AIR QUALITY EXPERT GROUP

Evidential Value of Defra Air Quality Compliance Monitoring

Prepared for:

Department for Environment, Food and Rural Affairs;
Scottish Government; Welsh Government; and
Department of the Environment in Northern Ireland

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This is a report from the Air Quality Expert Group to the Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of the Environment in Northern Ireland, on the evidential value of Defra air quality compliance monitoring.

United Kingdom air quality information received from the automatic monitoring sites and forecasts may be accessed via the following media:

Freephone Air Pollution Information Service	0800 556677
Internet	http://uk-air.defra.gov.uk

PB14312

Terms of reference

The Air Quality Expert Group (AQEG) is an expert committee of the Department for Environment, Food and Rural Affairs (Defra) and considers current knowledge on air pollution and provides advice on such things as the levels, sources and characteristics of air pollutants in the UK. AQEG reports to Defra's Chief Scientific Adviser, Defra Ministers, Scottish Ministers, the Welsh Government and the Department of the Environment in Northern Ireland (the Government and devolved administrations). Members of the Group are drawn from those with a proven track record in the fields of air pollution research and practice.

AQEG's functions are to:

- Provide advice to, and work collaboratively with, officials and key office holders in Defra and the devolved administrations, other delivery partners and public bodies, and EU and international technical expert groups;
- Report to Defra's Chief Scientific Adviser (CSA): Chairs of expert committees will meet annually with the CSA, and will provide an annual summary of the work of the Committee to the Science Advisory Council (SAC) for Defra's Annual Report. In exception, matters can be escalated to Ministers;
- Support the CSA as appropriate during emergencies;
- Contribute to developing the air quality evidence base by analysing, interpreting and synthesising evidence;
- Provide judgements on the quality and relevance of the evidence base;
- Suggest priority areas for future work, and advise on Defra's implementation of the air quality evidence plan (or equivalent);
- Give advice on current and future levels, trends, sources and characteristics of air pollutants in the UK;
- Provide independent advice and operate in line with the Government's Principles for Scientific Advice and the Code of Practice for Scientific Advisory Committees (CoPSAC).

Expert Committee Members are independent appointments made through open competition, in line with the Office of the Commissioner for Public Appointments (OCPA) guidelines on best practice for making public appointments. Members are expected to act in accord with the principles of public life.

Further information on AQEG can be found on the Group's website at:
https://www.gov.uk/government/policy-advisory-groups/air-quality-expert-group

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Executive Summary

By reviewing the evidential value of Defra compliance monitoring networks the Air Quality Expert Group (AQEG) has demonstrated that the monitoring networks support a wide range of evidential activities beyond their core mandatory reporting function. The UK Government will therefore greatly underestimate the 'true value' of the networks if it estimates their value purely in terms of their primary function. It is clear that the networks:

- underpin Defra assessment of policy and the effectiveness of mitigation measures;
- are fundamental to enabling UK epidemiology and health effects studies;
- support a diverse range of academic research, with hundreds of quantifiable outputs as papers; and
- support business and growth through consulting and planning processes.

Whilst funding is limited, the following relatively small changes to network operation may increase evidential value to data users:

- Investments in enhanced data analysis tools may increase the range of potential users.
- Improved urban meteorological data may increase the value of urban air quality observations.
- Further clustering of observations in supersites and their expansion outside London is likely to enhance their evidential value for research.
- Upgrading of certain key instruments, speedy fault identification, more immediate ratification of data, an increase in particulate matter (PM) speciation and higher frequency data recording are likely to have benefits for health and research evidence.
- Improved visibility of the network infrastructure and its capabilities may open up new dual use evidential applications for Government.

Recommendations

1. The Defra air quality compliance network is of high value to the United Kingdom in that it delivers the evidential needs associated with compliance with a range of European directives and the means to assess the effectiveness of air pollution mitigation policies. The networks have a wide range of external users including the public, academia and business, and support new knowledge creation and economic growth. **A key recommendation is that any valuation or business case for the compliance networks needs to consider the full range of users and outputs**, **and that these users should be engaged in the development and future planning of the network.**

2. The research bibliography indicates a significant use of air quality data to support high impact academic research in the UK relating to health, air pollutant emissions and atmospheric and urban science. Supersites are widely used by researchers to provide data, infrastructure and context for health studies and short-term research observations. **The Air Quality Expert Group (AQEG) recommends that Defra continues to endeavour to co-locate monitors and networks where possible, and that supersites in other major cities outside London be developed**.

3. There is potential to add substantial value to the Defra investment through enhanced co-ordination of supersite monitoring activities between Defra and academic users, and also with the research councils who often fund short-term research activities at these sites. The supersites within the compliance network should be viewed as important shared national resources with multiple roles, and the relevant external user communities should be engaged in discussions about future configurations of the network.

4. For data to be fully exploited they must be freely available and well organised, and include metadata and the information required to assess measurement uncertainties. Defra compliance monitoring data dissemination is well optimised for public users, but use of data may be enhanced through improved ease of access to bulk data holdings for academic and commercial users and with increased detail and accessibility of metadata. More generally, data accessibility requires regular reassessment to ensure that dissemination routes meet evolving Government requirements and keep pace with technological change.

5. **It is recommended that user needs for data access are considered alongside wider national policy initiatives on transparency, open data and the implementation of INSPIRE/SEIS principles (European Commission, 2015) to add further value to existing compliance monitoring data.** Increasing the range of users and value of the dataset may be supported by renewed efforts to increase the visibility of data holdings. Beyond this, there is a need for academic and policy making users of compliance monitoring data to work more closely together to develop a joint roadmap to improve the accessibility and reusability of air quality data, consistent with the Cabinet Office initiatives for transparency and the open data agenda. There is a further need for publishers of air quality data to work together to ensure consistent approaches to web-serviced information are adopted in line with the INSPIRE principles to maximise data interoperability, data access and end user experience to support policy, public information and research.

6. For some scientific and research applications the evidential value of compliance data would be greatly enhanced through the co-measurement and reporting of meteorological parameters. There is a lack of above canopy meteorological measurements in London and other major cities, and an over-reliance on the (often untested) extrapolation of meteorological conditions from a small number of locations where data are easily and freely available. The lack of access to historical Met Office data is considered a constraining factor that limits the extent to which air quality compliance data can be exploited by researchers and business. A case also exists for a limited number of roadside weather stations to be co-located with existing air quality sites for use in particle resuspension and dispersion and inverse modelling studies. **It is recommended that the Met Office and Defra collaborate to deliver the meteorological insight required to exploit the data.**

7. **Higher time resolution data could be delivered at marginal cost.** Collection of air pollution data from certain existing Automatic Urban and Rural Network (AURN) instruments at higher temporal resolution is likely to allow new and innovative use of the measurements to support a range of science and policy needs. Higher time resolution data (such as at 1 minute intervals) are not necessarily required in real time, and can be stored locally and on wider databases at very modest incremental costs. A clear delineation in data products would be required, highlighting that higher time resolution data was for research use rather than compliance monitoring.

8. As ambient concentrations have fallen, the networks for measurement of carbon monoxide (CO) and sulphur dioxide (SO_2) have decreased in scope, and levels are often close to instrument detection limits. Data on these species are however widely exploited in other applications and have great evidential value. **AQEG recommends that Defra considers the introduction of a smaller number of higher precision CO and SO_2 monitors in locations that meet appropriate Defra needs for compliance whilst also supporting the exacting measurement requirements for wider evidential needs**.

9. Further instrument-related recommendations are: **(i) to consider how co-location of monitors may help Defra and the Department of Energy and Climate Change (DECC) generate evidential data on climate and air pollution emissions from sources**, appreciating that many air pollutants are also important climate agents; and **(ii) to examine current measurement technology for particulate composition and consider whether the addition of molecular speciation monitoring at a limited number of locations may aid in particulate matter (PM) source apportionment.**

10. **AQEG has identified that the data and infrastructure of the compliance network may support other Government evidential needs in a highly cost effective way**. These might include the assessment of emerging pollutants, emissions and trends, and planning for events of national importance, including civil contingency. Supporting these wider evidential requirements will require renewed efforts to raise the visibility of the network and its capabilities across Government.

