Progressing Real Time Source Identification for Particulate Matter

Curzon Street

May, 2022

Transition Project

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1 Introduction

This project was funded by the TRANSITION Clean Air Network through the first round of its Discovery & Innovation Fund in 2021. TRANSITION is a UK-wide network, led by the University of Birmingham in collaboration with nine universities and over 20 cross-sector partners, aiming to optimise the air quality and health outcomes of transport decarbonisation. The network (NERC ref. NE/V002449/1) is itself funded by UK Research & Innovation through its Clean Air Strategic Priorities Fund, administered by the Natural Environment Research Council.

This report is the final project report of the research work funded by the Transition Clean Air project. £10,000 of grant funding was awarded to Dustscan Ltd (trading as DustScanAQ, abbreviated to DS). The principal academic investigators were Dr Suzanne Bartington and Professor Francis Pope of the University of Birmingham. DS sub-contracted University of Birmingham Post-Doctoral Research Assistant, Dr Dmitris Bousiotis to perform the statistical analyses on data collected from sites by DS.

1.1 Project Overview

The project title is: "Progressing Real-Time Source Identification".

Dust or airborne particulate matter is a cause of air pollution to people the world over. Although it is technically possible to measure it in real-time relatively cheaply, it is often difficult to know where it is coming from and what the sources are: maybe a nearby construction site or a road. Advances in optical particle counting and statistical techniques mean that it may be possible to tell in near real time what the sources are, by identifying the 'fingerprint' patterns of typical sources. This could allow them to be stopped quickly to prevent the air pollution and harm to people.

Enabling real-time air quality management at high spatial coverage, Dustscan Ltd will develop statistical techniques for machine learning to differentiate between construction dust and non-exhaust vehicle emissions using its new DustScan Cloud 'low-cost' air quality sensor, including on the HS2 Curzon Street site.

The way in which particulate matter in the air affects air quality in the UK is regulated by measurements of the mass concentration i.e. the weight of all the particles as dry matter in a volume of air. This is done for two size thresholds, for particles of less than 10 µm diameter (PM_{10}) and less than 2.5 µm diameter ($PM_{2.5}$). This does not directly tell us the number and size of the particles, which is useful information in trying to understand the sources of the particles. While the measurements of particulate matter at a site can give a general idea of the quality of the air, the additional information of the sources and conditions that affect it can help in not only understanding the factors that affect it, but also the conditions that may either deteriorate or improve it. Thus, knowing the sources and conditions that affect the air quality at a site can help in understanding better the activities that are polluting, as well as focusing on those that have the more distinct effect. This can help in making policies and taking action to improve the air quality at a given site, thus improving the quality of life and health of those living nearby.

In the present report we present a combination of statistical analyses which use data from a low-cost sensor (DustScan Cloud) along with additional meteorological data to find the main sources of particles (and pollution) at an urban area next to a construction site. Such analyses were done until recently solely with the use of very expensive instruments, which resulted to an increased cost and limited coverage. This can help in understanding the effect of the construction site on the air quality in the nearby area compared to other sources of pollution, as well as the meteorological conditions that may deteriorate or improve it.

1.2 Project details

The project subtitle is "Real Time Particulate Matter Source Apportionment".

Tiny particles in the air, known as particulate matter (PM) air pollution, are harmful to human health with some particles worse than others. PM comes in different size patterns that are typical of different sources, i.e. diesel smoke is smaller than construction/brake dust. Low cost ways to measure and understand the sources of PM pollution form a new field pioneered by the University of Birmingham (UoB) that has great commercial potential. This project joins the business and consulting expertise of DustScanAQ with the academic expertise of the UoB. The measurement and source apportionment of atmospheric pollutants is crucial for the assessment of air quality and the implementation of policies for its improvement.

Up to now for particle sizing, measurements have used bulky, expensive regulatory grade instruments costing approximately £100k, which makes it difficult to put many instruments around sources. Low cost sensors (£sub-5k) provide an affordable alternative, as evidenced by recent work by Bousiotis et al. 2021 (https://doi.org/10.5194/amt-2021-11), but their capability and reliability have yet to be tested with real world problems. In this project, low cost PM sensors will be used to differentiate particle sources from two policy relevant areas that relate to low carbon transport transitions: 1. Nuisance dust from railways infrastructure construction; and 2. Non-exhaust vehicle emissions.

Furthermore, the project will develop the technology so it can perform real-time source identification in the cloud, utilizing machine learning techniques to allow for source identification in real-time. This gives the potential for real-time identification of emissions from sources, helping drive the transition to a cleaner world. The project is in collaboration with HS2, which is building the next generation infrastructure for the UK's high speed rail service.

One short-coming of traditional methods of air pollution measurement for deposited dust (such as the DS stickypad, the Frisbee and the glass slide) is that they report a long time after any pollution incident (normally several weeks), which is too late for any active intervention. This led HS2 to prescribe real-time fence-line monitoring for construction dust for the works, based on a threshold of PM_{10} concentration. The limitation of only using a mass concentration is that is non-discriminatory and it cannot distinguish the source of particulate matter. The indicative MCERTS monitors required for such applications are also prone to interferences, especially from fog or mist droplets, which optical particle counters can count as solid matter.

1.3 Objectives

This report provides a particulate matter source apportionment study of a construction site in the city of Birmingham, over a period of six weeks, using an optical particle counting instrument now being marketed as DustScan Cloud.

One objective of the report is to demonstrate that low cost sensors and advanced analytical techniques can be applied to make them available more widely as a tool in environmental regulation and air pollution management.

The report also evaluates two statistical methods for characterising particle size distributions, k-means clustering and positive matrix factorisation.

1.4 Study Locations

1.4.1 Study Location 1

The first site studied in this project is located in the city centre of Birmingham at Curzon Street, hosted as part of the HS2 innovation programme. As can be seen by the aerial photo, at a distance of only a few meters from the measuring station lie the construction sites of one of the stations of the new HS2 railway, both south and to the ENE of the measuring station. As expected, the presence of the construction site results in the deterioration of the air quality, with respect to the concentrations of particulate matter in the air. The conditions that enhance the effect of the construction site on the measuring station, as well as the conditions that reduce this effect are studied in this report. 'Conditions' refers mainly to wind speed and direction, as well as boundary layer height. Construction site activities are also included in the considerations.

Figure 1-1: Study location 1 – Curzon Street in Birmingham UK

Figure 1-2: Detail of instrument location – small white instrument with a black aerial

1.4.2 Study Location 2

The second study location was intended to be the A38 roadside ai quality monitoring site at the University of Birmingham, to investigate non-exhaust particulate matter emissions. Unfortunately this was made unserviceable by vandalism and theft before data could be collected at this site.

The second study location was therefore found at a hard rock quarry in the midlands, with permission of the site operator, a client of DS. At this point in time, the site operator has not reviewed the study output and therefore has not yet given permission for the details to be published. This site produces material for transport infrastructure (roads and railways) and was therefore considered acceptably within the aims of the Transition project.

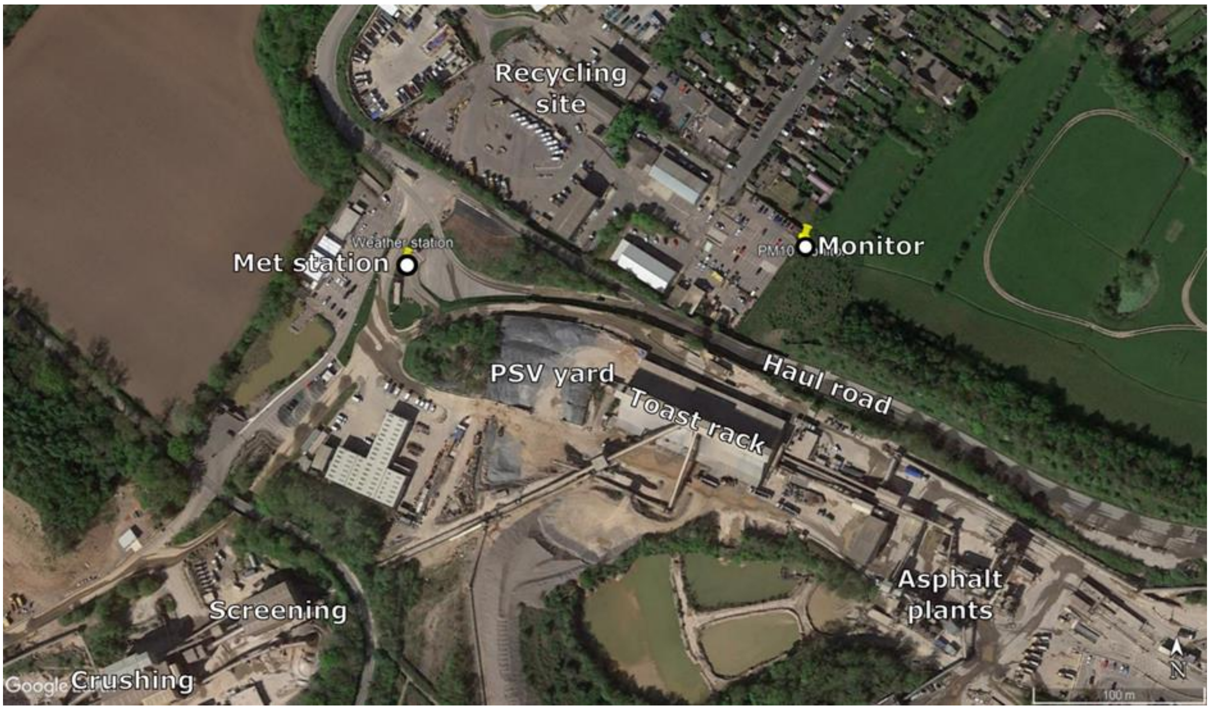


Figure 1-3 Aerial photo outline of second study site

1.5 Key Pollutants

The key pollutant associated with the construction phase of the project will be ‘disamenity’ or ‘nuisance’ dust, and PM_{10} emissions. It has been found by research sponsored by the HS2 project that hourly concentrations of over 190 µg/m^3 are indicative of sources of construction dust in the urban environment.

