitoring sites at which they are measured. The preliminary model verification is shown for two years, 2015 and 2017, using Casement Airport meteorological data. Note that there are no measured diffusion tube data for the year 2015.

6.1. 2015 Verification

Table 6.1 and Figure 6.1 show the measured and modelled annual average NO_2 at five continuous automatic monitoring sites for the year 2015. Figure 6.2 and Table 6.2 show the measured and modelled annual average PM_{10} concentrations. Figure 6.3 and Table 6.3 show the measured and modelled $\text{PM}_{2.5}$ concentrations.

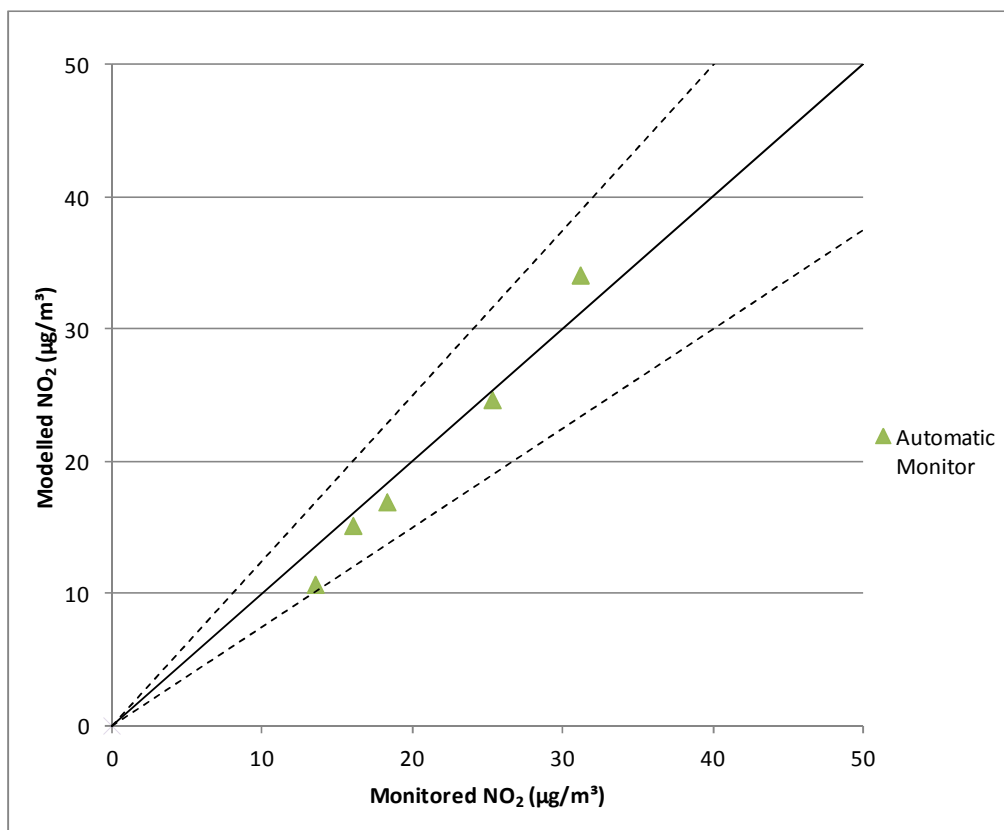


Figure 6.1: Measured and modelled annual average NO_2 concentrations for 2015

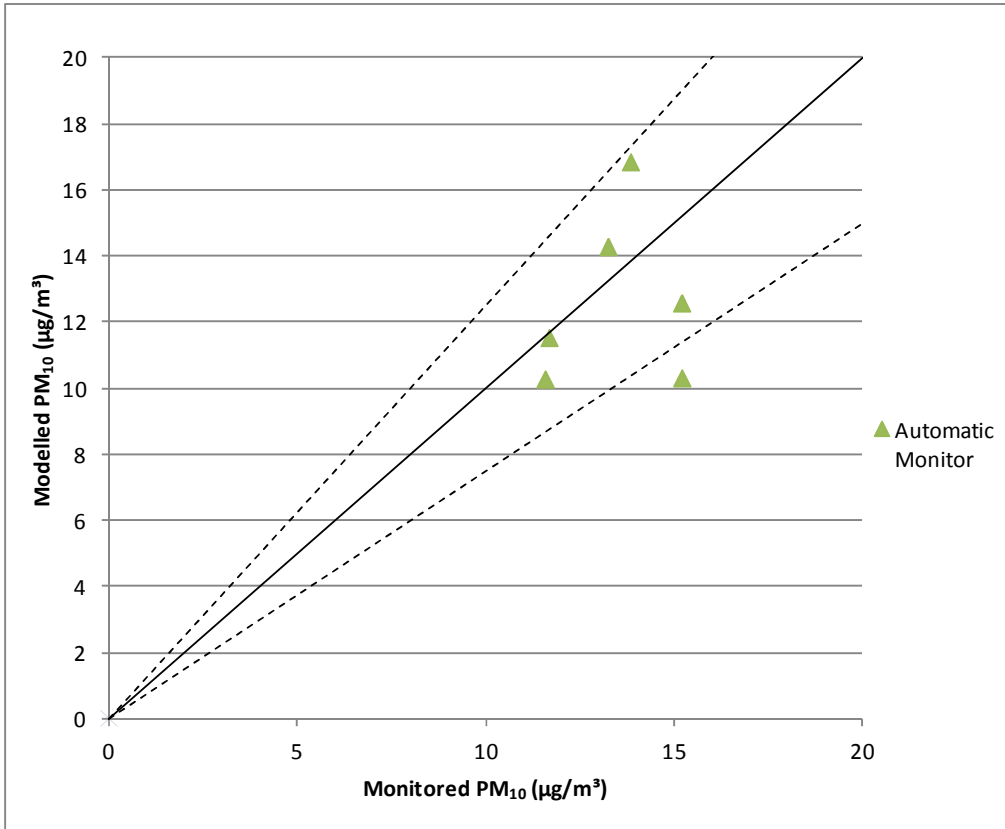


Figure 6.2: Measured and modelled annual average PM₁₀ concentrations for 2015

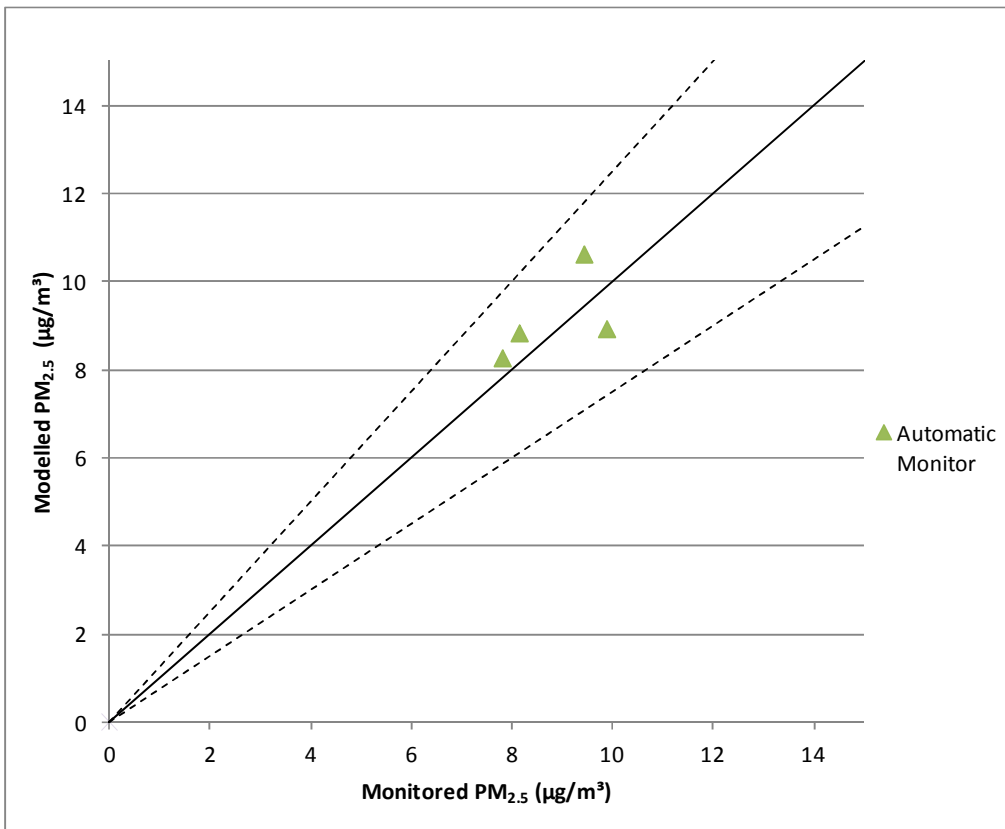


Figure 6.3: Measured and modelled annual average PM_{2.5} concentrations for 2015