Scope of the Report

In compiling this report, AQEG addressed the following set of questions.

Question 1

What is the current structure of air pollution monitoring in the UK and how are the data made available?

The UK has a comprehensive network for air pollution monitoring that provides the Department for Environment, Food and Rural Affairs (Defra) with evidence of national compliance with a number of EC directives on air quality. The network is configured to provide the greatest density of measurements in those regions where the highest risk of air pollution exceeding Directive limit values coincides with the greatest population densities. The network has been rationalised over the years and continues to evolve dynamically to meet Defra requirements and to reflect changes in the atmosphere and in emissions. The co-location of monitors for different networks at single locations has created a number of ‘supersites’ in the UK. For species such as carbon monoxide, non-methane hydrocarbons and sulphur dioxide, the number of monitoring locations has decreased considerably in recent years as ambient levels of pollution have fallen well below environmental objectives.

Real-time data on certain air pollutants are available via Defra websites and are also retransmitted via various media channels. Historical archived data, including metadata, are made freely accessible to the public through sources such as the Defra website UK-AIR; data from some locations are available on other databases (e.g. the British Atmospheric Data Centre (Natural Environment Research Council) and AirBase (European Environment Agency) which target different user constituencies. Statistics from UK-AIR show a broad user base for compliance monitoring data, including academic research, education, local authority, urban planning and commercial practitioners.

Question 2

How can air quality compliance networks and their data be used to inform research and policy activities in the UK?

Well-organised, quality-assured and freely-available information on atmospheric composition is a key resource that can be used for multiple purposes. Defra compliance data provide a resource that can be used 'stand alone' to support hypothesis-driven research, temporal or spatial trend analysis or exposure assessments. Data can be combined with additional information from co-located measurements, or integrated with models, and can provide long-term context to short-term process studies of air pollution behaviour. Users of air quality data have different requirements, for example needing real-time data or historical datasets, metadata and differing levels of quality assurance/quality control (QA/QC), and these requirements must be considered when designing data dissemination strategies.

Question 3

What scientific or policy outcomes have been generated from the use of compliance data in the past?

Compliance monitoring data underpin a wide range of evidential activities for air quality and air pollution. They support virtually all national research associated with the public health impacts of air pollution, including epidemiological studies, and have a wide range of atmospheric science users in the academic sector. Bibliographic analysis indicates that many hundreds of research papers have been generated from compliance monitoring data, and that the compliance supersites within the Defra network also act as key national research assets. For example, compliance monitoring data have been used to: track pollution from industrial accidents and volcanic eruptions; support Government policy for major events such as the Olympics; inform Defra estimates of national pollution emissions; provide the evidence base for local authority and private sector environmental planning; and support epidemiological studies.

Question 4

How might the evidential value of compliance monitoring activities be further enhanced, for example through improved access to data and data analysis tools, through additional observations or by the realignment of observations?

Significant improvements have been made in increasing the accessibility of data, as reflected in the diversity of users and applications. However, continued attention is required to ensure that web-based data dissemination meets changing Government requirements for openness, whilst also keeping pace with rapid technological change and the emerging developers and users of private sector applications. Openly accessible data require tools for interpretation; further investment in supporting tools for data analysis and handling may increase the number of users exploiting compliance data, and enhance the value that Government, academic, local authority and private sector users may gain from it.

Epidemiological studies of the effects of short-term (e.g. daily) variations in air quality require air pollution datasets with few or no gaps in the ambient measurement time series. Active monitoring of observations and instrument performance in the network is essential to minimise data losses, thus ensuring that the full value of the data for health-related studies can be realised.

One limitation in the wider use of compliance monitoring data is a lack of co-located and/or suitable reference weather data, in conjunction with the challenge of obtaining appropriate free-to-user data from the UK Met Office. The relatively low cost of meteorological instruments and the low cost of data storage provide an opportunity for the addition of meteorological measurements at certain key compliance monitoring sites. There are also opportunities for existing instruments to have their evidential value enhanced through the collection and storage of raw data at higher measurement frequencies (such as at 1 minute intervals). This is not anticipated to add significantly to the cost burden of monitoring.

The compliance networks are constantly reviewed by Defra and have adapted over time, for example by the increased co-location of measurements in many places. The value of air quality data in the UK would however be further enhanced by an increase in the number of multi-species supersites, particularly in large urban centres outside of London, and the creation of triplicate sites that can detect pollution increments, based on geographically-linked rural, urban and traffic (roadside) locations. Improvements in measurement technology offer the opportunity for better source apportionment of particulate matter through the inclusion of measurements of greater numbers of chemical tracers in the compliance network. The inclusion of specific tracers would be highly beneficial for health studies, as would the co-location of PM_{10} and $PM_{2.5}$ monitors (those measuring particulate matter (PM) with diameter less than 10 micrometres and 2.5 micrometres respectively) to facilitate study of the effect of coarse particles.

Question 5

How might compliance monitoring infrastructure or data contribute to other governmental evidence needs?

The compliance dataset provides a key resource for infrastructure and development planning including the permitting of new developments and industries. Access to high quality data for this purpose provides valuable support for economic development.

There is potential for the networks to support policy related to emerging pollutants and pollutant sources, including, but not limited to, shale gas fracking, carbon capture and storage, and manufactured nanomaterials. There is therefore potential for compliance data to contribute further to the evaluation of emissions of pollutants important from both air quality and climate change perspectives. The networks may also provide support for those civil contingencies that have associated releases to the atmosphere, including large industrial accidents and spills, natural hazards such as volcanic events, chemical, biological, radiological or nuclear (CBRN) releases, and biosecurity and the spread of airborne disease.

1 Introduction

1.1 Background and aims

Defra invests significantly in air quality monitoring networks to support compliance reporting against European ambient air quality directives. The largest network is the Automatic Urban and Rural Network, which includes automatic air quality monitoring stations measuring oxides of nitrogen (NO_X), sulphur dioxide (SO_2), ozone (O_3), carbon monoxide (CO) and particles (PM_{10}, $PM_{2.5}$; particulate matter with a diameter of less than 10 micrometres and 2.5 micrometres respectively). Currently the AURN provides high resolution hourly information that can be communicated "rapidly" to the public using a wide range of dissemination means. Other networks in operation include the Polycyclic Aromatic Hydrocarbon (PAH), Toxic Organic Micro Pollutants (TOMPs), Black Carbon, UK Eutrophying and Acidifying Pollutants (UKEAP), Hydrocarbons, and both Urban and Rural Heavy Metals networks, which are either non-automatic or only report data periodically. There are also a number of *ad hoc* networks that are operated under research contracts for individual evidence needs.

Beyond the Defra networks, a small number of other long-term air quality measurement activities also exist, ranging from the instrumented observatories at Weybourne and Auchencorth Moss (some of the measurements made here contribute to the Defra networks), to local authority operated networks. In total around 180 active monitoring sites across the UK contribute to Defra air quality compliance activities, representing a very significant ongoing public investment. Monitoring may be supported directly by Defra or by local authorities whose activities are affiliated to the Defra networks. This latter class of measurement will also meet the quality assurance/quality control (QA/QC) and siting requirements for compliance monitoring. Many other local authority measurement stations exist for air pollutants, but they lie outside the scope of this report.

This report examines the extent to which the current United Kingdom air quality compliance monitoring networks are also used as a source of data and evidence for research and policy development. The report aims to identify instances where compliance monitoring has added value to research activities in Defra's Atmospheric and Industrial Emissions (AIE) Programme, to the research community more generally and to business.

The report aims to make some recommendations for incremental additions to or changes in the operation of networks that would enhance evidential value without compromising compliance functions. In the context of reduced resources and public expenditure, the intention is not to add to the financial costs of air quality monitoring and assessment in the UK but to seek ways in which the multiple goals of compliance with the requirements of European directives, public dissemination and the provision of a robust evidence base for policy and research can be met most cost effectively.