1.5.1 Particulate Matter

Particulate matter as a term refers to a mixture of solid particles and liquid droplets suspended in the air. These particles come in many sizes and shapes and can be made up of hundreds of different chemicals. Some particles, such as dust, dirt, soot or smoke, are large or dark enough to be seen with the naked eye. Others can be so small that they can only be detected using an electron microscope. Fine dust, essentially particles up to 10 microns (µm), is commonly referred to as PM_{10}.

PM_{10} is known to arise from a number of sources such as construction sites, road traffic movement, industrial and agricultural activities. Very fine particles ($PM_{0.1}$ – $PM_{2.5}$) are known to be associated with pollutants such as NO_x and sulphur dioxide (SO_2) emitted from power plants, industrial installations and road transport sources.

$PM_{2.5}$ is generally associated with combustion and traffic sources and is more likely to be associated with the operational phase of the proposed development.

1.5.2 Disamenity Dust

‘Dust’ is generally regarded as particulate matter up to 75 µm in diameter and in an environmental context can be considered in two size categories; coarser dust (particles greater than 10 µm) and fine particulate matter (PM_{10} and $PM_{2.5}$) as described above.

Coarser dust (particles greater than 10 µm) is generally regarded as ‘disamenity dust’ and can be associated with annoyance, although there are no official standards for dust annoyance[1]. Disamenity dust is more readily described than defined as it relates to the visual impact of short-lived dust clouds and the long-term soiling of surfaces.

Although it is a widespread environmental phenomenon, dust is also generated through many anthropogenic activities including materials handling, construction, demolition and vehicle use. Dust is generally produced by mechanical action on materials and is carried by moving air when there is sufficient energy in the airstream. More energy is required for dust to become airborne than for it to remain suspended.

[1] Note that the expression ‘nuisance dust’ refers here to ‘generally visible particulate matter’ rather than specifically and in a legal sense to statutory nuisance, as defined in Section 79 of the Environmental Protection Act 1990.

2 Legislation, Policy and Non-Statutory Guidance

This section summarises all legislation, policy, statutory and non-statutory guidelines relevant to the control of particulate matter in the air.

The UK left the EU on the 31st January 2020 and a new trade deal, the EU-UK Trade and Cooperation Agreement, was signed on 30th December 2020. Following exit day on the 31st January 2020, the current framework of air quality legislation was converted into domestic law through the European Union (Withdrawal) Act 2018[2].

2.1 International (European Union)

Whilst the UK has left the EU, it is relevant to understand the source of the current UK legislation. The European Union (EU) sets legally binding limit values for outdoor air pollutants to be met by EU countries by a given date. These limit values are based on the World Health Organisation (WHO) guidelines on outdoor air pollutants. These are legally binding and set out to protect human health and the environment by avoiding, preventing or reducing harmful air pollution effects.

Directive 2008/50/EC[3] on ambient air quality and cleaner air for Europe entered into force in June 2008. This merged the existing 'Daughter' Directives[4,5,6,7] (apart from the fourth Daughter Directive), maintaining existing air quality objectives set out by 'Daughter' Directives for:

- Sulphur dioxide (SO_2);
- Nitrogen dioxide (NO_2);
- Oxides of nitrogen (NO_x);
- Particulate matter ($PM_{2.5}$ and PM_{10});
- Lead (Pb);
- Benzene(C_6H_6);
- Carbon monoxide (CO); and
- Ozone (O_3).

Directive 2008/50/EC also includes related objectives, exposure concentration obligations and exposure reduction targets for $PM_{2.5}$ (fine particles). The 'Daughter' Directives were based upon requirements set out in the first EU Ambient Air Quality Framework Directive 96/92/EEC[8].

[2] European Union. (2018): http://www.legislation.gov.uk/ukpga/2018/16/contents/enacted
[3] European Union. (2008), 'Ambient air quality assessment management', Framework Directive 2008/50/EC.
[4] European Union. (1999), 'Ambient air quality assessment management', Framework Directive 1999/30/EC.
[5] European Union. (2000), 'Ambient air quality assessment management', Framework Directive 2000/3/EC.
[6] European Union. (2002), 'Ambient air quality assessment management', Framework Directive 2002/3/EC.
[7] European Union. (2004), 'Ambient air quality assessment management', Framework Directive 2004/107/EC.
[8] European Union. (1996), 'Ambient air quality assessment management', Framework Directive 96/62/EC.

2.2 National (England)

The 2008 EU ambient air quality directive 2008/50/EC was transposed into English law through the introduction of the Air Quality (Standards) Regulations in 2010[9] which also incorporated the fourth EU Daughter Directive (2004/107/EC) that set target values for certain toxic heavy metals and polycyclic aromatic hydrocarbons, (PAH).

The UK government has a responsibility to meet its own limit values, which mirror the EU limit values. Part IV of the 1995 Environment Act[10] sets guidelines for protecting air quality in the UK and forms the basis of local air quality management. The Environment Act requires local authorities in the UK to review air quality in their area periodically and designate Air Quality Management Areas (AQMAs) where the objectives are not being achieved or are not likely to be achieved within the relevant period. Where an AQMA is designated, local authorities are also required to produce an 'Air Quality Action Plan' (AQAP) detailing the pollution reduction measures that need to be adopted to achieve the relevant air quality objectives within an AQMA.

As part of the Environment Act, the UK Government was required to publish a National Air Quality Strategy (NAQS) to establish the system of 'local air quality management' (LAQM) for the designation of AQMAs. This led to the introduction of the first Air Quality Strategy in 1997[11] which has since progressed through several revisions until it was replaced by the Air Quality Strategy for England, Scotland, Wales and Northern Ireland 2007[12]. Each revision introduced strategies and regulations that considered measures for different pollutants by tightening existing objectives and also by introducing new ones to establish a common framework to protect human health and the environment by achieving ambient air quality improvements.

2.2.1 Relevant Air Quality Standards

A summary of the relevant AQO and where they are applicable are presented in Table 2.1 and Table 2.2 respectively. The AQO listed in Table 2.1 are only applicable at locations where a member of the public could be reasonably expected to spend the relevant averaging period. Further examples of this are presented in Table 2.2.

Table 2.1: AQO relevant to the proposed development

Pollutant	Averaging Period	AQO ($\mu g/m^3$)	Exceedance Allowance	Percentile Equivalent
Particulate Matter (as PM_{10})	Annual	40	-	-
	24-hour	50	35 per annum	90.4th
Particulate Matter (as $PM_{2.5}$)[(a)]	Annual	25	-	-

Notes: [(a)] This is a target value set for a 15% reduction in concentrations at urban background aimed to achieve between 2010 and 2020

[9] Statutory Instrument. (2010), 'The Air Quality Standards Regulations', No. 1001. Queen's Printer of Acts of Parliament.
[10] Parliament of the United Kingdom. (1990), 'Environmental Protection Act', Chapter 43. Queen's Printer of Acts of Parliament.
[11] Department for Environment Food and Rural Affairs. (1997), 'The United Kingdom National Air Quality Strategy', Cm 3587, Department for Environment Food and Rural Affairs.
[12] Department for Environment Food and Rural Affairs. (2007), 'The Air Quality Strategy for England, Scotland, Wales and Northern Ireland', Cm 7169, Department for Environment Food and Rural Affairs.

Pollutant	Averaging Period	AQO (µg/m³)	Exceedance Allowance	Percentile Equivalent

Source: Department for Environment Food and Rural Affairs (2016): 'Local Air Quality Management Technical Guidance' (TG.16).

Table 2.2: Examples of where the AQO should apply

Averaging period	Objectives should apply at	Objectives should not apply at
Annual	All locations where members of the public might be regularly exposed. Building façades of residential properties, schools, hospitals, care homes etc.	Building façades of offices or other places of work where members of the public do not have regular access. Hotels, unless people live there as their permanent residence. Gardens of residential properties. Kerbside sites (as opposed to locations at the building façade), or any other location where public exposure is expected to be short-term.
24 Hour	All locations where the annual mean objective would apply, together with hotels and gardens of residential properties[(a)].	Kerbside sites (as opposed to locations at the building façade), or any other location where public exposure is expected to be short-term.
1 Hour	All locations where the annual mean and 24 and 8-hour mean objectives apply. Kerbside sites (for example, pavements of busy shopping streets). Those parts of car parks, bus stations and railway stations etc. which are not fully enclosed, where members of the public might reasonably be expected to spend one hour or more. Any outdoor locations where members of the public might reasonably have expected to spend one hour or longer.	Kerbside sites where the public would not be expected to have regular access.

Note:

(a) "*Such locations should represent parts of the garden where relevant public exposure to pollutants is likely, for example where there is seating or play areas. It is unlikely that relevant public exposure to pollutants would occur at the extremities of the garden boundary, or in front gardens, although local judgement should always be applied.*"

Source: Department for Environment Food and Rural Affairs (2016): 'Local Air Quality Management Technical Guidance' (TG.16).

The Environment Act 2021 (published in November) has set a date by which the UK government must introduce a new target for $PM_{2.5}$ concentrations, which is by the 31st October 2022.