Table 6.1: Measured and modelled NO₂ concentrations at automatic monitoring sites for 2015 (µg/m³)

Site Name	Annual average			99.79 th percentile		
	Measured	Modelled	Modelled %	Measured	Modelled	Modelled %
Ballyfermot	16.0	15.2	93	94	120	128
Coleraine St	25.3	24.7	98	106	127	119
Rathmines	18.3	17.0	93	88	126	143
St Anne's Park	13.5	10.7	80	67	107	160
Winetavern St	31.1	34.1	110	127	168	132

Table 6.2: Measured and modelled PM₁₀ concentrations at automatic monitoring sites for 2015 (µg/m³)

Site Name	Annual average			90.41 st percentile		
	Measured	Modelled	Modelled %	Measured	Modelled	Modelled %
Ballyfermot	11.7	11.5	99	21.8	21.8	100
Davitt Road	13.2	14.3	108	25.4	26.4	104
Phoenix Park	11.6	10.3	89	20.4	19.3	95
Rathmines	15.2	12.6	83	27.7	23.1	83
St Anne's Park	15.2	10.3	68	22.3	18.8	84
Winetavern St	13.8	16.9	122	24.5	29.6	121

Table 6.3: Measured and modelled PM_{2.5} concentrations at automatic monitoring sites for 2015 (µg/m³)

Site Name	Annual average		
	Measured	Modelled	Modelled %
Coleraine St	9.4	10.6	113
Finglas	8.1	8.8	109
Marino	7.8	8.3	106
Rathmines	9.9	8.9	91

6.2. 2017 Verification

Table 6.4, Table 6.5 and Figure 6.4 show the measured and modelled NO_2 concentrations at continuous automatic monitoring sites and diffusion tubes for the year 2017. Table 6.6 shows the measured and modelled annual average PM_{10} concentrations and Table 6.7 shows the measured and modelled annual average $\text{PM}_{2.5}$ concentrations for 2017.

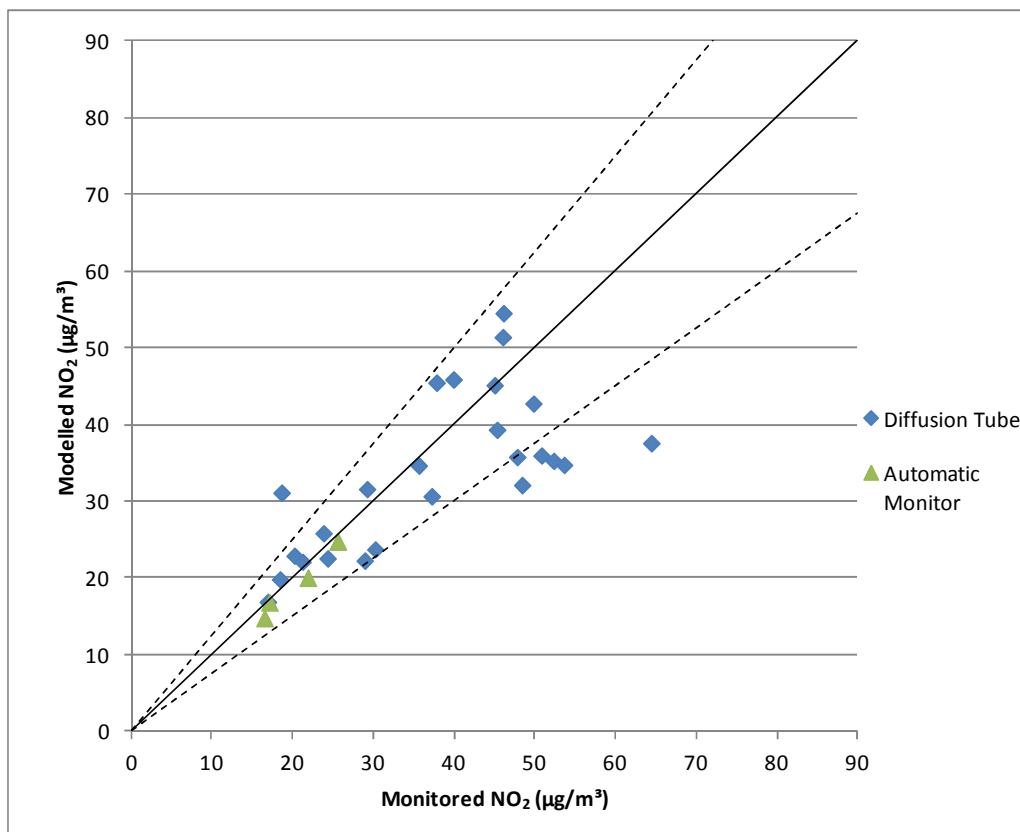


Figure 6.4: Measured and modelled annual average NO_2 concentrations for 2017

Table 6.4: Measured and modelled NO_2 concentrations at automatic monitoring sites for 2017 ($\mu\text{g}/\text{m}^3$)

Site Name	Annual average			99.79 th percentile		
	Measured	Modelled	Modelled %	Measured	Modelled	Modelled %
Ballyfermot	16.5	14.8	90%	102	104	102%
Coleraine St	25.6	24.8	97%	102	119	117%
Rathmines	17.1	16.8	98%	83	111	133%
Ringsend	21.9	20.0	92%	92	125	136%

Table 6.5: Measured and modelled annual average NO₂ concentrations at diffusion tube sites for 2017 (µg/m³)

ID	Site Name	Measured	Casement Airport 2017	
			Modelled	Modelled %
DT1	Dr Steevens' Hospital	53.6	34.7	65%
DT2	Victoria Quay	52.3	35.3	67%
DT3	Wolfe Tone Quay	48.4	32.1	66%
DT4	Benburb Street	30.2	23.8	79%
DT5	Old Abbey Street	37.8	45.5	120%
DT6	Gardiner Street Lowe	49.8	42.7	86%
DT7	Amien Street North	46.1	54.5	118%
DT8	Amien Street South	45.0	45.1	100%
DT9	North Wall Quay 1	47.8	35.8	75%
DT10	North Wall Quay 2	35.6	34.7	97%
DT11	North Wall Quay 3	39.9	45.9	115%
DT12	North Wall Quay 4	37.2	30.7	82%
DT13	Pigeon House Road	24.3	22.6	93%
DT14	Sean Moore Road	20.2	22.9	113%
DT15	Ringsend Fitzwilliam	29.2	31.6	108%
DT16	York Street	18.4	19.8	108%
DT17	Pearse Street 1	45.3	39.3	87%
DT18	Pearse Street 2	46.0	51.4	112%
DT19	Pearse Street 3	50.8	36.0	71%
DT20	Pearse Street 4	64.4	37.6	58%
DT21	Charlemont Mall	23.8	25.8	109%
DT22	Charlemont Place	21.2	22.1	104%
DT23	Ranelagh Road	18.6	31.1	167%
DT24	Kingsland Parade	28.9	22.3	77%
DT25	Wynnefield Road	16.9	16.9	100%

Table 6.6: Measured and modelled annual average PM₁₀ concentrations at automatic monitoring sites for 2017 (µg/m³)

Site Name	Annual average			90.41 st percentile		
	Measured	Modelled	Modelled %	Measured	Modelled	Modelled %
Rathmines	11.5	11.8	103%	19.4	20.3	105%
Ringsend	12.9	11.3	87%	18.9	19.7	104%

Table 6.7: Measured and modelled PM_{2.5} concentrations at automatic monitoring sites for 2017 (µg/m³)

Site Name	Annual average		
	Measured	Modelled	Modelled %
Rathmines	8.5	8.8	103%

The modelled concentrations show generally good agreement with the measured data.