2 The development of compliance monitoring capability in the UK

2.1 Introduction

Air pollution monitoring in the UK has evolved over several decades from small-scale initial investigations on matters that caused nuisance (such as odour) to the development of well-structured networks that respond to specific legislative and research requirements. In 1956 the Clean Air Act was instrumental in setting up one of the first networked approaches to the monitoring of air pollution (for black smoke and sulphur dioxide (SO_2)). Since this time the UK has seen considerable broadening in air quality monitoring activities across a wide variety of pollutants and networks formulated to respond to different aspects of legislation at UK and European levels.

The earliest measurements of pollutants used relatively simple, manual techniques whereby a sample would often be collected at a site and then returned to a laboratory for analysis. This is still a common practice today due to the relative low cost and high reliability of these types of measurements. However, in the 1970s the UK also introduced automatic analysers to the monitoring networks. These had the benefit of lower labour costs and could provide higher temporal resolution (e.g. hourly) and continuous measurements. These continuous measurements became a requirement for regulatory purposes and networks have continued to develop in response to changing legislative requirements over the last few decades.

The evidence base for the annual assessment of compliance is derived from a combination of information from the UK national monitoring networks and the results of modelling assessments. Considerably more monitoring sites would be required across the whole of the UK if monitoring data were to be used as the sole source of information for compliance assessment. The use of models has the added benefits of enabling air quality to be assessed at locations without monitoring sites and providing additional information on source apportionment and the projections required for the development and implementation of air quality plans.

Annex III of the EC Ambient Air Quality Directive (AQD) (2008/50/EC) provides guidance on where ambient air quality should be assessed, applying to both measurements and modelling. The UK is divided into 43 zones and agglomerations for the purpose of air quality management and assessment, as shown in Figure 1 below.

The AQD Annexes are prescriptive and identify how many monitoring sites are needed in each zone and agglomeration and broadly where they should be located. The current network is designed to be compliant with the requirements of Annex V. A relatively complex set of rules governs the required density of measurements, which is a function of both population density and likelihood of air pollution exceedences. This means that different pollutants are measured at different levels of geographic coverage across the UK. In simple terms, the more likely a pollutant is to exceed AQD thresholds, the greater the number of measurements made in the network.

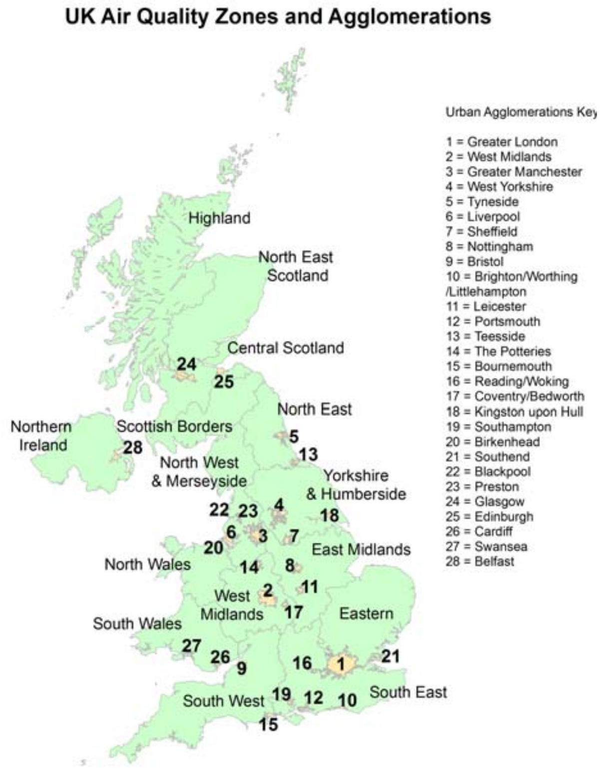

Figure 1: Map of UK air quality zones and agglomerations.

The number of automatic air quality measurement stations contributing to Defra compliance requirements in the UK has grown significantly over time, as shown in Figure 2 since 1972.

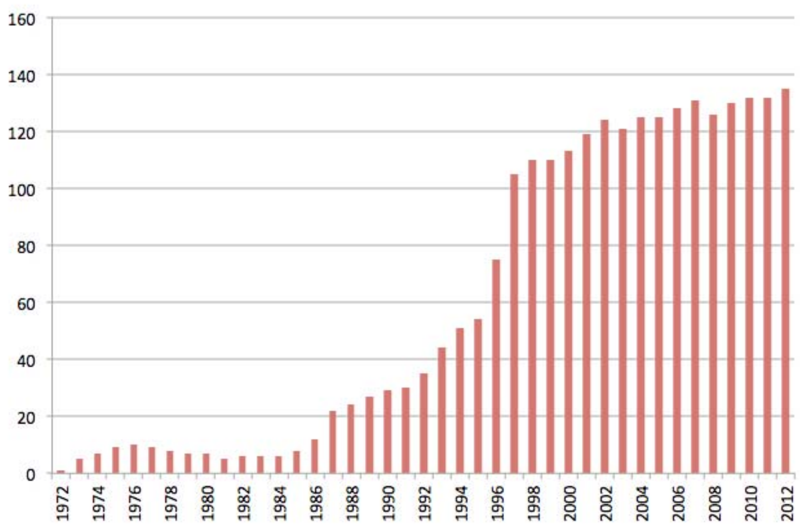

Figure 2: The number of measurement stations within the Automatic Urban and Rural Network (AURN) and affiliated local authority sites. Approximately 40 additional compliance monitoring stations were in operation during 2012 that were not part of the AURN. Other sites for air pollution monitoring exist outside of the Defra compliance networks, for example, those operated by local authorities and for research.

3 Current UK air quality monitoring networks

3.1 Statutory and research networks

The Department for Environment, Food and Rural Affairs (Defra) currently supports a wide range of monitoring activities, some for the purpose of meeting statutory requirements and others for research. In combination, they contribute to the annual Defra reporting for compliance with air quality standards in the UK. Other air pollution monitoring activities are supported by other organisations including local authorities and the Natural Environment Research Council (NERC).

Many Defra networks have been set up along similar lines, although finer nuances exist with respect to the specific locations and methodologies required for each network. Typically a network approach to monitoring requires the following to be in place:

- A Central Management and Co-ordination Unit (CMCU) responsible for the overall management of the infrastructure of the network and day-to-day management of network procedures and operational data/information.
- An independent Quality Assurance and Quality Control Unit (QA/QC Unit) responsible for third party validation of the data.

Additional roles vary from network to network and can include (depending upon geographic coverage):

- appointed Local Site Operators (LSOs) undertaking routine site attendance and dispatch of samples to laboratories;
- Equipment Support Units (ESUs) for the provision of emergency call-out on equipment malfunction and routine service and maintenance;
- an analytical laboratory for the receipt and subsequent analysis of samples; and
- a supplier of calibration gases.

The set-up of a network in this way facilitates the primary objectives of compliance networks, which is to enable an assessment of compliance attainment and provide reliable data for dissemination to the general public. Secondary but important objectives include provision of data for use by scientific and medical researchers and the air quality community in general. Moreover, each network achieves a geographic spread of sampling points across the UK whereby each site is considered to be representative of a specific site type (i.e. rural, suburban, urban). A report describing this process is available on the UK-AIR website (Vincent and Stedman, 2013).

Each compliance network is required to meet fundamental criteria as set out within the relevant European directive, referred to as Data Quality Objectives (DQOs). These take the form of: (i) minimum data capture requirements of 90% coverage within any one year; and (ii) an assessment of the uncertainty of measurement methods (expressed as an expanded uncertainty (W_{CM} (%)). The document *Quality Assurance and Quality Control (QA/QC) Procedures for UK Air Quality Monitoring under 2008/50/EC and 2004/107/EC* details the relevant procedures in place in the various networks and the uncertainty estimates for compliance measurements for comparison with the Data Quality Objectives. Further details can be found on the UK-AIR website (Defra, 2013a).