2.2.2 Statutory Nuisance

It is recognised that the planning system presents a way of protecting amenity. However, in cases where planning conditions are not applicable to a development/installation, the requirements of the Environmental Protection Act 1990 still apply. Under Part III of the Environmental Protection Act 1990, local authorities have a statutory duty to investigate any complaints of:

- *"any premises in such a state as to be prejudicial to health or a nuisance*
- *smoke emitted from premises so as to be prejudicial to health or a nuisance*
- *fumes or gases emitted from premises so as to be prejudicial to health or a nuisance*
- *any dust, steam, smell or other effluvia arising on industrial, trade or business premises and being prejudicial to health or a nuisance*
- *any accumulation or deposit which is prejudicial to health or a nuisance"*

Where the local authority establishes any one of these issues constitutes a statutory nuisance and believes it to be unreasonably interfering with the use or enjoyment of someone's premises and/or is prejudicial to health, an abatement notice will be served on the person responsible for the offence or the owner / occupier. Failure to comply with the notice could lead to a prosecution. However, it is considered as a defence if the best practicable means to prevent or to counteract the effects of the nuisance are employed.

2.2.3 Non-Statutory Guidance Relevant to Particulate Emissions and Management

There are several best practice guidance notes relating to the management and monitoring of particulate matter around various types of sites.

These are:

Environment Agency Technical Guidance Note M8[13] 'Ambient Air Quality Monitoring'.

Environment Agency Technical Guidance Note M17[14] 'Monitoring of particulate matter in ambient air around waste facilities'.

Institute of Air Quality Management 'Guidance[15] on Monitoring in the Vicinity of Demolition and Construction Sites' 2018

Mineral Industry Research Organisation: 'Good Practice guide[16]: control and measurement of nuisance dust and PM10 from the extractive industries' (2011).

The Environment Agency is currently revising M8 and M17, with an expectation that the new guidance will be published in 2022 in the accessible format (non-PDF) on the gov.uk

[13] https://www.gov.uk/government/publications/m8-monitoring-ambient-air
[14] https://www.gov.uk/government/publications/m17-monitoring-of-particulate-matter-in-ambient-air-around-waste-facilities
[15] https://iaqm.co.uk/text/guidance/guidance_monitoring_dust_2018.pdf
[16] https://www.researchgate.net/publication/324994313_Good_practice_guide_control_and_measurement_of_nuisance_dust_and_PM10_from_the_extractive_industries_Final_Report_to_The_Mineral_Industry_Research_Organisation_MIRO

website. A contract was let to RPS environmental consultants to do a review of the guidance.

Up to this point in time, particulate source apportionment as a technique has not been available to the industrial activities referenced above and is not generally referenced in the best practice guidance.

3 Methodology

This section sets out the approach taken to analyse the datasets collected of particulate matter number counts, concentrations and site activities.

3.1 Details of the Method

Particle number size distribution data in the size range 0.4 to 40 µm were collected using a DS Cloud Optical Particle Counter (version as South Coast Science Praxis Urban with Alphasense OPC-N3, Alphasense, 2019) (2/9/2020 to 26/10/2020 with a ten second resolution), the cost of which is only a fraction compared to the more precise but expensive regulatory grade instruments that were used so far for such analyses. Additionally, data from the meteorological station at the University of Birmingham were used for the Curzon Street site. The UoB meteorological station is about 6-7 km away from the measuring site, the implication of this is that the data provided are not affected by the local urban topography at Curzon Street, thus provide a representation of the general meteorological conditions in the wider area. A further dataset between 3/7/21 and 3/8/21 was collected using a DS Cloud (South Coast Science OPCube version with Alphasense OPC-N3) and analysed. The instruments were installed on site by DS, supported by the HS2 Innovation programme.

The data at the quarry was collected with a non-commercial UoB instrument (Alphasense OPC-N3). For the analyses of the particles at the quarry site, meteorological data was obtained from a recording station on site. The instrument was installed on site by DS, with the permission of the operator.

For the separation and identification of the different sources and conditions resulting to different air quality levels, two methods were used, the Positive Matrix Factorization (PMF) and the k-means clustering statistical analysis. The PMF is a multivariate data analysis method developed by Paatero (Paatero and Tapper, 1994) and can be described as a least square formulation of factor analysis, used numerous times in the aerosol science. The k-means clustering is another widely used statistical method that identifies and separates different groups of particle number size distribution patterns according to their similarity, which then can be associated with different sources when additional data are applied. It is a method of vector quantisation which aims to partition observations (x_1 , x_2 , ..., x_n) into k sets, minimising within-cluster variances (squared Euclidean distances). In the present study the separation and identification of the different sources is done by associating them to different wind directions (which point to the direction of the source) as well as to different temporal patterns, associating them to different activities. No additional chemical composition data are available, which would help in better understanding the sources of the particles (ie. Pollution) as well as the anticipated concentrations of pollutants.

Additional analyses were carried out using the Openair statistical software package for analysing air pollution data. Metadata was supplied in the form of information on the geographical locations of site activities i.e. where the particulate forming activities were taking place in relation to the measurement locations and the times of the activities (i.e. time of day and day of week).

3.2 Measurement Data

The measurement data recorded for this project can be found here: https://edata.bham.ac.uk/811/ .

4 Results

4.1 Commentary on the results section

The results of the analyses are not presented in full in this report, because the results of the measurement exercises are planned for publishing in the journal 'Atmospheric Measurement Techniques', and the results for one site have not yet been agreed for publication by the site operator. A limited description of the analysis is given below, to illustrate what was done in the project.

4.2 HS2 Curzon Street - Construction Site Dust

4.2.1 Positive Matrix Factorisation

The particle size and number counts were analysed by a statistical method known as positive matrix factorisation (PMF). Being a descriptive model, for PMF there is no objective criterion that provides an optimal solution (Paatero, 2002). For the present analysis the solution chosen provided 4 unique factors. Choosing a higher number of factors provided separation of the sources from the construction site, though no additional information is added to the 4-factor solution, as it further separates a factor into two with similar characteristics. The profiles of the factors formed as well as their temporal contribution are presented in the next figure.

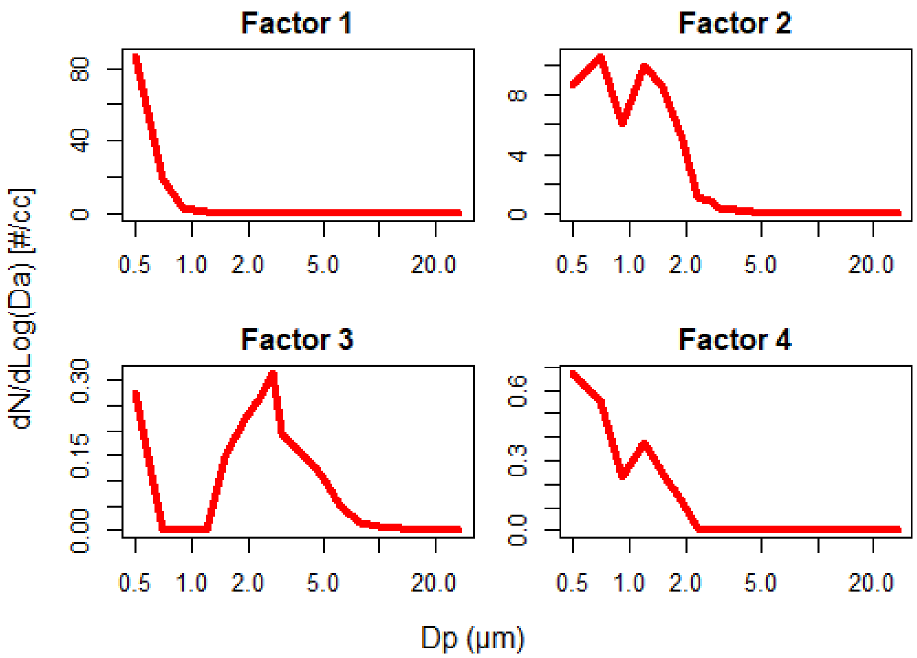


Figure 4-1: Plot of particle number per unit volume against particle diameter in μm for each of four factors

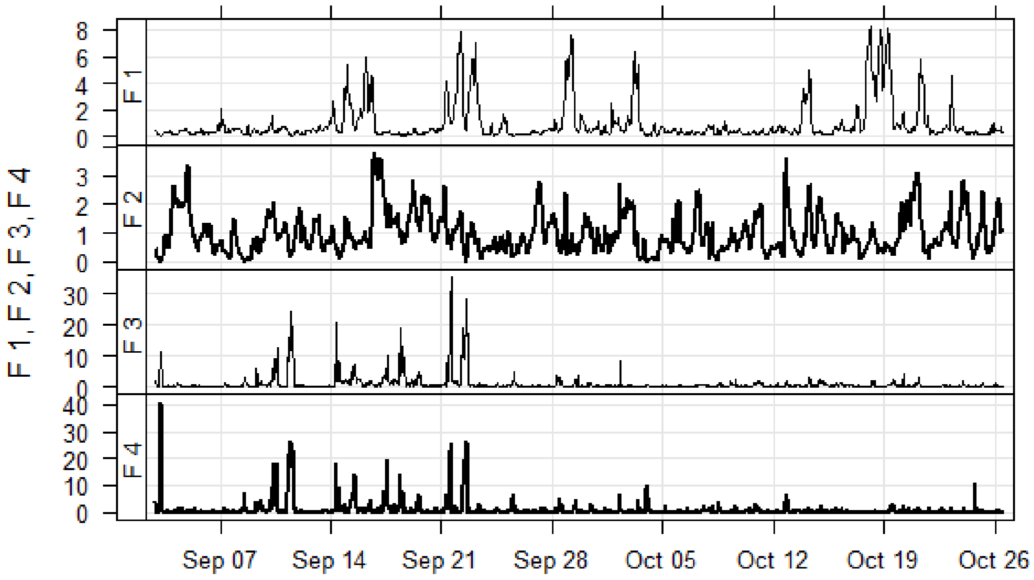


Figure 4-2: Time series of each of the four factors during the measurement period of 6 weeks

The diurnal variation and polar plot and the polar annulus of the contribution of each factor are presented in the next figures.