The modelled annual average NO₂ concentrations are within 10% of the measured values at the majority of automatic monitoring sites for both 2015 and 2017. The greatest differences are at St Anne's Park, where the model underpredicts concentrations, and at Winetavern Street, where it overpredicts concentrations. The modelled 99.79th percentiles of hourly average NO₂ concentrations are consistently higher than the measured concentrations.

The modelled annual average PM₁₀ concentrations are within 25% at the majority of the automatic monitoring sites. The modelled 90.41st percentile of 24-hour average concentrations are within 25% of the measured concentrations at all of the monitoring sites and within 10% at half of them.

The modelled annual average PM_{2.5} concentrations are within 10% of the measured concentrations at three of the four monitoring sites.

At the diffusion tube sites, the modelled annual average NO₂ concentrations are within 25% of the measured concentrations at approximately three quarters of the sites and within 10% at about one third of the sites.

The main differences are general underprediction in the Heuston Station area, significant underprediction at one of the Pearse Street sites and significant overprediction at Ranelagh Road. These are all likely to be due to local effects not represented adequately in the modelling, for instance emissions from Heuston Station, emissions from idling buses on Pearse Street or complex road and street canyon layouts.

7. Model Evaluation

This section discusses the plots generated by the two evaluation tools: the FAIRMODE DELTA Tool (version 5.4) and CERC's Model Evaluation Toolkit (version 4.0). Section 7.1 presents example DELTA Tool plots and the Toolkit results are given in Section 7.2.

7.1. DELTA Tool

The target plots use a model quality indicator (MQI) which has been developed as an overall metric of model performance which depends on the measurement uncertainty. The MQI is defined as the ratio between the model bias and twice the measurement uncertainty; lower values reflect better model performance and values of the MQI less than 1 are considered to fulfil the modelling quality objective, in which case model bias is less than twice the measurement uncertainty.

The target plots show the normalized bias against the centred root mean square error (CRMSE) for each monitoring site. The distance of points from the origin gives the value of the MQI. The area of the plot with green shading shows where the model errors are within a factor of 2 of the measurement uncertainty, leading to a value of MQI below 1

DELTA Tool target plots for NO₂ and PM₁₀ are presented in Figure 7.1 and Figure 7.2. These target plots indicate that, for all sites except Winetavern Street, model predictions lie within the target. The target plot results are supported by the Toolkit statistical results shown Table 7.1.

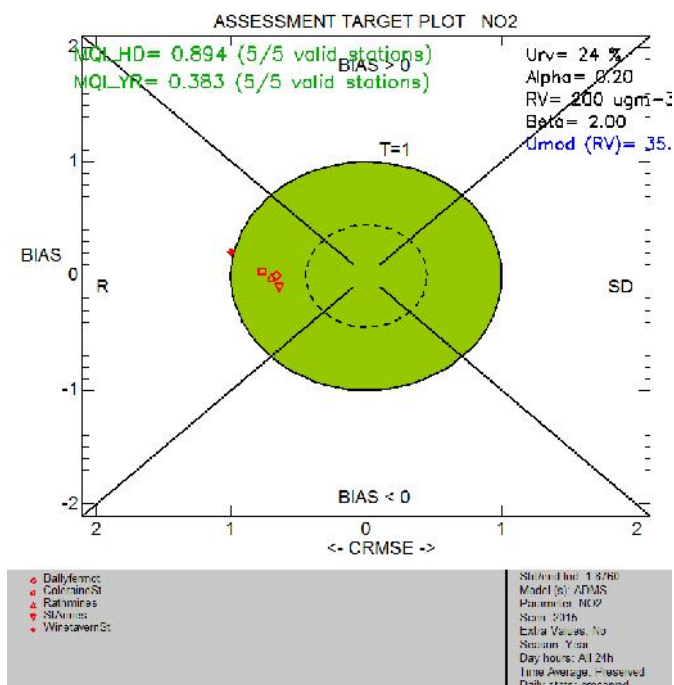


Figure 7.1: Target plot of NO₂ for 2015

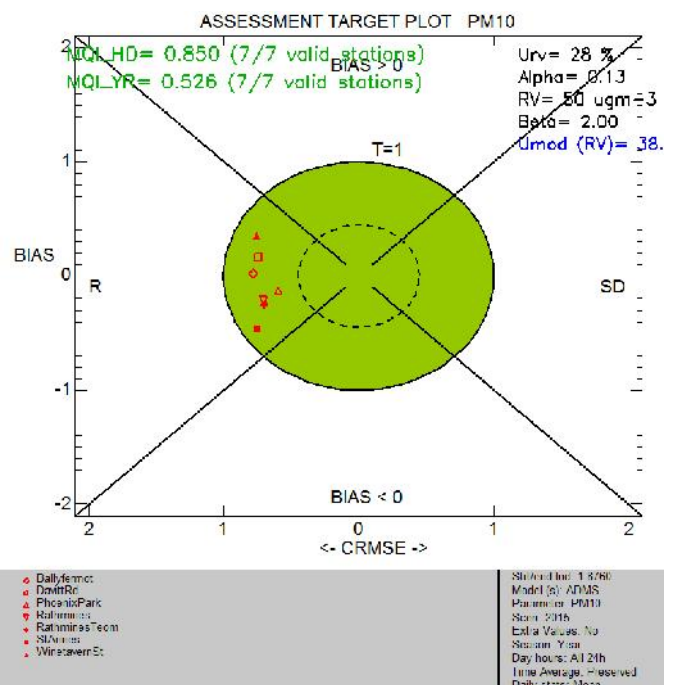


Figure 7.2: Target plot of PM₁₀ for 2015

7.2. Model Evaluation Toolkit

The Model Evaluation Toolkit calculates statistics that can be used to evaluate overall model performance. A range of statistics is calculated which include:

- the number of valid observations;
- the observed and modelled mean concentrations;
- the normalised mean square error (NMSE), a positive number for which a value closest to zero is best;
- the correlation coefficient (R), which varies between 0 (worst) and 1 (best);
- the fraction of modelled values within a factor of two of the observed (Fac2), which varies between 0 (worst) and 1 (best);
- and the fractional bias (Fb), which can be either positive or negative, with zero being the best value.

The Model Evaluation Toolkit statistical results for NO₂ and PM₁₀ for the year 2015 are shown in Table 7.1.