A more detailed consideration of each of the compliance networks currently reporting monitored data across the UK is provided below and later in this section:

- Automatic Urban and Rural Network (AURN) – reporting compliance with the Ambient Air Quality Directive 2008/50/EC (AQD).
- Non-Automatic and Automatic Hydrocarbon Networks – characterisation of a number of volatile organic compounds (VOCs) with photochemical oxidant forming potential and reporting compliance with the benzene limit value under the AQD.
- Polycyclic Aromatic Hydrocarbon (PAH) Network – reporting compliance with the Fourth Air Quality Daughter Directive (2004/107/EC) including the target value for benzo-[a]-pyrene.
- UK Urban/Industrial Heavy Metals network (previously the Lead, Multi-element and Industrial Metals Networks) – reporting compliance with the Fourth Air Quality Daughter Directive (2004/107/EC) target values and the AQD limit value for lead.
- Rural Metals Network – statutory aspects relating to measurements of concentrations of metals in PM_{10} (arsenic, cadmium, nickel and mercury) and deposition of the same metals at background locations. This network also fulfils a research function.
- Elemental Carbon/Organic Carbon (EC/OC) fraction in $PM_{2.5}$ and ions in $PM_{2.5}$ – reporting compliance with the AQD.

Additional monitoring networks are operated across the UK for the purposes of informing research outcomes, fulfilling international agreements and providing an evidence base to support policy formulation and development. These include:

- European Monitoring and Evaluation Programme (EMEP) – site reporting under the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP)
- Black Carbon Network
- Toxic Organic Micro Pollutants (TOMPs) Network
- UK Eutrophying and Acidifying Pollutants (UKEAP) Network which includes;
  - Precipitation Network (PrecipNet)
  - Rural Nitrogen Dioxide Diffusion Tube Network (NO_2Net).
  - Acid Gas and Aerosol Network (AGANet)
  - National Ammonia Monitoring Network (NAMN).

Table 1 provides a summary of the current monitoring networks documented in the annual report for UK compliance on air quality in the UK. Further information can be found at: http://uk-air.defra.gov.uk/library/annualreport/index.

Table 1: Summary of current Defra monitoring networks for compliance with European air quality directives. Some of the measurements are used as input for modelling for statutory compliance assessment and are marked with *. Other measurements are used to comply with international legally-binding requirements, e.g. UNECE conventions, but have here been classified as research networks.

Network	Statutory or research	Pollutants	Reported averaging period	Number of sites in 2012
Automatic Urban and Rural Network	Statutory	CO, NO_X, NO_2, SO_2, O_3, PM_{10}, $PM_{2.5}$	1 hour[1]	131
UK Urban and Industrial Metals	Statutory	Metals : As, Cd, Co, Cr, Cu, Fe, Hg[p] (Hg in PM_{10}), Hg[t] (total gaseous Hg), Mn, Ni, Pb, Pt, Se, V, Zn	4 weeks	25
Non-Automatic Hydrocarbon	Statutory	benzene	2 weeks	41
Automatic Hydrocarbon	Statutory	range of VOCs	1 hour	4
Polycyclic Aromatic Hydrocarbon (PAH) (Digitel samplers)	Statutory	21 PAH species (and deposition) including benzo[a]pyrene	monthly[2]	32
Toxic Organic Micro Pollutants	Research	range of toxic organics including dioxins and dibenzofurans	quarterly	6
UKEAP: NO_2-Net (rural diffusion tubes)	Research*	NO_2	monthly	24
UKEAP: Acid Gas and Aerosol Network	Research*	NO_3, HCl, HNO_3, HONO, SO_2 gases and SO_4^{2-}, Na^+, Cl^-, Ca^{2+}, Mg^{2+} in aerosol	monthly	30
UKEAP: National Ammonia Monitoring Network	Research*	NH_3 and/or NH_4^+	monthly	58
UKEAP: Precipitation Network	Research	major ions in rainwater	2 weeks	38
European Monitoring and Evaluation Programme	Research and statutory	wide range of parameters relating to air quality, precipitation, meteorology and composition of aerosol in PM_{10} and $PM_{2.5}$	mostly 1 hour	2
Particle Numbers and Concentrations	Research with some statutory functions	total particle number, concentration, size distribution, anions, EC/OC, PM_{10} and $PM_{2.5}$ speciation	various[3]	5
Black Carbon	Research	black carbon	1 hour	14
Acid Waters Monitoring	Research	chemical and biological species in water	monthly for streams;	22

Network	Statutory or research	Pollutants	Reported averaging period	Number of sites in 2012
			quarterly for lakes	
Rural Heavy Metals	Research and statutory	Al, As, Ba, Be, Cd, Co, Cr, Cs, Cu, Fe, Hg, Li, Mn, Mo, Ni, Pb, Rb, Sb, Sc, Se, Sn, Sr, Ti, U, V, W, Zn, total gaseous Hg, reactive Hg and elemental Hg	monthly[4]	11 particulate 14 rainwater

Notes:

1. In addition, daily $PM_{2.5}$ and PM_{10} concentrations are measured by gravimetric techniques at a small number of stations.

2. Air sample collection is daily but samples are aggregated to monthly samples for analysis. PAH concentrations are also measured in rainwater samples collected every four weeks.

3. Total particle number concentration and size distribution (every 15 minutes); EC/OC (daily for PM_{10} and weekly for $PM_{2.5}$); PM_{10} speciation (hourly).

4. Metal concentrations in rainwater are measured monthly, total gaseous mercury concentrations are measured every two weeks and metals in particulates measured weekly. Reactive mercury (Hg), elemental mercury and particulate mercury are measured hourly at Auchencorth Moss.

3.1.1 The Automatic Urban and Rural Network (AURN)

The AURN is currently the largest and most comprehensive automatic national air quality monitoring network in the UK. The most important role of the AURN is to provide accurate air quality monitoring data as required to fulfil the UK Government's statutory reporting obligations under the EU Air Quality Directive 2008/50/EC (AQD). The AURN focuses on measurement of the following pollutants:

- nitrogen dioxide and oxides of nitrogen (NO_2/NO_X)
- particulate matter (PM_{10} and $PM_{2.5}$)
- sulphur dioxide (SO_2)
- carbon monoxide (CO)
- ozone (O_3).

Articles 5 and 9 of the AQD require that pollutant concentrations within each geographic zone and/or agglomeration be compared with the relevant upper and lower assessment thresholds as defined in Annex II of the AQD. Fixed monitoring is used to assess zones / agglomerations where levels of pollution exceed the upper assessment threshold. The minimum number of fixed monitoring stations required is then determined by application of the criteria set out in Annex V of the AQD. This includes criteria relating to the population size within each zone/agglomeration; the existence of point sources; provisions for $PM_{2.5}$ exposure reduction; and the number of monitoring stations for the protection of vegetation in zones other than agglomerations.

An important element of the AQD is the new approach to exposure reduction for $PM_{2.5}$, reflecting the understanding that continued reduction in the concentrations experienced across the wider population is likely to bring about net improvements in health. This contrasts with a focus on compliance with a given target or limit value, which results in measures being directed towards pollution hot spots only. In this regard, the specifications for monitoring in the UK are for one sampling point per million inhabitants summed over agglomerations and additional urban areas in excess of 100,000 persons. The sampling points may coincide with sampling points for other pollutants. Part C of Annex V provides the criteria to be applied for compliance with critical levels for the protection of vegetation in zones not classed as agglomerations. Where existing levels are found to exceed the upper assessment threshold, one monitoring station for every 20,000 km^2 is required. If pollutant levels fall between the lower and upper assessment thresholds, criteria for a monitoring station for every 40,000 km^2 can be applied.

These complex compliance requirements mean the number of monitors for each pollutant vary considerably across the AURN. Carbon monoxide is measured at only seven locations across the UK, reflecting the fact that its ambient concentrations very rarely approach air quality limit values. NO_2 is measured much more widely, at 118 locations (correct at time of writing), reflecting the more widespread potential for exceedence of air quality limits. The geographic coverage of the AURN by different target species is shown in Figure 3.