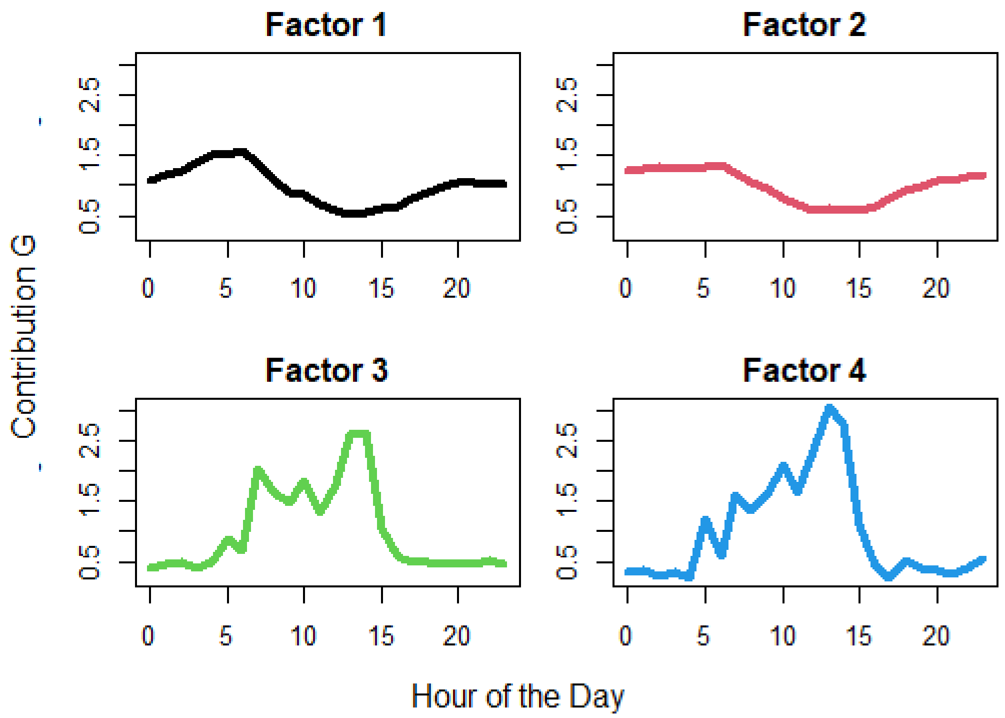


Figure 4-3: Diurnal variation of Contribution G (a mathematical component) of the four factors

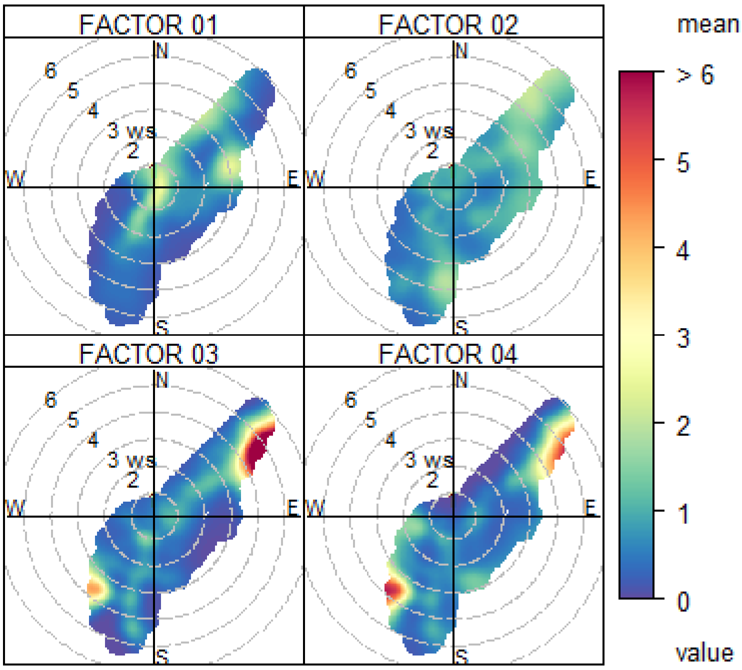


Figure 4-4: Polar plots of the four factors

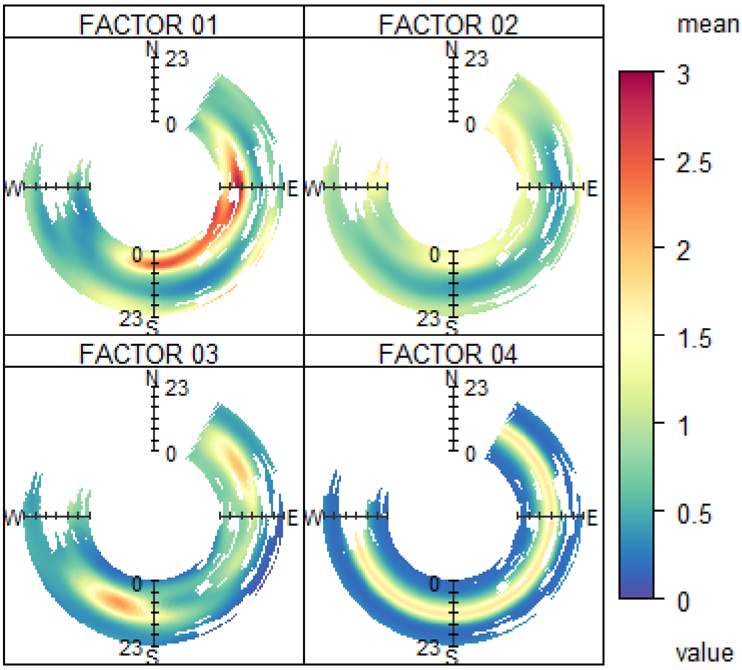


Figure 4-5 Open-air polar annulus plot: time of day, wind direction, contribution (the redder the value, the more the contribution of the factor).

Due to the size range measured by the OPC, any direct effect from a nearby traffic or other combustion source is not expected to be visible (direct exhaust emissions are in most cases in the ultrafine size range, which is smaller than 0.1 μm). The first two factors which are not associated to the construction site. **Factor 01** presents increased contribution from the southeast (factor 1) and whole east side for the second factor, while their diurnal variation favours early morning and late-night hours. This may be associated to the effect of the reduced Boundary Layer Height (BLH) during these times, reducing the mix of pollutants and increasing their concentrations. The source to the southeast with which the first factor is mainly associated is probably the railroad in that direction. This appears to be the source with the greatest particle concentrations in the area (reaching an average of about 500 N/cm^3 at the smallest size measured by the OPC – 0.4 μm), though its contribution in the general air quality is not as significant as the ones associated with the construction site. It presents an interesting weekly variation being almost absent during the middle days of the week when it occurs.

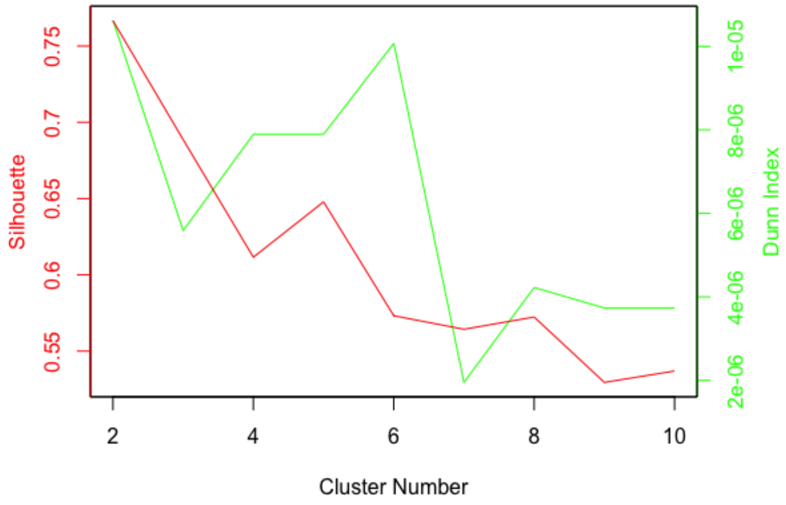
Factor 02 presents two peaks at about 0.7 and 1.5 μm, with very low particle concentrations and unclear incoming direction and temporal variation. This is probably the urban background footprint which is the combination of many different sources affecting the site.

Factor 03 and Factor 04 present a temporal variation which directly associates it with the construct site. They have increased contribution during the working hours, and this significantly reduces after the 22nd of September (the earth-moving works ended the previous day according to the schedule provided by the operators). Specifically, the third factor presents two hot-spots directly in the south and northeast which are the location of the earth-moving parts with two distinct peaks (one below the measuring limit of the OPC and the other at 2 μm) probably associated with the dust coming from the works. The fourth one which bears great resemblance to the urban background factor (factor 2) presents high contributions from all sides associated to the construct site and it probably incorporates all other activities related to the work on the construct site.