Table 7.1: Model Evaluation Toolkit NO₂ and PM₁₀ statistics for 2015

Station	Number of valid observations	Monitored mean (µg/m ³)	Modelled mean (µg/m ³)	NMSE	R	Fac2	Fb
NO₂							
Ballyfermot	8677	16.1	15.2	0.84	0.63	0.75	-0.05
Coleraine Street	8657	25.3	24.7	0.52	0.59	0.71	-0.02
Rathmines	8709	18.3	17.0	0.75	0.59	0.74	-0.07
St Anne's Park	8362	13.5	10.9	1.20	0.42	0.57	-0.22
Winetavern Street	8263	31.1	34.5	0.57	0.60	0.71	0.10
PM₁₀							
Ballyfermot	7944	11.7	11.6	0.43	0.59	0.89	0.00
Davitt Road	8520	13.2	14.4	0.44	0.61	0.84	0.09
Phoenix Park	8712	11.6	10.3	0.30	0.73	0.89	-0.12
Rathmines	8712	15.3	12.6	0.46	0.61	0.85	-0.19
St Anne's Park	8736	15.2	10.3	0.59	0.48	0.68	-0.39
Winetavern Street	8592	13.8	16.7	0.48	0.55	0.79	0.19

Figure 7.3 shows scatter diagrams comparing modelled concentrations (vertical axis) against observations (horizontal axis). Figure 7.4 shows box and whisker plots of hourly NO₂ concentrations for all the monitoring sites and Figure 7.5 shows example time variation plots for Ballyfermot and Winetavern Street. The plots show that the measured and modelled concentrations generally show good agreement, but there is a tendency to underpredict night-time NO₂ concentrations and overpredict concentrations during the afternoon peak.

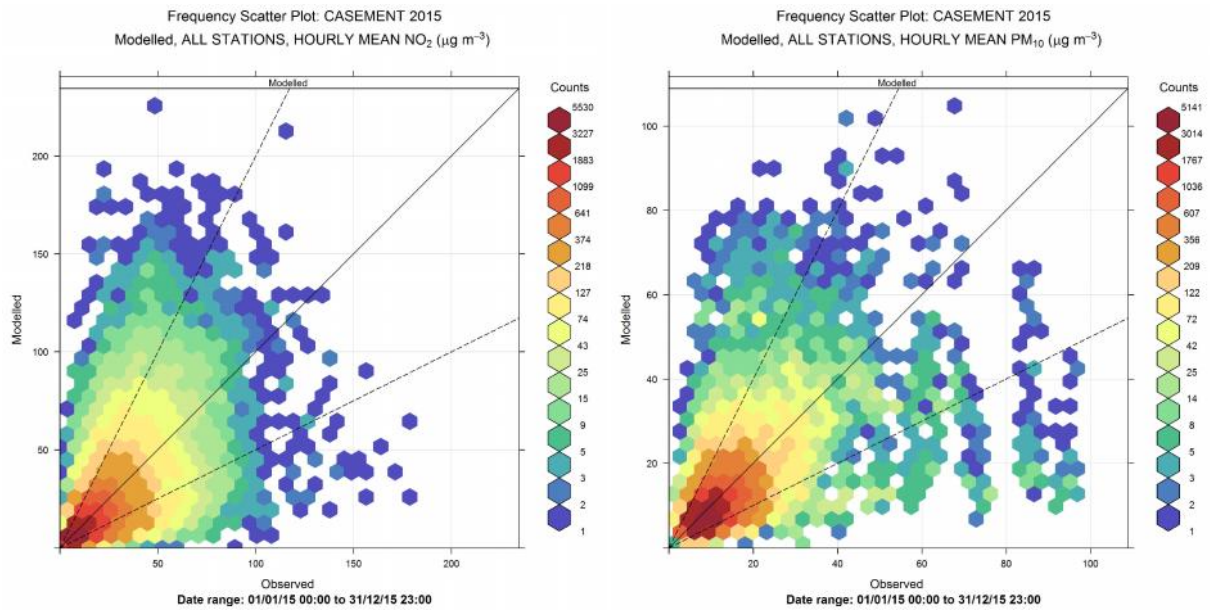


Figure 7.3: Frequency scatter plots for hourly mean NO_2 and PM_{10} concentrations for 2015

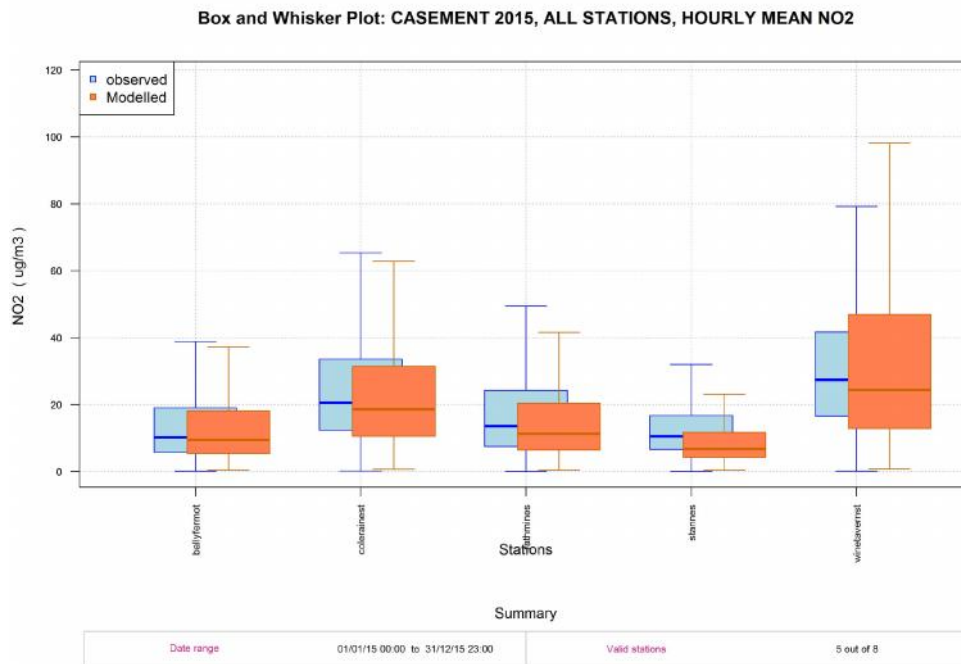


Figure 7.4: Box plots for measured and modelled hourly average NO_2 concentrations