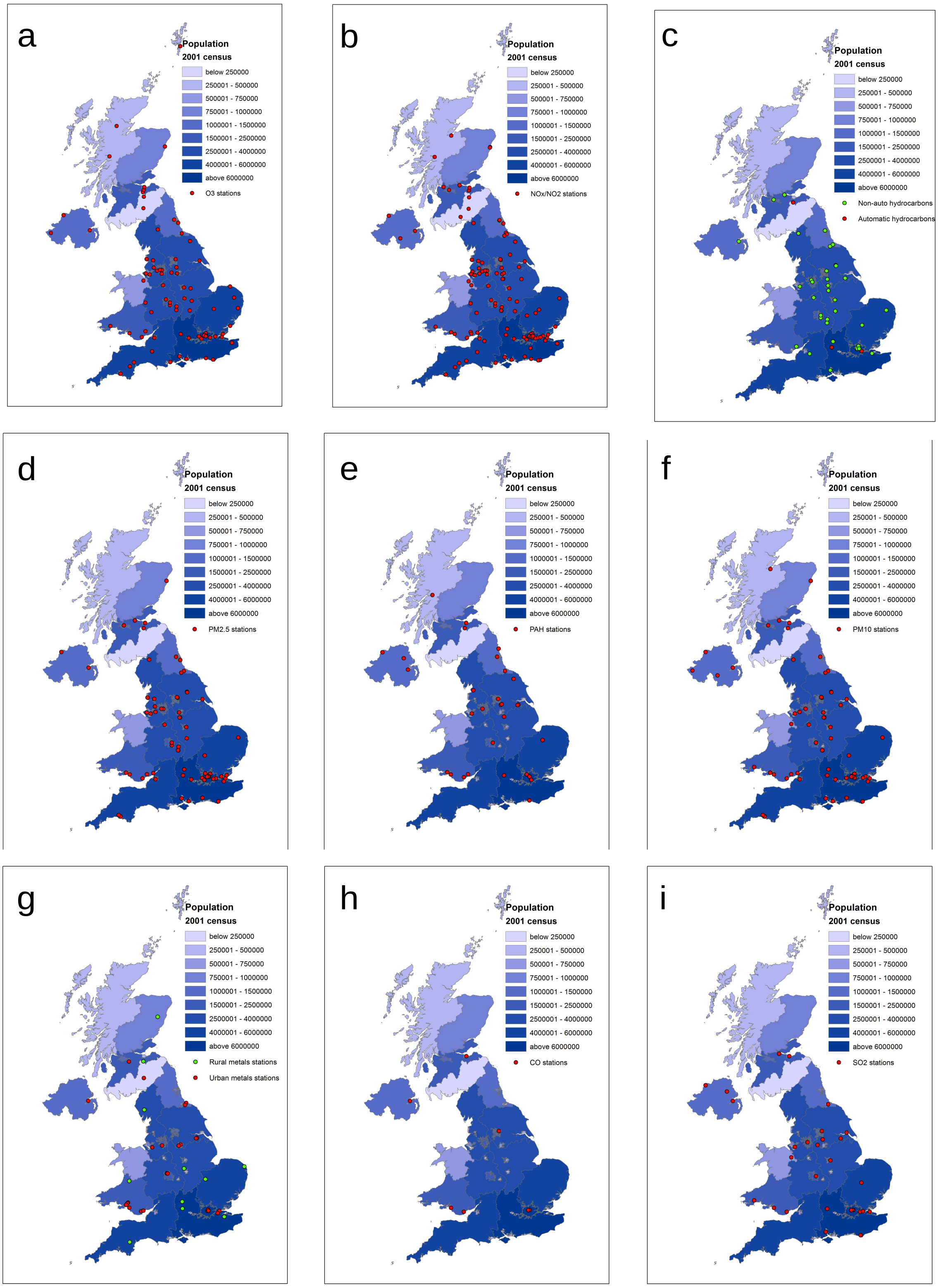

Figure 3: Location of Defra measurement sites (early 2013) and their relation to UK population for: (a) ozone; (b) NO_X/NO_2; (c) hydrocarbons; (d) $PM_{2.5}$; (e) PAHs; (f) PM_{10}; (g) rural and urban metals; (h) CO; and (i) SO_2.

A number of organisations are involved in the day-to-day running of the AURN. The relationship between these organisations, and their functions are shown in Figure 4 (descriptions of each of the functions were provided in earlier sections).

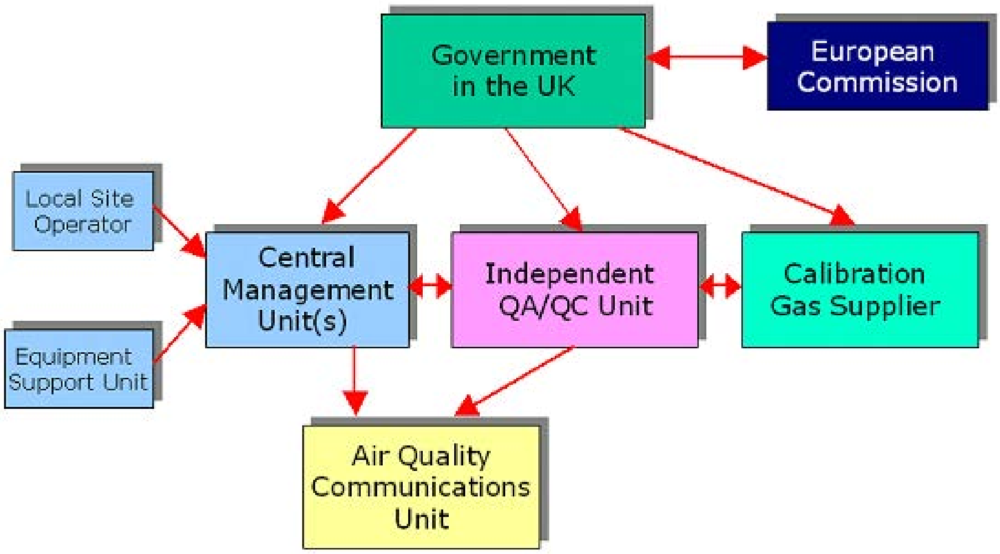

Figure 4: Organisation and management of the AURN.

Dissemination of the data from the AURN takes place via the UK Air Information Resource (UK-AIR) website (DEFRA, 2015a).

3.1.2 UK metals monitoring networks

The UK Urban and Industrial Metals Network is a regulatory air quality monitoring network that fulfils the UK's statutory requirements as set out in the EU Fourth Air Quality Daughter Directive (2004/107/EC) and the Ambient Air Quality Directive. The primary focus is on the monitoring of the mass concentrations of lead (Pb), nickel (Ni), arsenic (As) and cadmium (Cd) in the PM_{10} phase of ambient air. The Rural Heavy Metals Network provides additional information on these metals in rural locations and on concentrations of total gaseous mercury (Hg(v)).

The metals networks have a number of objectives:

- to achieve compliance with monitoring requirements set out in European legislation;
- to provide data to the UK Government and European Commission on the UK's performance against the limit values, target values and data quality objectives described in the relevant legislation; and
- to assess impacts around 'hot spots' of metallic pollution to air, particularly in industrial areas.

In 2012 the UK Urban and Industrial Metals Network comprised 25 monitoring sites around the country (15 in England, 7 in Wales, 2 in Scotland and 1 in Northern Ireland). Ambient concentrations of metals are measured by sampling in the PM_{10} phase of ambient air, onto filters. This is done using Partisol 2000 instruments operating at a calibrated flow rate, nominally of 1 m^3 h^{-1}. This sampling is carried out in accordance with EN 12341:2014 (BSI, 2014). The filters are then returned to the contractor's laboratory where they are analysed to determine the content of various metals in the particulate matter, and thus to produce concentration values for these metals in ambient air according to EN 14902:2005 (BSI, 2005b). Further details can be found in Defra (2013)

Total gaseous mercury is additionally sampled onto adsorption tubes at 13 of these sites (7 in England, 3 in Wales, 2 in Scotland and 1 in Northern Ireland). These adsorption tubes are analysed at the contractor's laboratory according to EN 15852:2010 (BSI, 2010) to produce concentration values for total gaseous mercury in ambient air. Weekly concentration data are produced for metals in PM_{10} at six locations and for mercury vapour at three locations. All other stations produce data averaged over four-weekly periods.