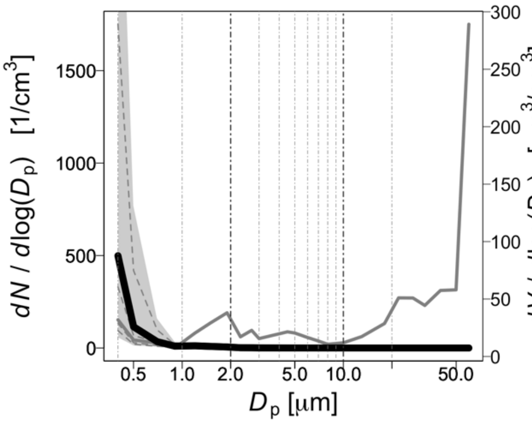
4.2.2 Clustering

This section presents an analysis of the same 6 weeks' measurement data, analysed by a statistical method referred to as clustering.

A solution of five clusters was chosen, as being among the ones suggested by the evaluation of a statistical test, as shown by the figure below: it is the solution that presents high values for both the Dunn index and Silhouette metrics, as proposed by Beddows et al., 2009. In addition, it provided enough information about the different sources and conditions that affect the air quality at the site. While two of the clusters formed present great similarities, reducing the number of clusters resulting in the loss of a unique group (CL5) which has different characteristics compared to the others.



The Particle Number Size Distribution (PNSD) profiles and frequency of occurrence of the five clusters formed are rather similar and are presented in the next five figures.



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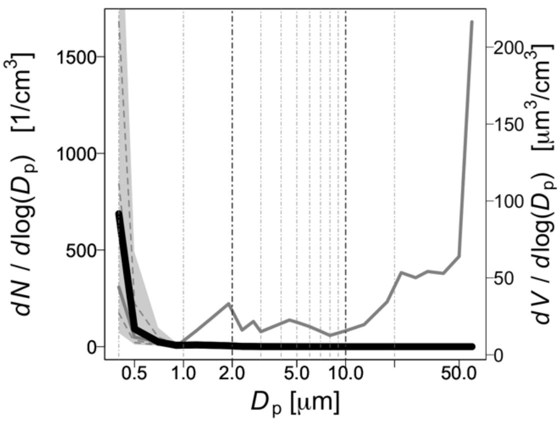

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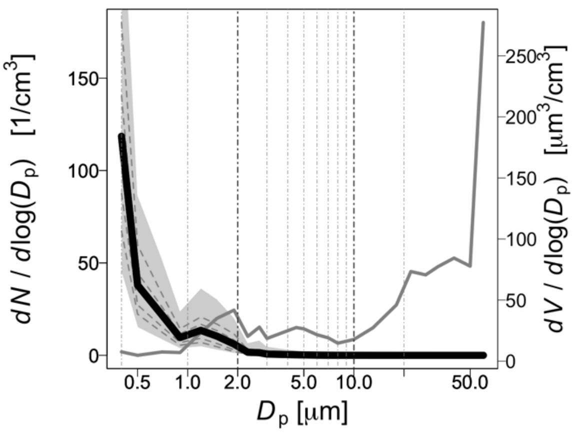

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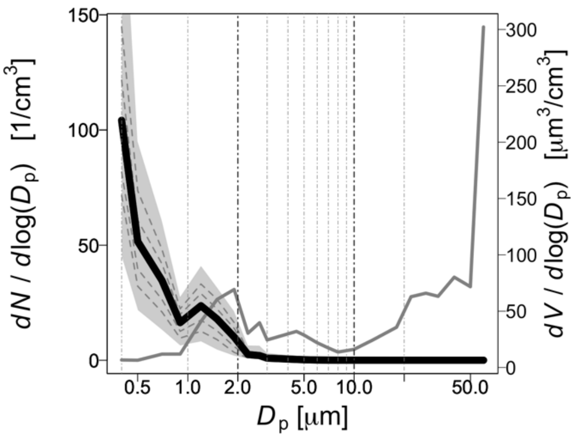

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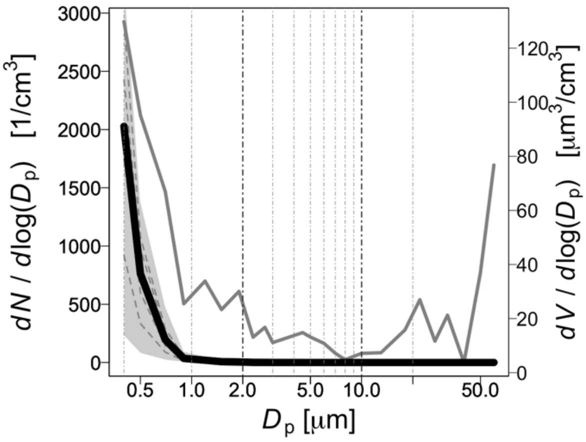

5

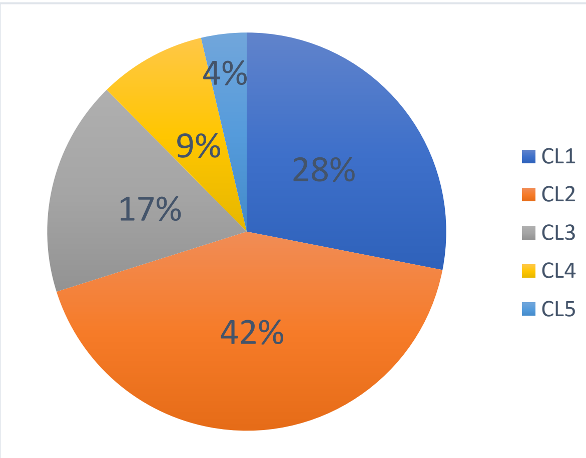

Figure 4-6: Each cluster as a percentage

Small differences were found for the average wind profiles other than the wind speed for the five clusters as can be seen by the following figure, which will be discussed later for each cluster. This is expected as the site is within the urban environment and in close proximity to many of the sources of pollution that affect it. Similar is the case for the other meteorological parameters (temperature and relative humidity), the variation of which is mainly associated to their diurnal variation (favouring daytime or night-time). As a result, the main differences between the clusters formed are expected to be found from their temporal variation which would define the different sources and conditions that play the most important role for each one of them.

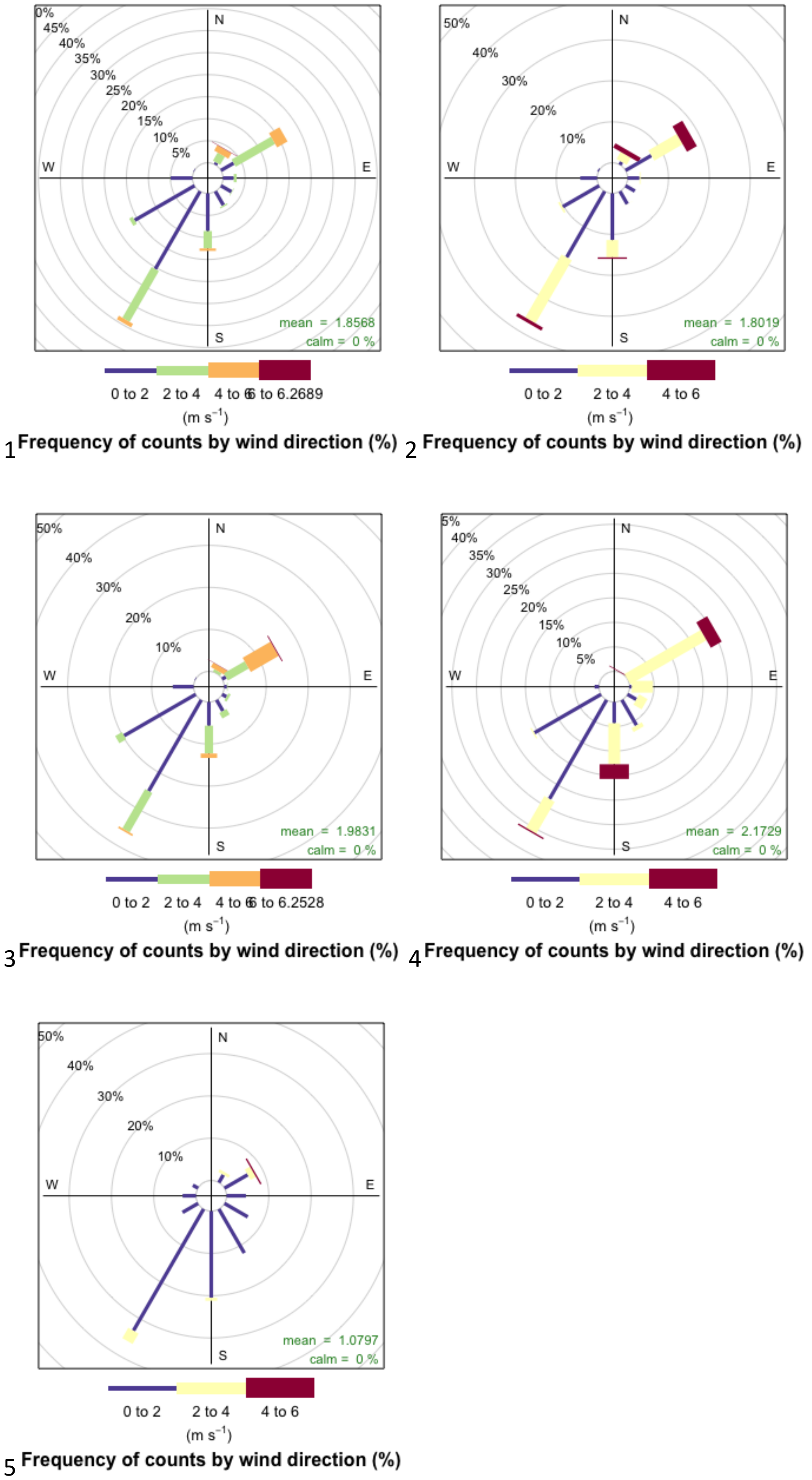

Figure 4-7: 5 plots showing the frequency of counts by wind direction for each of the 5 clusters