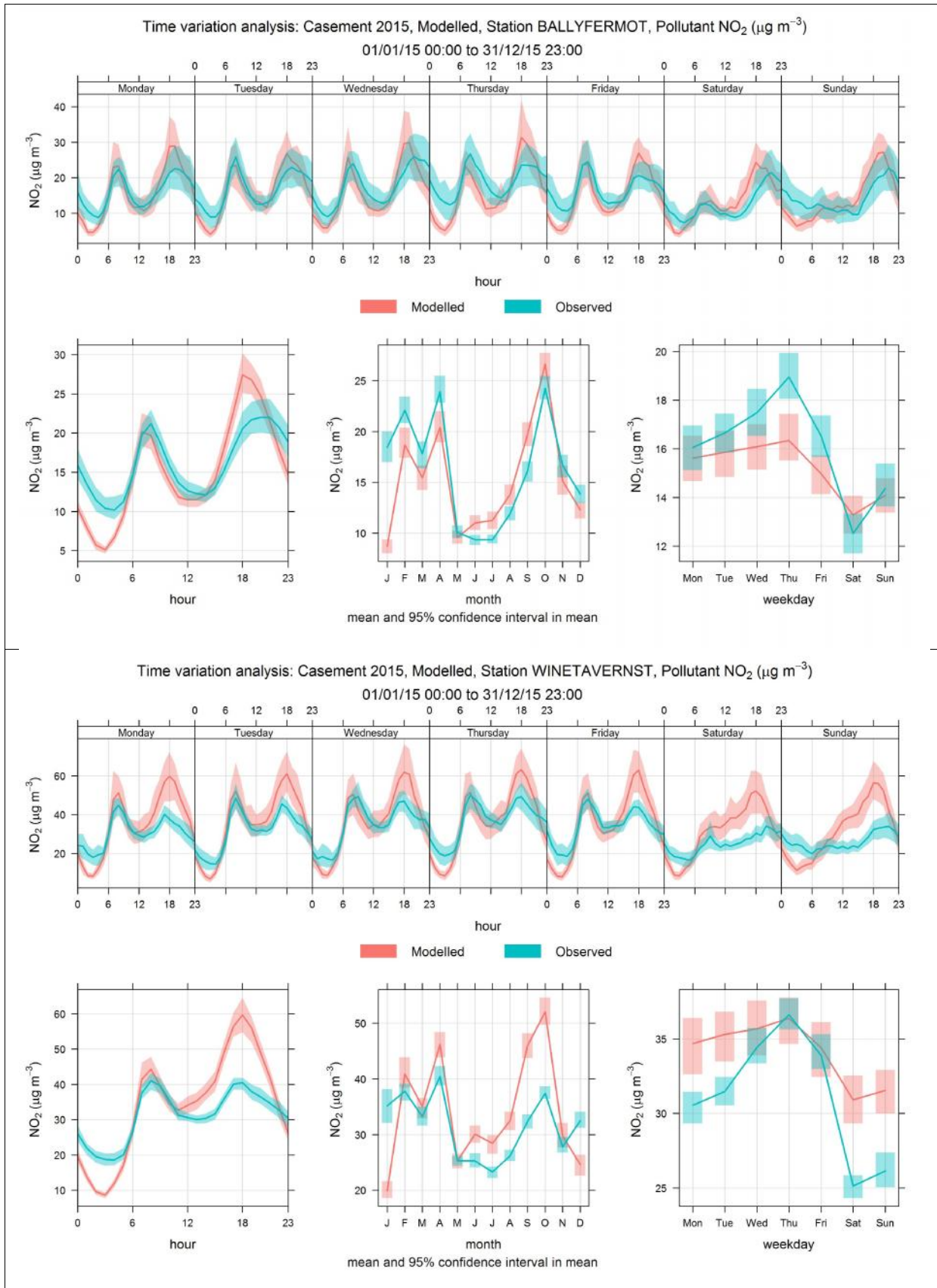


Figure 7.5: time variation plots of NO₂ concentrations at Ballyfermot and Winetavern Street

8. Modelled concentrations

This section presents modelled annual average NO₂ and PM₁₀ concentrations across the modelled area for 2015. Ground level concentrations were calculated on a regular grid of receptor points, with additional points added in the vicinity of major roads, in order to more accurately capture roadside concentrations. Concentrations were calculated to allow comparison against the air quality limits presented in Section 2, and presented in the form of coloured contour maps. The contour maps are presented showing areas with concentrations exceeding the air quality limits shown in yellow and red and areas with concentrations below the limits shown in green and blue.

Figure 8.1, Figure 8.2 and Figure 8.3, respectively, show the modelled annual average NO₂, PM₁₀ and PM_{2.5} concentrations for 2015.

The modelled concentrations show some exceedences of the annual average NO₂ limit value of 40 µg/m³, in particular along the city ring road (M50), in the city centre and at both ends of Dublin port tunnel. Arterial roads into the city centre also show some exceedences of the limit value, but the extent of these exceedences is smaller. Figure 8.4 and Figure 8.5 show the exceedences in the city centre and at Dublin port tunnel in more detail.

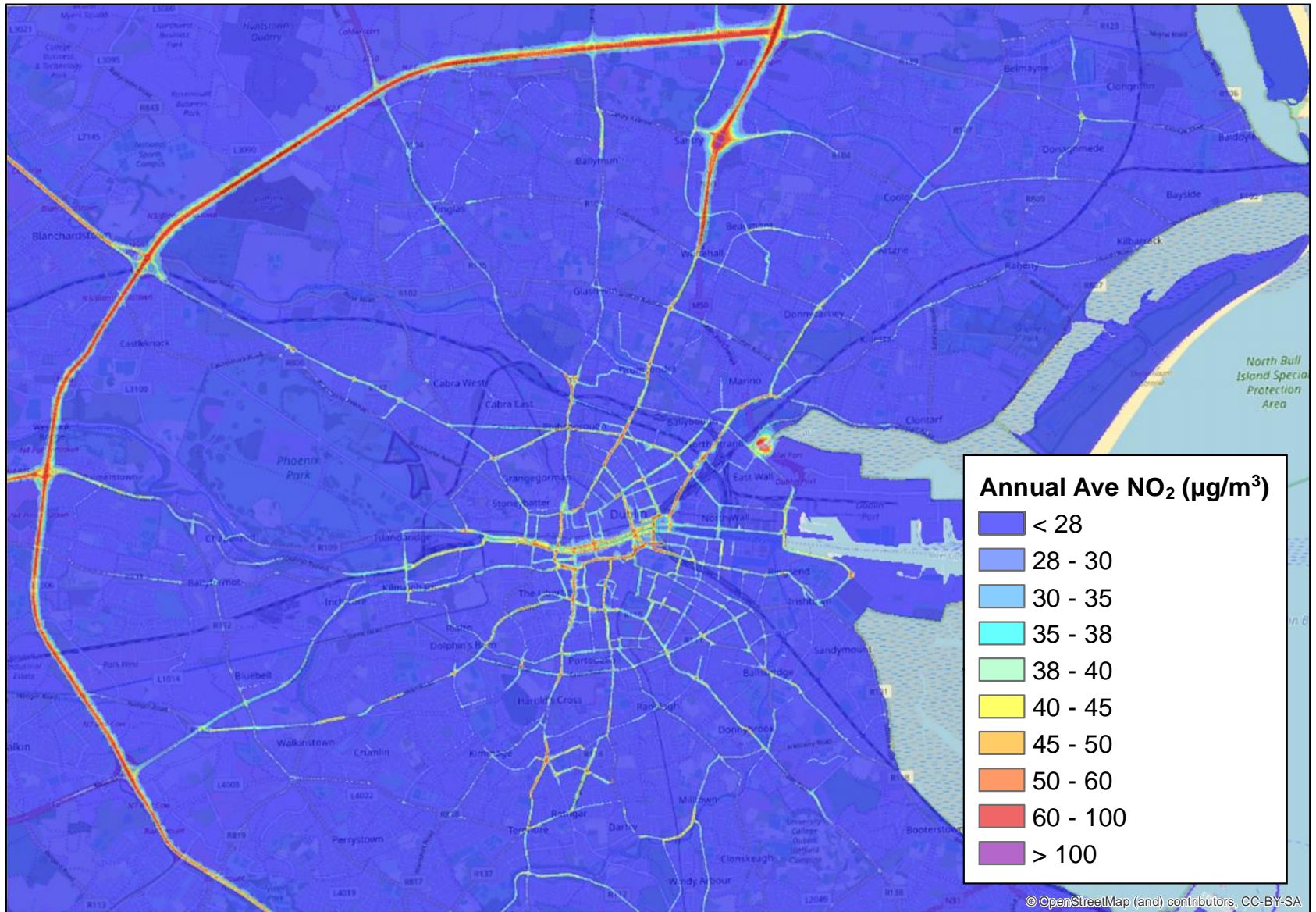


Figure 8.1: Modelled annual average NO₂ concentrations for 2015 (μg/m³)