The Rural Heavy Metals Network measures metal concentrations in PM_{10} (at 11 rural sites) and concentrations in rain water (at 14 rural sites, the same 11 sites with 3 additional rainwater only sites). The concentration fields are combined with local meteorological data (rainfall, etc.) to calculate values for wet deposition (from rain and snow, etc.), dry deposition (from dust settling, etc.) and cloud deposition (condensation of cloud droplets). A total of 27 different metals are analysed as follows: aluminium (Al), arsenic (As), antimony (Sb), barium (Ba), beryllium (Be), cadmium (Cd), caesium (Cs), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), lithium (Li), manganese (Mn), mercury (Hg), molybdenum (Mo), nickel (Ni), rubidium (Rb), scandium (Sc), selenium (Se), strontium (Sr), tin (Sn), titanium (Ti), tungsten (W), uranium (U), vanadium (V) and zinc (Zn). Continuous mercury concentrations are also measured at the two EMEP supersites within the Network (Auchencorth Moss and Harwell) fulfilling statutory mercury monitoring requirements under the Fourth Air Quality Daughter Directive.

In the Rural Heavy Metals Network aerosol is sampled using Thermo Partisol Plus 2025 sequential PM_{10} samplers that are operated at a flow rate of 1 m^3 h^{-1} using 47 mm diameter nitrocellulose filters; the air sampling period is 1 week. Bulk collectors, bottle and funnel type, are deployed within the deposition network for the collection of bulk precipitation. Mercury in air is sampled using an integrated sampler using the gold amalgamation technique. A small pump pulls air at about 25 ml min^{-1} through two sequential traps containing gold-coated sand, onto which the mercury adsorbs by amalgamation.

With the exception of mercury, all metals in the Rural Heavy Metals Network are analysed using inductively coupled plasma mass spectrometry (ICP-MS). Mercury in precipitation is determined by atomic fluorescence spectrometry (AFS) using a PS Analytical Galahad detector employing pre-concentration of mercury on a gold trap to increase instrument sensitivity. Mercury in air is analysed using a PS Analytical Millennium Merlin analyser.

3.1.3 Hydrocarbon networks

Two networks exist for making ambient measurements of non-methane hydrocarbons (NMHCs), one automatic and one non-automatic. Each network monitors a different range of hydrocarbons with different time integrations.

Automatic Hydrocarbon Network: The two main aims of this measurement network are: (i) to assess ambient concentrations of a range of volatile organic compounds (VOCs) with significant photochemical oxidant forming potential; and (ii) to measure benzene for comparison with the

AQD Limit Value and UK Air Quality Objectives and 1,3-butadiene for comparison with the UK Air Quality Objectives.

The Network consists of four sites located at Harwell, London Eltham, London Marylebone Road and Auchencorth Moss. Automatic hourly measurements of a range of hydrocarbon species (including all the ozone precursor species specified in Annex X of the AQD except formaldehyde and total non-methane hydrocarbons) are made at all four sites using automated pumped sampling with *in situ* gas chromatography.

Measurements from London Eltham are reported to the European Commission, satisfying requirements under the AQD for monitoring photochemical ozone precursors. Data for other sites are reported under the European Community Exchange of Information programme. Corresponding benzene and 1,3-butadiene data are used for comparison with the UK Air Quality Objectives, whilst benzene data are reported to the European Commission to fulfil the requirements of the AQD.

Hourly benzene and 1,3-butadiene data from all sites are reported to the public, although typically with a time delay of around 3 months, through the website UK-AIR.

Non-Automatic Hydrocarbon Network: In this network of 37 sites, ambient concentrations of benzene are measured by the CEN standard method (BSI, 2005a), which involves pumping air through an adsorption tube to trap the compound, which is later analysed in a laboratory. The Network monitors compliance with the AQD Limit Value for benzene. All sites in the Non-Automatic Hydrocarbon Network are co-located with AURN sites.

3.1.4 Polycyclic Aromatic Hydrocarbon (PAH) Network

The PAH Network monitors compliance with the Fourth Air Quality Daughter Directive target value for benzo[a]pyrene and provides data on a range of other PAHs. The Network uses the PM_{10} Digitel sampler. Ambient air is sampled through glass fibre filters and polyurethane foam pads (PUFs), which capture the PAH compounds in the particulate and gas phases respectively for later analysis in a laboratory. In 2012 there were 32 sites in the Network; at all stations particulate samples of the PM_{10} fraction in air are taken using the Digitel samplers on filters with a sampling period of 24 hours. These samples are bulked into groups representing calendar months for analysis. At two locations, Auchencorth Moss and Harwell, samples of the PM_{10} fraction and the vapour phase are taken using Digitel samplers with automatic filter and PUF changers. These samples are collected over 24 hours with 72 hours between the beginning of one sampling period and the next. These samples are also bulked into groups representing calendar months for analysis. Deposition samples are taken fortnightly at two network stations (Auchencorth Moss and Harwell) with each sample collected over 14 days. The samples are bulked into groups representing a four-week time period for analysis. Sampling is in accordance with EN 15980:2011 (BSI, 2011).

Following sampling, all filters, PUFs and deposition gauges are returned to the contractor's laboratory. Analysis takes place according to EN 15549:2008 for particulate and vapour phase samples and at an external laboratory for deposition samples according to EN 15980:2011 (BSI, 2011). All analysis is accredited by UKAS to ISO 17025:2005 (ISO, 2005).

3.1.5 EMEP

The European Monitoring and Evaluation Programme (EMEP) was set up by EU Member States under the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP) to provide governments with quality assured scientific information on air pollutants. In the UK there are two EMEP supersites at Auchencorth Moss in Lothian (representing the north of the UK) and at Harwell in Oxfordshire (representing the south). A very wide range of measurements is taken at these sites, some are used for compliance monitoring, others for research, and this information is supplemented by data from other UK networks which are co-located. Monitoring includes:

- hourly meteorological data
- metallic elements in PM_{10} and precipitation
- deposition of inorganic ions
- trace gases (ozone, NO_X and SO_2)
- black carbon, organic carbon (OC) and elemental carbon (EC)
- ammonia
- daily and hourly PM_{10} and $PM_{2.5}$ (by mass)
- volatile organic compounds
- PAHs in PM_{10} and rainwater.

3.1.6 Research council monitoring activity

The primary funder of environmental science research in the UK is the Natural Environment Research Council (NERC). It supports strategic research programmes, discovery science or 'blue sky' research, and a range of long-term 'National Capability' science and infrastructure. Previous NERC strategies have specifically referenced air pollution as a research topic and evidence need. The new 2013-18 strategy is more general in nature, highlighting securing natural resources, building resilience to natural hazards and managing environmental change as the key research foci. It is therefore difficult to accurately estimate NERC investment in air quality science, and in measurements more specifically, due to blurring across the scientific descriptors used to categorise research. A reasonable estimate of NERC investment in air quality measurement and related activities would be in the range £2-4 million per year.

The majority of NERC activity in air quality monitoring is associated with short-term process studies. These studies typically span periods of one month, but exceptionally may last for one to two years. Notable community experiments on measuring urban air quality, where much of the UK university expertise has been mobilised, include the PUMA experiments during 1999, TORCH in 2003/04, REPARTEE in 2006, DAPPLE in 2003/04 and 2007/08, and ClearfLo in 2011/12. Such community experiments are relatively infrequent.

NERC monitoring brings together research grade measurement technology to provide comprehensive descriptions of air quality processes for comparison with models. Whilst the experiments are typically short in time, they do allow long-term compliance monitoring approaches at AURN locations to be compared with emerging technologies. The Engineering and Physical Sciences Research Council (EPSRC) and NERC have also funded technology demonstration projects of relevance to air quality, including sensor networks in London (MESSAGE project) and around Heathrow airport.

A more limited number of longer-term air quality measurements is made through NERC research centres. NERC centres have a continuing mandate to undertake research and maintain national capability for the UK. Two research centres are relevant to air quality monitoring: the Centre for Ecology and Hydrology (CEH) and the National Centre for Atmospheric Science (NCAS). These Centres have engaged full time research staff on air quality and atmospheric chemistry research, although much of this is directed towards science outside the UK.