Table 5-1: Average particle concentrations, meteorological conditions and PM mass concentrations for the groups formed by the clustering analysis

	0.4 µm (N cm^{-3})	0.5 µm (N cm^{-3})	RH (%)	T (°C)	WS (m s^{-1})	PM_1 (µg cm^{-3})	$PM_{2.5}$ (µg m^{-3})	PM_{10} (mg cm^{-3})	PM_1:PM_{10}
CL1	499	115	83.5	11.5	1.86	3.45	10.7	33.8	10.2
CL2	687	91.6	87.1	12.7	1.80	3.34	8.82	29.1	11.5
CL3	119	38.0	77.2	12.0	1.98	2.04	11.1	42.7	4.78
CL4	104	51.6	78.9	12.3	2.17	3.20	19.2	62.7	5.11
CL5	2028	762	91.9	10.4	1.08	14.7	23.2	37.4	39.2

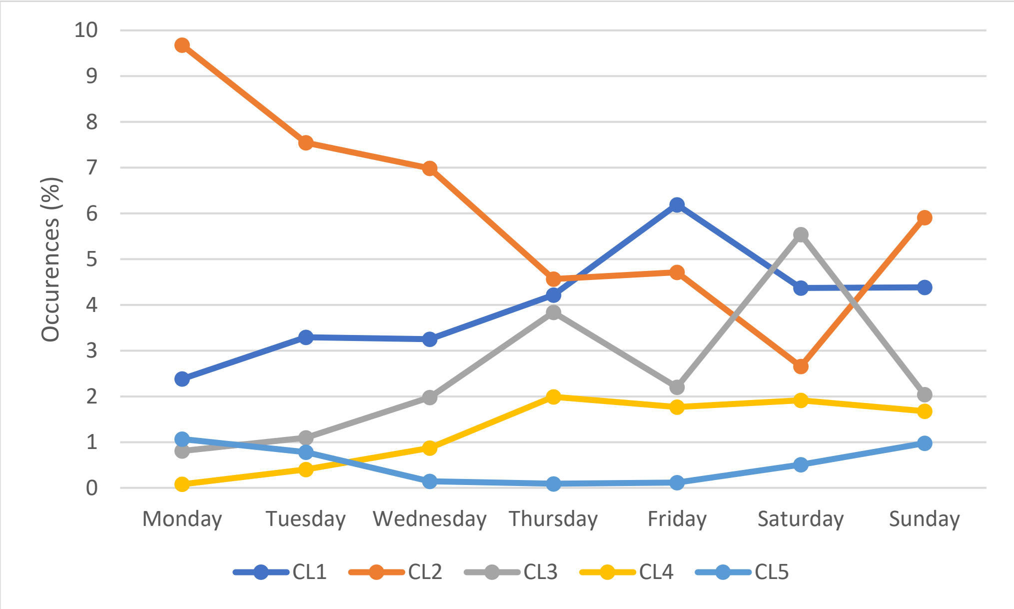