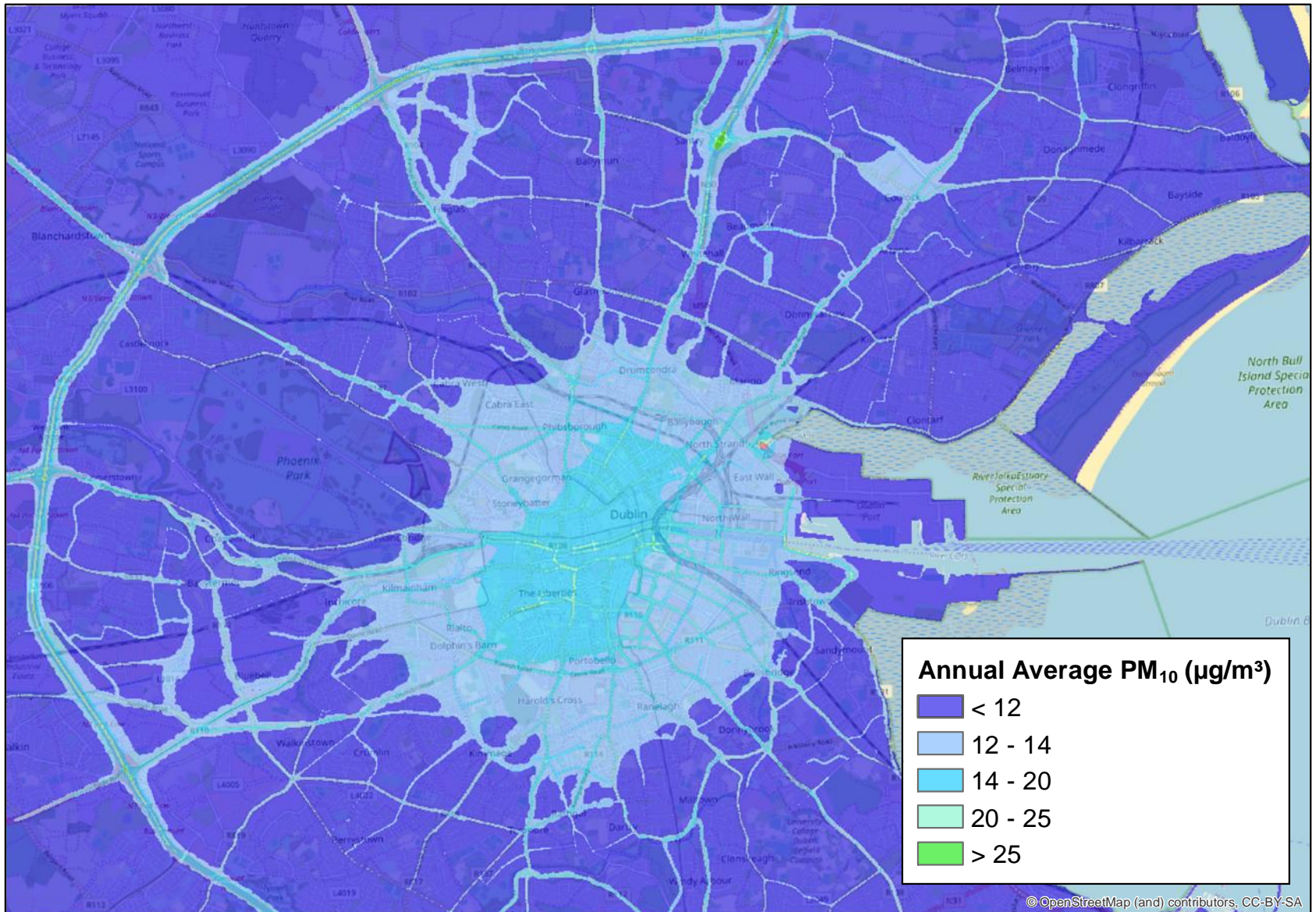


Figure 8.2: Modelled annual average PM₁₀ concentrations for 2015 (μg/m³)

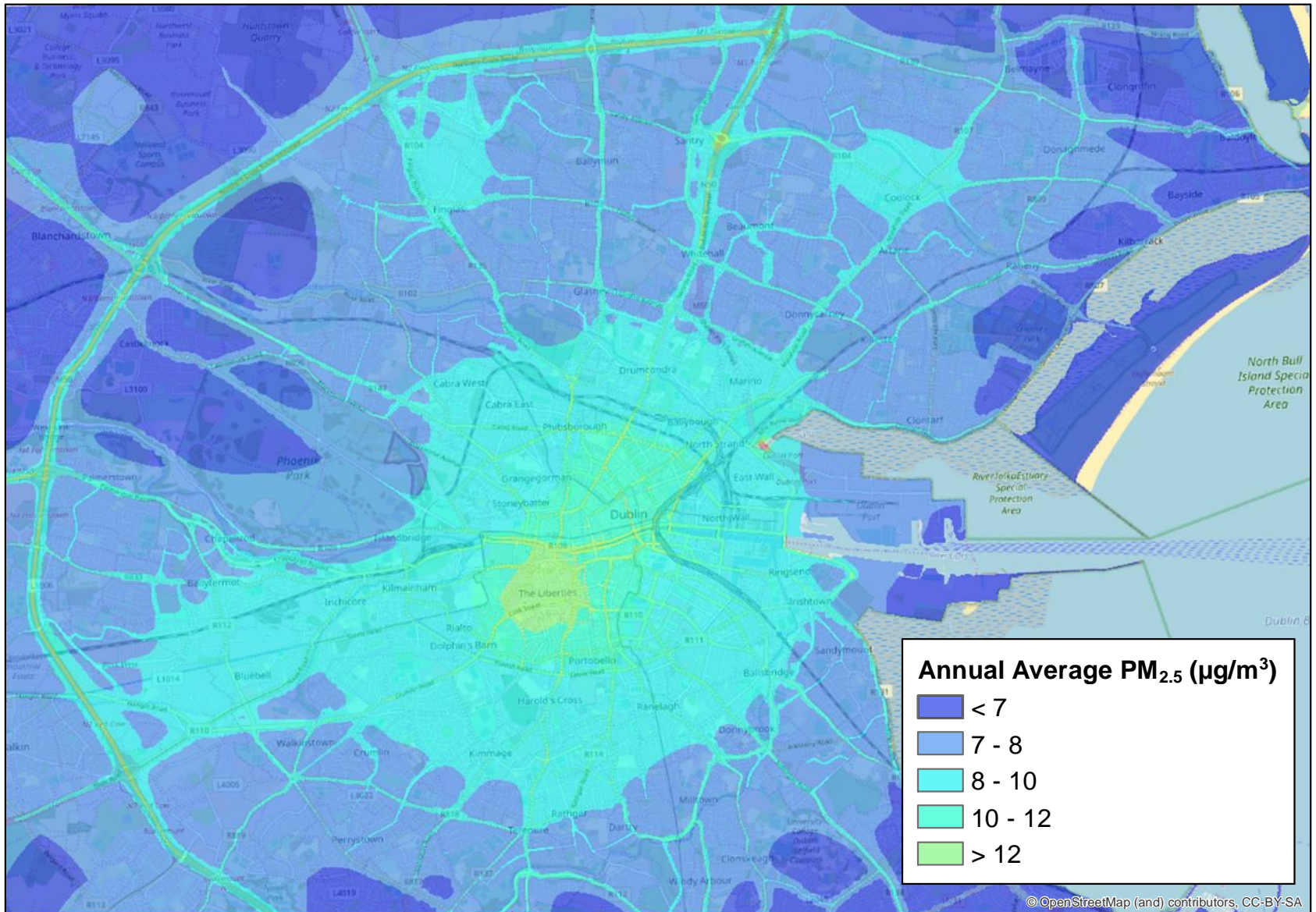


Figure 8.3: Modelled annual average PM_{2.5} concentrations for 2015 ($\mu\text{g}/\text{m}^3$)