Whilst the atmospheric monitoring activities of both NERC centres are global in view, there are some key intersections of relevance to UK air quality compliance monitoring. CEH operates the large EMEP supersite at Auchencorth Moss in Scotland, which has contributed over many years to air quality compliance, with support from a range of funders including NERC, the EU and Defra. CEH also operates a number of long-term measurement sites used for the assessment of the atmospheric deposition of a number of species.

NCAS supports long-term air pollution measurements in the UK at the Weybourne Atmospheric Observatory on the north Norfolk coast; ozone measurement at this location contribute to Defra networks. NCAS also supports long-term measurements of O_3 and CO at the Science and Technology Facilities Council (STFC) Chilbolton Observatory in rural Hampshire, co-locating air quality observations with the UK's largest weather radar. The NERC centres are currently working together to provide a long-term assessment of air pollution emissions (PM, CO, NO, NO_2, greenhouse gases (GHGs)) from central London using an observatory at the top of the BT Tower. This activity began in 2010 and is currently funded by the NERC ClearfLo strategic research programme, but its long-term future is not clear.

In general terms NERC long-term air quality measurements are made in cases where a strategic scientific challenge can only be answered through making such observations. The data are not used generally for compliance purposes, although the co-location of research measurements with compliance observations has been of benefit in improving science outcomes. This is expanded on in later sections associated with measurement clustering.

3.2 Co-location of observations

The preceding description of the various compliance monitoring networks illustrates how legislation has evolved and the requirements for monitoring have been implemented over time. Network designs (pollutants monitored, site location, etc.) have emerged as an inherent part of dealing with the specific requirements of the separate statutes.

The design requirements for the compliance monitoring networks are well prescribed in accordance with population size, zones and agglomerations, and compliance with the upper and lower assessment thresholds and long-term objectives enshrined in legislation. Networks have been integrated and stations co-located where there is opportunity to do so. For the monitoring of metals and PAHs, stand-alone monitoring stations have been specifically established to provide information on industrial installations.

There is, in practice, some significant degree of clustering of monitoring activities for different pollutants into a smaller number of multi-parameter locations. Such a rationalisation has both evidential and economic benefits. Figure 5 shows monitoring sites in the UK scaled by the number of compliance networks operating at each location. Monitoring locations range from those determining only a single parameter through to so-called supersites measuring a wide range of different pollutants.

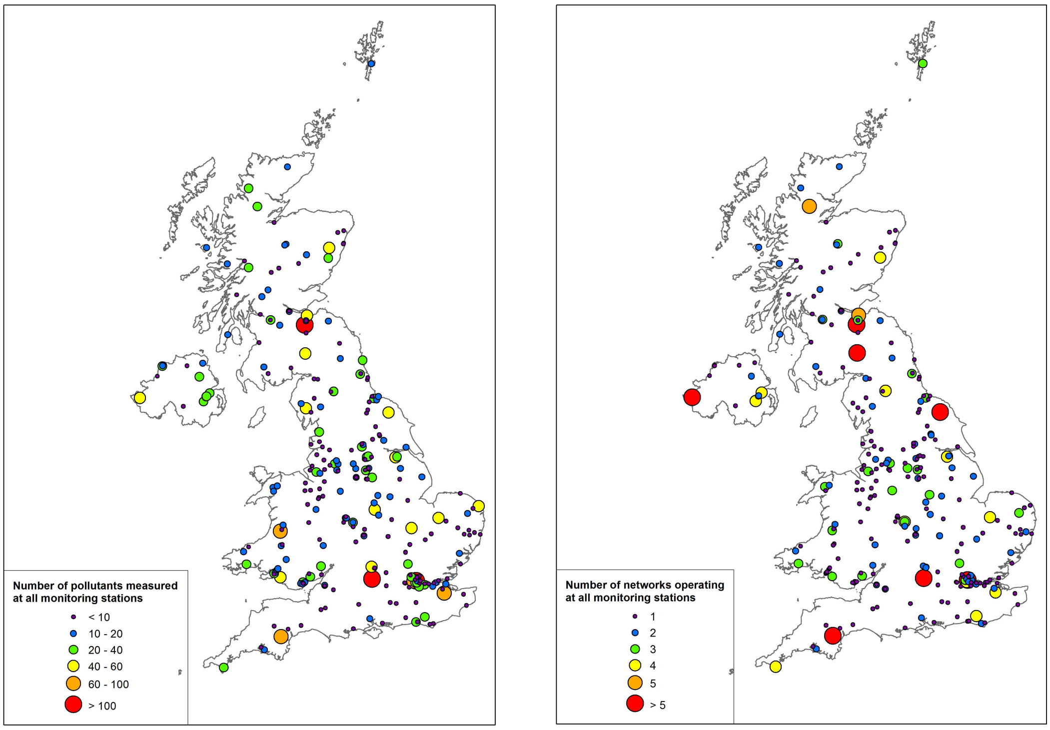

Figure 5: Left: Current UK air pollution monitoring network locations scaled by the number of different pollutant networks operating at an individual site. Right: Measurements scaled by the number of different individual pollutants measured at each site (note this is skewed to those networks that monitor large numbers of species, such as PAHs and metals).

In most cases straightforward rationalisation of network design into more clustered locations has been achieved. It is worth noting that the intersection of compliance monitoring and short-term research activities in air quality tends to occur at those highly instrumented locations where many parameters are now measured simultaneously. This is expanded on in the later section on bibliographic reporting of data usage. The major supersites used widely for research activities are at London Marylebone Road, Harwell and Auchencorth Moss, and essentially span the extremes of air pollution exposure in the UK, from roadside to remote rural background via rural. Around London the density of monitoring locations also provides opportunities for the comparison of upwind, urban and downwind air pollution, which is very useful for determining the urban increment in pollution and for evaluation of emissions.

3.3 Using monitoring data for compliance and research

3.3.1 Introduction

Defra and the devolved administrations are the primary customers and users of compliance monitoring data, for national reporting purposes and to aid with the development of national and European policy.

Compliance monitoring data are also widely used by local authorities to assist with delivering their Local Air Quality Management (LAQM) responsibilities, and by local authorities, planners and consultants in planning applications, environmental impact assessments (EIAs) and development control. The UK’s compliance monitoring stations may not provide the complete picture required for an EIA or LAQM report, but they do provide a reliable and robust baseline against which shorter-term local studies can be benchmarked and scaled to give the best value. Good examples are in the use of compliance monitoring stations to provide local bias adjustment factors for diffusion tube monitoring studies, and to provide data for annualising short-term monitoring results as described in the Local Air Quality Management Technical Guidance (Defra, 2009).

Monitoring data, and the modelling studies based on these data, are used to support epidemiological studies on the health effects of air pollution, and to assess the health burden air pollution imposes on the population; data users include the Department of Health, agencies such as Public Health England and academic researchers. This important use of compliance monitoring data informs the standards and advice that are developed for air pollutants, which in turn feeds back into policy at national and European levels. Recent examples of the use of compliance monitoring data for such policy purposes include the 2011 *Review of the UK Air Quality Index* by the Committee on the Medical Effects of Air Pollutants (COMEAP, 2011)), and the development of a health indicator for the fraction of mortality attributable to particulate air pollution, included in the Public Health Outcomes Framework for England (PHE, n.d).

Compliance data are also used for external academic research purposes and for science that informs Defra on emerging issues to support policy. In some cases new scientific breakthroughs in the field of air quality and atmospheric science are made using data from the compliance networks. For example, the first identification of increasing primary NO_2 came from re-analysis of AURN NO_2 observations (Carslaw *et al*., 2011). Network NO_2 measurements when analysed with respect to roadside trends showed a clear flattening of NO_2 concentrations when compared to the reduction expected from emission inventories.

Whilst many anecdotal examples show compliance data being used to support other evidential needs, there is no systematic means by which this information is collected, since data are publically available and free download does not require user registration. Historically no obligation has existed on the data user to inform Defra of data use. Defra and devolved administration data have recently moved to being published under the Open Government Licence (OGL) framework (The National Archives, n.d), which includes a requirement for users to acknowledge information sources and will thus improve the tracking of data users. A data policy is now outlined on the UK-AIR and National Atmospheric Emissions Inventory (NAEI) websites (Defra, 2013b). There are also developments in the publishing of data via the issuance of a Digital Object Identifier (DOI) and/or Unique Resource Indicator (URI); such routes may also aid in the future tracking of data usage, since they provide means for users to reference the originating material. The most accessible way of assessing the use of compliance data by academia is to search the research bibliography; this is examined in later sections.