Figure 4-8: Weekly variation of the groups formed by the clustering analysis

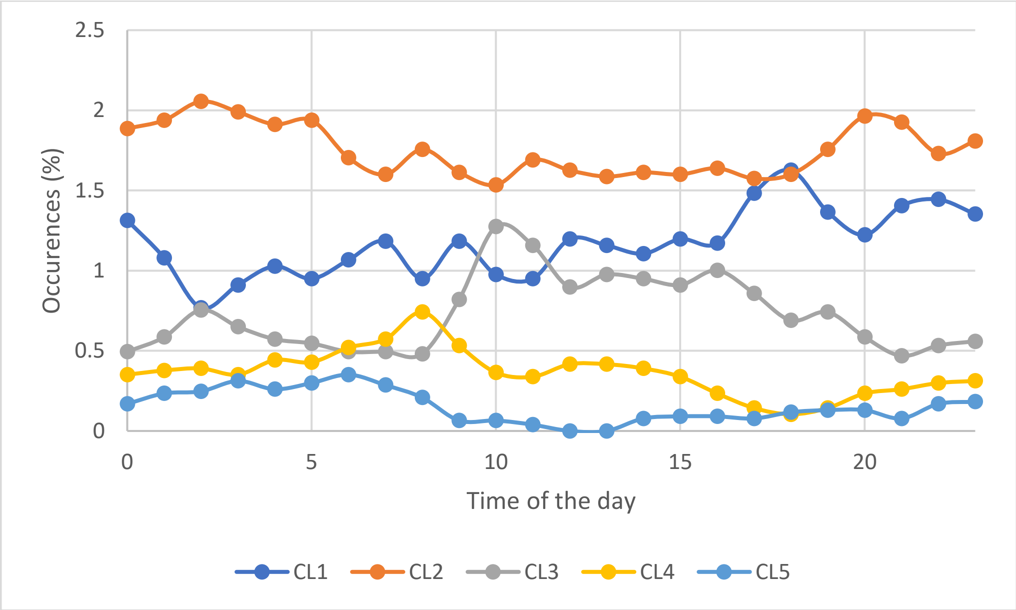

Figure 4-9: Diurnal variation of the groups formed by the clustering analysis

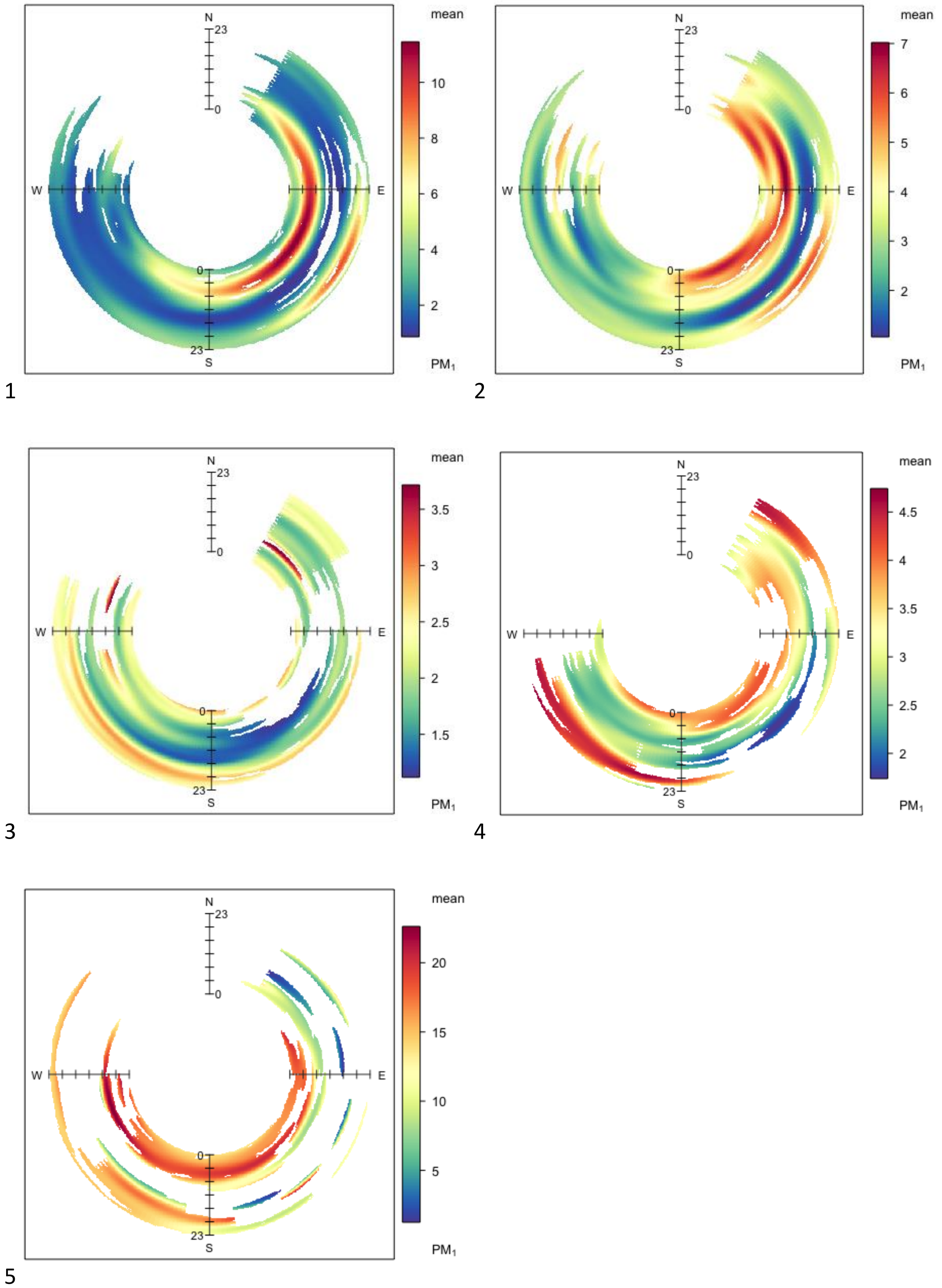

Figure 4-10: Polar annulus plots of the PM1 mass concentrations for each cluster

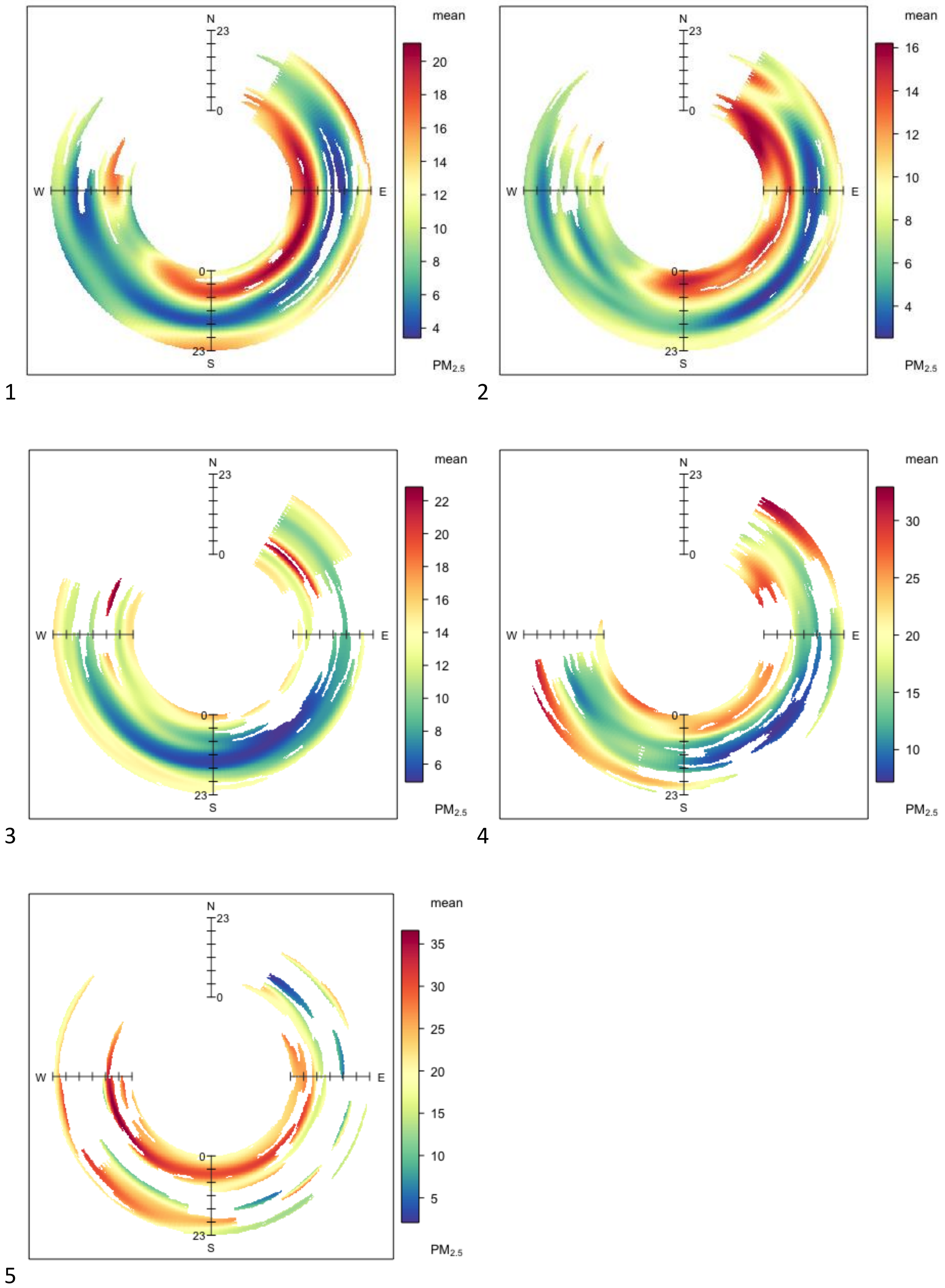

Figure 4-11: Polar annulus plots of the PM2.5 mass concentrations for each cluster

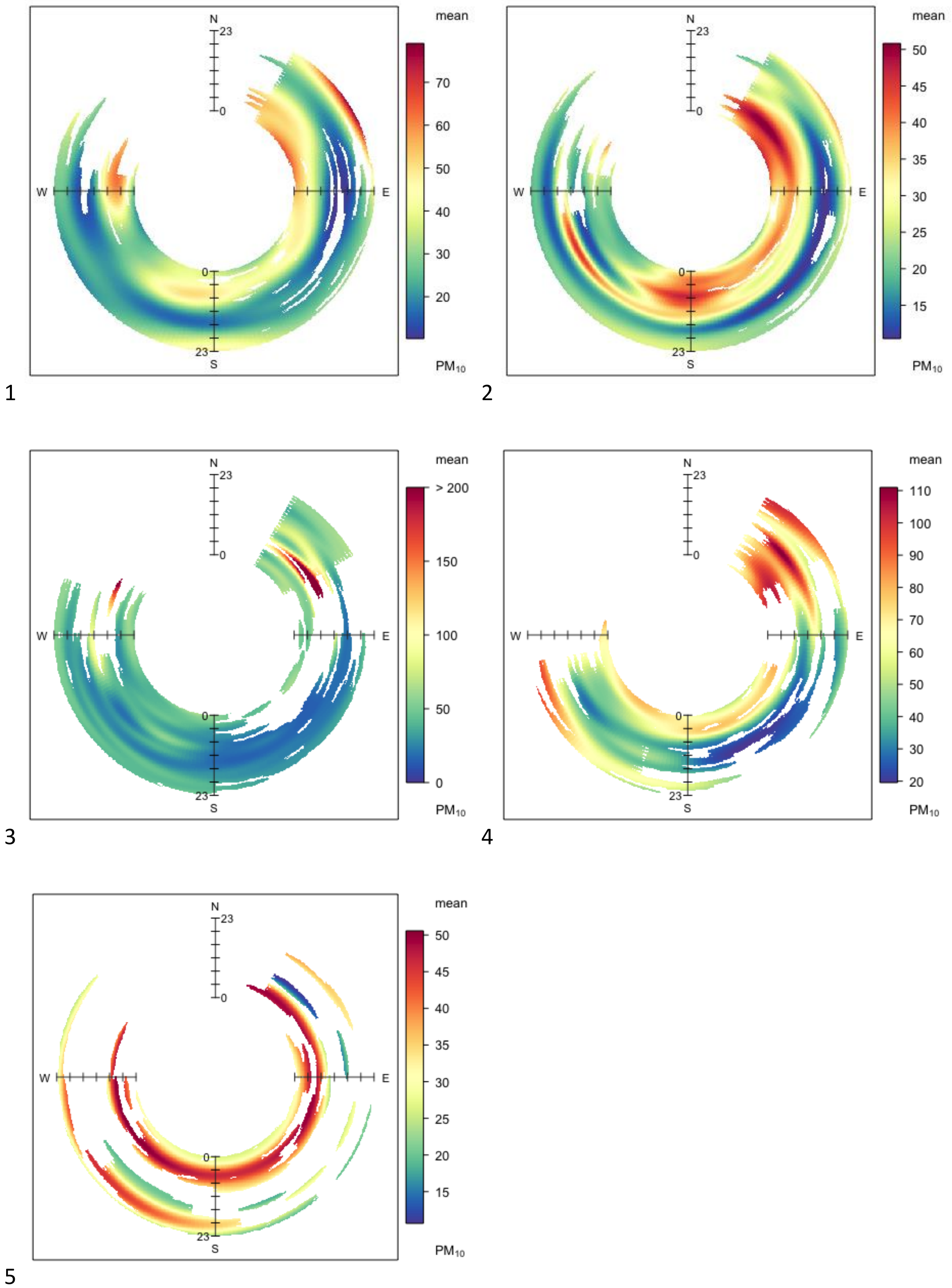

Figure 4-12: Polar annulus plots of the PM10 mass concentrations for each cluster