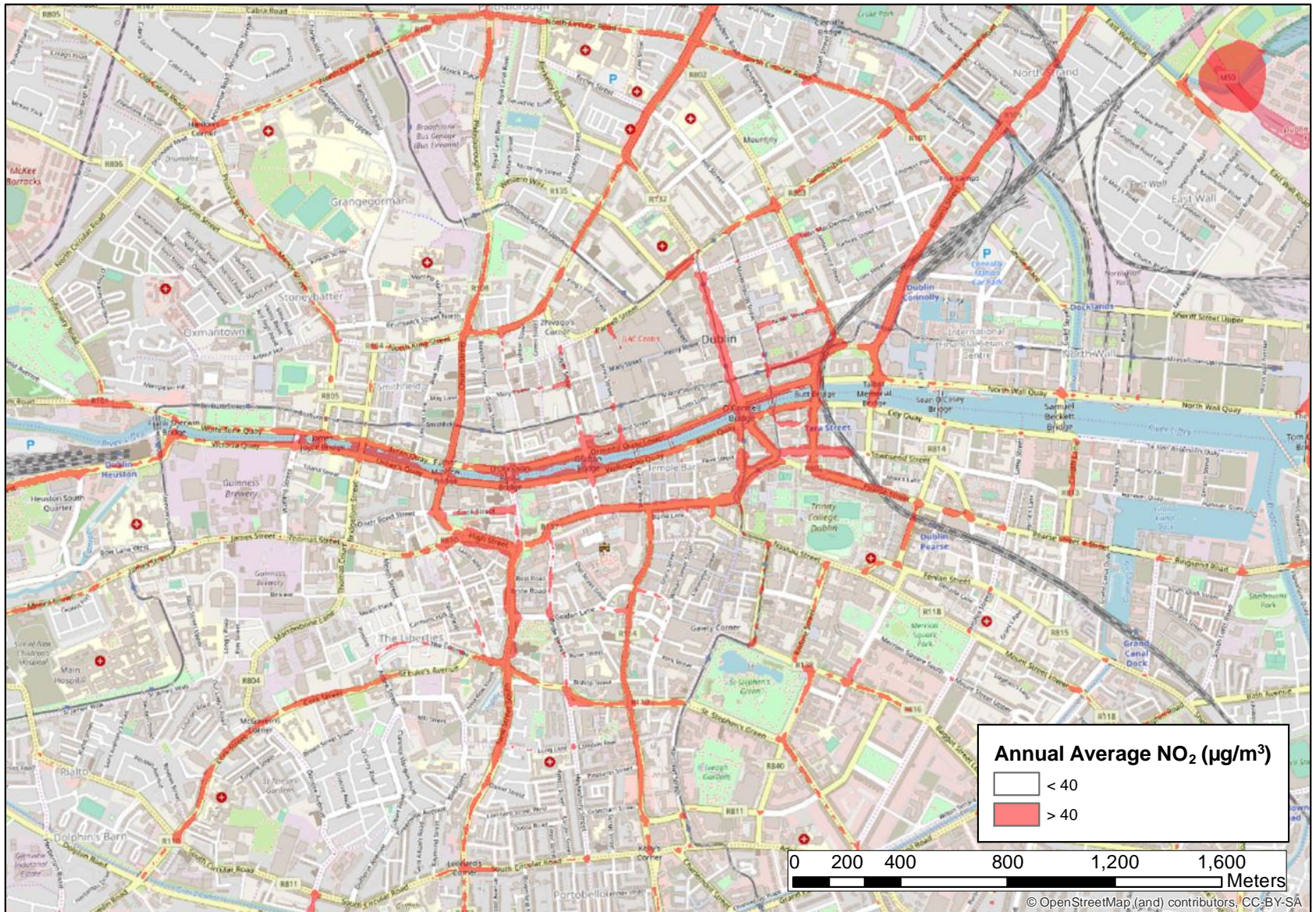


Figure 8.4: Modelled exceedences of annual average NO₂ limit in central Dublin for 2015

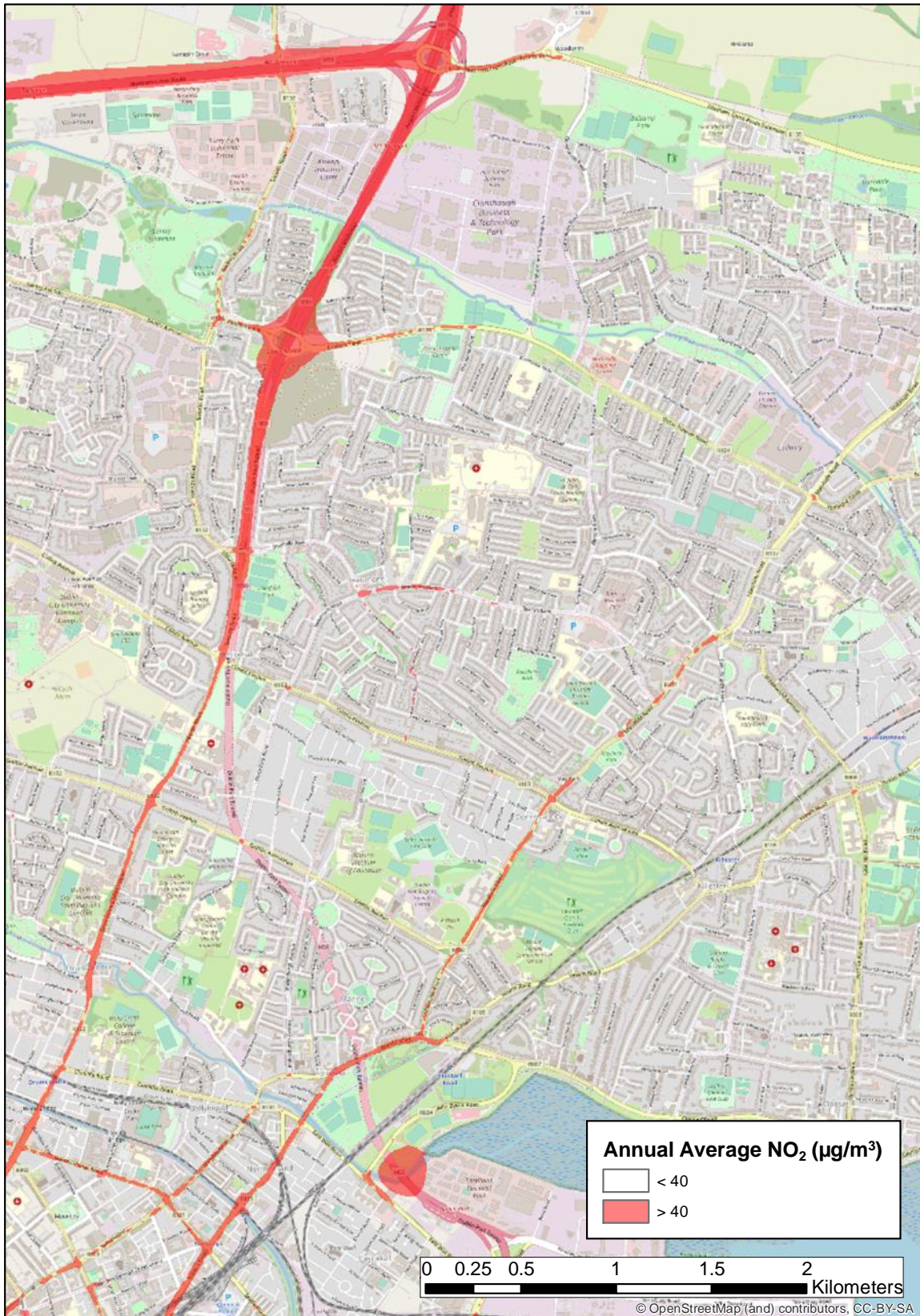


Figure 8.5: Modelled exceedences of annual average NO₂ limit around Dublin Port Tunnel for 2015

APPENDIX A: Summary of ADMS-Urban

ADMS-Urban is a scientifically advanced but practical air pollution modelling tool, which has been developed to provide high resolution calculations of pollution concentrations for all sizes of study area relevant to the urban environment. The model can be used to look at concentrations near a single road junction or over a region extending across the whole of a major city. ADMS-Urban has been extensively used for the Review and Assessment of Air Quality carried out by Local Authorities in the UK and for a wide range of planning and policy studies across the world. The following is a summary of the capabilities and validation of ADMS-Urban. More details can be found on the CERC web site at www.cerc.co.uk.