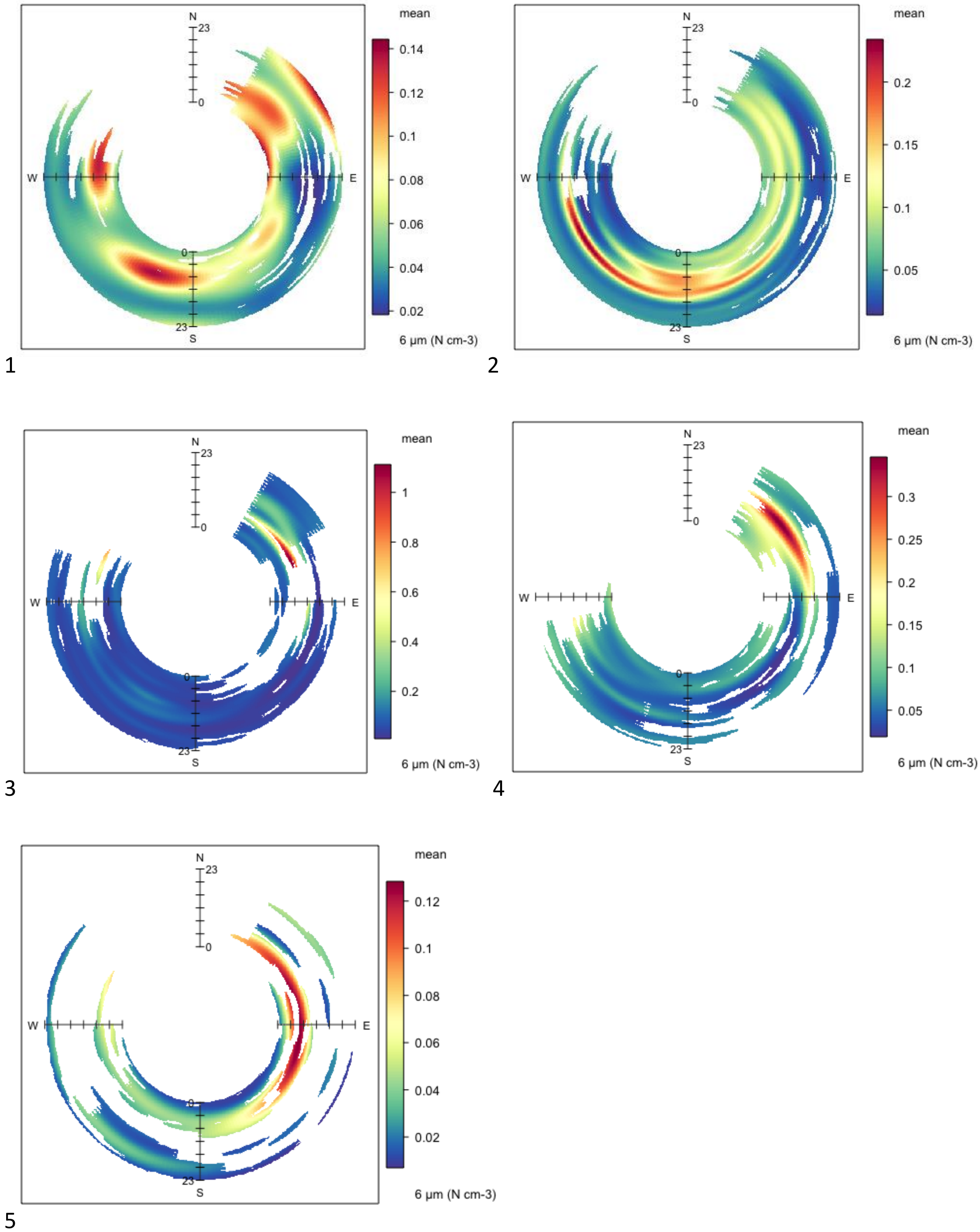

Figure 4-13: Polar annulus plots of 6µm particle concentrations for each cluster

According to the weekly schedule in the construction site, the effect of the activities there should be visible between 8:00 and 18:00. Looking at the diurnal variation of the clusters, CL5, the one with the smallest frequency, occurs mainly during the night-time, with its peak being at 6 AM. From that point its frequency is reduced thus probably associating it with other nearby sources, not related to the activities at the construction site. Due to the time of the day, it may be affected by the low BLH, which results in less mixing and higher concentrations of pollutants. While no additional data are available for the atmospheric chemical composition the PM mass concentrations can be considered to elucidate the level of pollution. This cluster presents the highest PM1 and PM2.5 values further confirming the aforementioned conditions. This probably, similarly to what was found from the PMF analysis, associates it to pollution from the railroad found to the south, as its wind rose has a different profile slightly favouring southern winds (compared to the other clusters).

It is interesting that the weekly variation between the clusters seems to be separated into two periods within the week. CL2 and CL5 (though CL5 is not associated to the work on the construction site) have higher frequency of occurrence during the first days of the week, while the rest (CL1, CL3 and CL4) are more frequent during the second part of the week, with an increasing trend from Thursday. It is unknown though whether this is an artefact of the dataset or from different activities undertaken within the week at the construction site.

Looking at the PM polar annulus plots it is rather hard to distinguish the sources of each of the remaining clusters. Especially at smaller sizes, all clusters seem to carry the effect of the source to the southeast, which is the main source of smaller particles (in the range the OPC measures). Further scanning of the OPC dataset though shows that the particles associated with the activities at the construction site are "visible" from the particle size of 5 μm and above, from which the effect of the two different sites is clearly visible.

CL2 is associated mainly with the emissions from the south. It does not have a clear diurnal variation, as it seems to be similarly frequent at all hours. As with all clusters, the smaller particles of this group are not associated with activities at the site and originate mainly directly from the east but stop at about 9 AM. This cluster presents smaller PM2.5 and PM10 concentrations compared to the CL3 and CL4, which are more associated to the source on the NE as discussed later.

CL3 is mainly associated with NE, though as in all other clusters this group is also affected by sources from other directions for smaller particles. It is less polluted than CL4, with which they seem to have similar peak for larger particles in the NE at working hours. This is further confirmed as the diurnal variation points that this is directly associated to the construction site. Smaller particles during the active time of the construction site are rather low.

CL4 is also mainly associated with the activities to the NE and its wind profile is somehow more associated to winds from that direction (also having the highest average wind speed). It presents the highest PM2.5 and PM10. It appears that the northeastern part is the one polluting more (among the two sides of the construction site) and due to its position (being further from the measuring station compared to the southern part), higher wind speeds are needed for the large particles to be transported. Diurnal variation points that this cluster is also directly associated to the construction site. Smaller particles are found on this one as well, but they do not have the same direction and diurnal variation with the larger ones.

CL1 is greatly affected by both the NE and south part of the construction site. Once again, the high PM1 from the SE point are from the site to the southeast which greatly affects all clusters. This source of smaller particles, while visible to other clusters as well, it is more enhanced on this one, though as with all other clusters its diurnal variation points to times between 4:00 and 8:00 which are outside of the working hours at the construction site. Being affected by both sides of the construction site its average PM concentrations are between the one associated with the southern part and the ones associated with the NE side.

4.2.3 Further analysis

Another data set was analysed for the period between 3/7/21 and 3/8/21. The results are not presented here, as there is an intention to publish them.

The results from the additional analysis with newer data strengthened the findings from the source apportionment attempted in the previous analysis, and showed the consistency and repeatability of the results, as well as help in understanding the sources of particles at the site and the perceived effect these have in the air quality there. Thus shows the importance of the results found in the previous analysis and the successful application of the methods used in it.

4.3 Study Site 2 – Hard Rock Quarry

The results of the measurements made at this site are not presented in this report, they are pending agreement for publication. They are intended to be published in a scientific paper.

5 Discussion

5.1 Discussion of the analysis of particulate matter at the construction site

5.1.1 Sources of PM - Comparison of the two statistical methods

The use of the two statistical methods on low-cost sensor data provided sufficient insight into both the sources that affect the air quality at the site, as well as an estimation of the effect of each source. The analysis showed that the main source of particles smaller than 1 μm is to the southeast, in which side there is a railway. The effect of this source is greater during night-time and early morning hours. This may be associated to the daily variation of the BLH, which is reduced during these hours and tends to increase the effect of any pollution source due to reduced mixing. This source was pinpointed by both methods and it was associated with the most polluted conditions (particle concentration wise) for particle sizes up to $PM_{2.5}$. The effect of the activities from the construction site were also found from both methods. Using the PMF, two hotspots of particle emissions were found, peaking at about 3 μm and having increased concentrations for larger particles. This source also presented a peak at the smallest available particle size, which in most cases points to increased particle concentrations at a smaller size than the measuring limit of the sensor. Looking at the temporal trend of this source, it is directly associated to the earth-moving works done at the construction site, though a small contribution of this source is also visible outside the period when such works were undertaken. Another source of large particles associated with the activities within the area and time-period of the earth moving activities was also pinpointed, having a peak at about 1.5 μm (as well as another below the measuring range of the OPC). This though presented a wider area as a source location, though with a similar temporal variation as the aforementioned factor, and is probably associated with other activities at the construction site, though the possible effect of other external sources occurring at the same time cannot be excluded. Finally, the PMF also identified a more constant source of particles, which did not present a clear temporal variation or clear incoming direction. This is probably associated with other emissions related to activities in the urban background, which are not associated with the construction site.

The use of the clustering provides insight to the real-world conditions occurring at the site. Thus, while the separation of the sources that affect the air quality at the site is not as distinct as with the PMF, this method helps in better understanding the combination of the sources as well as their effect with different conditions. The small wind variation for the period studied resulted in rather homogenised clusters, with wind blowing mainly from the directions of the construction activities. All clusters carry the effect of the source to the southeast (potentially the railway into New Street Station), which affects the site throughout the day for the whole measuring period, though its effect is enhanced during the night hours, as mentioned earlier. While not clearly visible when considering PM measurements, the activities of the construction site are better visible when different particle size ranges are considered. Thus, it is found that for particles at the size range of about 5 μm and above, two hotspots are found similar to the ones found from the PMF analysis. The clustering method though managed to further quantify the effect of these two hotspots, showing that the one on the northeast formed greater number of larger particles, not only having a larger

PM_{10} concentration, but a greater PM_{10} to PM_1 ratio as well. The latter though may be the effect of the sources of smaller particles found at the south side. This information though cannot be clarified without measurements of particles at smaller sizes than that the OPC provides, or without chemical composition data that were not available for this study.

6 Conclusion

The research grant funded the collection and analysis of particle count data at two sites in the midlands in the UK, related to the transition of the transport infrastructure to clean energy. The first was the HS2 Curzon Street construction site, and the second was a hard rock quarry in the midlands, supplying raw material to transport infrastructure projects.

Approximately 3 months' worth of continuous particle size data was analysed and it was successfully shown that specific particle size patterns and particle number distributions in the air could be attributed to activities being carried out on the sites. The associations could be made by time and by wind direction. The work is being prepared for publication in the journal Atmospheric Measurement Techniques.

Dustscan Ltd has registered for an account with the Centre for Environmental Data Analysis to archive the datasets recorded and analysed in this project.

The success in the research work so far has been used to obtain more funding from the UoB, from an EPSRC fund to continue collecting and analysing data from other sources, and for DS/UoB to apply for an Innovate smart grant to do further industrial research towards commercialising the approach.

6.1 Impact

The results of the research have been disseminated as part of the programme of work. DS have promoted the methods as potentially offering solutions to real-life problems for our metals, mineral and waste sector clients in environmental management, planning, consenting, inquiry and litigation situations. The research has been presented to the UK Environment Agency which has expressed interest in the development of the techniques. The approach described has been positively evaluated by Innovate UK.

Appendix A – References

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