ADMS-Urban is a development of the Atmospheric Dispersion Modelling System (ADMS), which has been developed to investigate the impacts of emissions from industrial facilities. ADMS-Urban allows full characterisation of the wide variety of emissions in urban areas, including an extensively validated road traffic emissions model. It also includes a number of other features, which include consideration of:

- the effects of vehicle movement on the dispersion of traffic emissions;
- the behaviour of material released into street-canyons;
- the chemical reactions occurring between nitrogen oxides, ozone and Volatile Organic Compounds (VOCs);
- the pollution entering a study area from beyond its boundaries;
- the effects of complex terrain on the dispersion of pollutants; and
- the effects of a building on the dispersion of pollutants emitted nearby.

Further details of these features are provided below.

Studies of extensive urban areas are necessarily complex, requiring the manipulation of large amounts of data. To allow users to cope effectively with this requirement, ADMS-Urban runs in Windows 10, Windows 8, Windows 7 and Windows Vista environments. The manipulation of data is further facilitated by the possible integration of ADMS-Urban with a Geographical Information System (GIS) (MapInfo, ArcGIS, or the ADMS-Mapper) and the CERC Emissions Inventory Toolkit, EMIT.

Dispersion Modelling

ADMS and ADMS-Urban use boundary layer similarity profiles to parameterise the variation of turbulence with height within the boundary layer, and the use of a skewed-Gaussian distribution to determine the vertical variation of pollutant concentrations in the plume under convective conditions.

The main dispersion modelling features of ADMS-Urban are as follows:

- ADMS-Urban is an **advanced dispersion model** in which the boundary layer structure is characterised by the height of the boundary layer and the Monin-Obukhov length, a length scale dependent on the friction velocity and the heat flux at the surface. This method supersedes methods based on Pasquill Stability Categories, as used in, for example, Caline and ISC. Concentrations are calculated hour by hour and are fully dependent on prevailing weather conditions.
- For convective conditions, a **non-Gaussian vertical profile of concentration** allows for the skewed nature of turbulence within the atmospheric boundary layer, which can lead to high concentrations near to the source.
- A **meteorological pre-processor** calculates boundary layer parameters from a variety of input data, typically including date and time, wind speed and direction, surface temperature and cloud cover. Meteorological data may be raw, hourly averaged or statistically analysed data.

Emissions

Emissions into the atmosphere across an urban area typically come from a wide variety of sources. There are likely to be industrial emissions from chimneys as well as emissions from road traffic and domestic heating systems. To represent the full range of emissions configurations, the explicit source types available within ADMS-Urban are:

- **Roads**, for which emissions are specified in terms of vehicle flows and the additional initial dispersion caused by moving vehicles is also taken into account.
- **Industrial points**, for which plume rise and stack downwash are included in the modelling.
- **Areas**, where a source or sources is best represented as uniformly spread over an area.
- **Volumes**, where a source or sources is best represented as uniformly spread throughout a volume.

In addition, sources can also be modelled as a regular grid of emissions. This allows the contributions of large numbers of minor sources to be efficiently included in a study while the majority of the modelling effort is used for the relatively few significant sources.

ADMS-Urban can be used in conjunction with CERC's Emissions Inventory Toolkit, EMIT, which facilitates the management and manipulation of large and complex data sets into usable emissions inventories.

Presentation of Results

The results from the model can be based on a wide range of averaging times, and include rolling averages. Maximum concentration values and percentiles can be calculated where appropriate meteorological input data have been input to the model. This allows ADMS-Urban to be used to calculate concentrations for direct comparison with existing air quality limits, guidelines and objectives, in whatever form they are specified.

ADMS-Urban can be integrated with the ArcGIS or MapInfo to facilitate both the compilation and manipulation of the emissions information required as input to the model and the interpretation and presentation of the air quality results provided.

Complex Effects - Street Canyons

ADMS-Urban incorporates two methods for representing the effect of street canyons on the dispersion of road traffic emissions: a basic canyon method based on the *Operational Street Pollution Model (OSPM)*¹², developed by the Danish National Environmental Research Institute (NERI); and an advanced street canyon module, developed by CERC. The basic canyon model was designed for simple symmetric canyons with height similar to width and assumes that road traffic emissions originate throughout the base of the canyon, i.e. that the emissions are spread across both the road and neighbouring pavements.

The advanced canyon model¹³ was developed to overcome these limitations and is our model of choice. It represents the effects of channelling flow along and recirculating flow across a street canyon, dispersion out of the canyon through gaps in the walls, over the top of the buildings or out of the end of the canyon. It can take into account canyon asymmetry and restricts the emissions area to the road carriageway.

Complex Effects - Chemistry

ADMS-Urban includes the *Generic Reaction Set (GRS)*¹⁴ atmospheric chemistry scheme. The original scheme has seven reactions, including those occurring between nitrogen oxides and ozone. The remaining reactions are parameterisations of the large number of reactions involving a wide range of Volatile Organic Compounds (VOCs). In addition, an eighth reaction has been included within ADMS-Urban for the situation when high concentrations of nitric oxide (NO) can convert to nitrogen dioxide (NO₂) using molecular oxygen.

In addition to the basic GRS scheme, ADMS-Urban also includes a trajectory model¹⁵ for use when modelling large areas. This permits the chemical conversions of the emissions and background concentrations upwind of each location to be properly taken into account.

¹² Hertel, O., Berkowicz, R. and Larssen, S., 1990, 'The Operational Street Pollution Model (OSPM).' *18th International meeting of NATO/CCMS on Air Pollution Modelling and its Applications*. Vancouver, Canada, pp741-749.

¹³ Hood C, Carruthers D, Seaton M, Stocker J and Johnson K, 2014. *Urban canopy flow field and advanced street canyon modelling in ADMS-Urban*. 16th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Varna, Bulgaria, September 2014.
http://www.harmo.org/Conferences/Proceedings/_Varna/publishedSections/H16-067-Hood-EA.pdf

¹⁴ Venkatram, A., Karamchandani, P., Pai, P. and Goldstein, R., 1994, 'The Development and Application of a Simplified Ozone Modelling System.' *Atmospheric Environment*, Vol 28, No 22, pp3665-3678.

¹⁵ Singles, R.J., Sutton, M.A. and Weston, K.J., 1997, 'A multi-layer model to describe the atmospheric transport and deposition of ammonia in Great Britain.' In: *International Conference on Atmospheric Ammonia: Emission, Deposition and Environmental Impacts*. *Atmospheric Environment*, Vol 32, No 3.

Complex Effects - Terrain

As well as the effect that complex terrain has on wind direction and, consequently, pollution transport, it can also enhance turbulence and therefore increase dispersion. These effects are taken into account in ADMS-Urban using the FLOWSTAR¹⁶ model developed by CERC.

Data Comparisons – Model Validation

ADMS-Urban is a development of the Atmospheric Dispersion Modelling System (ADMS), which is used throughout the UK by industry and the Environment Agency to model emissions from industrial sources. ADMS has been subject to extensive validation, both of individual components (e.g. point source, street canyon, building effects and meteorological pre-processor) and of its overall performance.

ADMS-Urban has been extensively tested and validated against monitoring data for large urban areas in the UK and overseas, including London, Birmingham, Manchester, Glasgow, Riga, Cape Town, Hong Kong and Beijing, during projects supported by local governments and research organisations. A summary of published model validation studies is available at www.cerc.co.uk/Validation, with other publications available at www.cerc.co.uk/publications.

¹⁶ Carruthers D.J., Hunt J.C.R. and Weng W-S. 1988. 'A computational model of stratified turbulent airflow over hills – FLOWSTAR I.' Proceedings of Envirosoft. In: *Computer Techniques in Environmental Studies*, P. Zanetti (Ed) pp 481-492. Springer-Verlag.