The latest up-to-date provisional data from compliance monitoring stations are frequently used and viewed by members of the general public through websites such as UK-AIR, in messaging and alert services, and increasingly through delivery to applications for smart phones and tablet devices. In a typical month the UK-AIR website services 20-25,000 visitors with a further 5-10,000 visitors to the equivalent devolved administration air quality websites. A large proportion of these visitors are likely to be members of the public who can therefore also be considered as important data users. The public use of historical air quality data for general interest, personal health decision making and so on falls outside of the scope of this report.

Further analysis and breakdown of the users of the UK-AIR website are provided in Section 4 of this report.

3.3.2 EMEP data exploitation

The EMEP monitoring network emerged from measurement activities associated with the UNECE Convention on Long-range Transboundary Air Pollution. The main objective of EMEP is to provide governments with information on the deposition and concentration of air pollutants, as well as on the quantity and significance of the long-range transmission of air pollutants and their fluxes across boundaries (Tørseth *et al.,* 2012). Although EMEP data are not in a strict sense collected for compliance purposes, the UK is a signatory to an agreement to participate in the programme through the contribution of monitoring data. EMEP observations include measurements of species linked to acidification and eutrophication, photochemical oxidants, heavy metals, persistent organic pollutants and particulate matter, and the multiple uses of data from this network are informative when considering the uses of UK compliance network information.

EMEP operates primarily multi-species observatories – or supersites – across Europe and many of these locations have data records stretching back over more than 40 years. Two classes of supersite exist: Level 1, which are broadly similar to AURN locations, and Level 2, which have a greater degree of chemical and physical speciation. Although the network of stations is generally well equipped to monitor a range of species, there isn't a uniform distribution of instrumentation. Ozone is measured at more than 120 locations in the EMEP network, whereas VOCs are measured at less than 15.

There has been widespread use of EMEP monitoring data to inform on trends in various pollutants across the European region. This has been recently reviewed by Torseth *et al.* More than 30 separate papers have been published in the last 15 years reporting trends in virtually all the major classes of air pollutants, although the uncertainties in these trend assessments are often impacted by the density of the network and measurement difficulties.

Although not explicitly identified in the review of Torseth *et al.*, it seems reasonable that the data have been so widely used for trend analysis because the network measurements have good academic visibility, common QA/QC traceability and an open data dissemination policy. The data have standardised data collection methodologies and archiving, with good metadata and supporting meteorological observations. Most of these are characteristics that can also be ascribed to the UK compliance monitoring data, but it is still useful to consider EMEP as a model of what can be achieved in terms of widespread academic use of routine air pollution monitoring information.

3.3.3 Research bibliography

This section aims to find evidence for the use of compliance monitoring activity in other research activities, through the citation of datasets or monitoring activities in peer-reviewed publications. The Web of Science database (Thomson Reuters, 2015) has been used to provide a means of identifying users of UK compliance monitoring data in research publications. The database itself is limited to ISI (Institute for Scientific Information) listed journals, and does not cover 'grey' literature such as national or European position papers, meeting or project reports or indeed UK Government/Defra publications themselves. The database is searchable in a range of different ways, most useful here being a search of the research funder, key words, and abstract, although full text searching is not available.

A challenge in searching for information on the research use of air quality compliance data is that there is no single universal term or acronym used to describe the originating measurement activity. Searching for the exact phrase “Automatic Urban and Rural Network” OR “Defra” in funding text (i.e. acknowledgements) AND "air" in topic yields (with some journal filtering) some 63 unique papers. Some of these papers are related to EMEP and Nitroeurope activities, as well as other Defra-funded programmes.

Using other search terms (e.g. such as "air quality", "network", etc.) returns many papers that are definitely not related to Defra compliance network data, but that cannot be filtered out by any obvious sorting or adjustment of search terms. Alternatively, searching for more specific network names can yield very few papers (10 or less).

Whilst most academic papers using Defra compliance network data have UK authors, papers found on the Web of Science database from overseas researchers have used AURN data (for example, a study on extreme values of ozone; Quintela-del-Rio and Francisco-Fernandez (2011)), but have not included obvious links to Defra in the publication. This suggests that the accessibility of UK data makes them useful to researchers and that other countries may not make their data as available. Compliance and other data specified within the Exchange of Information Decision (97/101/EC) should be available for all Member States in AirBase.

Searching instead by geographic location can sometimes be informative: a Science Direct search for “Marylebone Road” and “air pollution” gives 92 articles and for “air quality” 126 articles. As a search term, location is therefore far more effective than Defra or network names such as AURN. Since 1999, publications including some contribution from Defra measurements at Marylebone Road have averaged eight a year. “Harwell” and “air quality” gives 361 papers since 1993, that is on average 10 publications a year – a remarkable research return on investment. “Auchencorth Moss” and “air quality” gives 13 articles with the earliest being from 2002, although a much larger number of articles is found if "air quality" is replaced with "atmospheric" or "deposition" as search terms.

Such a search has limitations in capturing health-related studies. In many cases epidemiological studies may reference modelling activities that use compliance data, but will not refer back directly to the measurements themselves. In this respect the analysis is likely to be an underestimate of activity.

In combination the larger supersite locations in the UK compliance monitoring network have therefore historically made a very significant contribution to academic research in the field. The evidence of extensive research use of compliance data is perhaps not a surprise, although the relative volume of academic material that uses supersites versus research that uses data from the AURN as a whole perhaps is.

Three broad conclusions can be drawn from this brief bibliometric exercise:

1. Without a historical requirement to make reference to the originating data or to Defra, or the universal adoption of a single searchable term to describe UK compliance monitoring activity, it has been difficult to track the true research and evidential use of data via academic or knowledge databases, even though that exploitation is clearly taking place. The decision to release data under the OGL and the use of DOIs or URIs may improve the position in the future. Registration to access data may significantly improve traceability of use, whilst not necessarily creating any onerous barriers to users.

2. Accepting the imperfections of search terms, a conclusion is that the use of compliance datasets *as a whole,* for example exploiting the spatial resolution afforded by the network, is not widespread, but that there is substantial academic and research output that uses information from the multi-species supersite locations.

3. Supersites within the compliance monitoring network have over many years made an important contribution to UK academic outputs in air pollution science. However, there is little co-ordination in terms of observations or data policy between Defra, academic institutions or the research councils.

Defra network locations also on occasion provide a supporting infrastructure for atmospheric observations hosting third party instruments from academic users that are installed alongside network instruments for defined periods of time. The value of the network infrastructure, as opposed to the data themselves, may not necessarily always be captured in the bibliography when research is simply co-located with compliance monitoring activities. It is however valuable and highly cost effective. Data accessibility issues are discussed more widely in the next section.

3.3.4 Recommendations

The research bibliography indicates a significant use of supersite air quality data to support academic research in the UK, and supersites are often used by researchers to provide infrastructure and context for short-term research observations. There is scope for improved co-ordination of supersite monitoring activity between Defra, academic users and the research councils who often fund short-term research activities at these sites. It may be useful to consider air quality UK supersites as shared national resources with multiple roles, such that the academic user base and research councils can influence how those locations develop and are operated.

4 Accessibility of data

4.1 Accessing air quality data

4.1.1 Defra air quality data

Defra's 2013 *Guide to UK Air Information Resources* (Defra, 2013c) summarises the main places where UK air quality data can be accessed. The UK-AIR website (Defra, 2015a) remains the primary access point for air quality compliance monitoring data for the UK and includes a range of ways of accessing the data for different user groups, such as:

- Real-time latest data summaries and interactive maps for public users (Defra, 2015b; 2015c; and 2015d).
- A downloadable data archive for access to primary measured data and calculated statistics (Defra, 2015e).
- Associated "sign-up" services to follow data on UK-AIR Twitter, by hourly or daily email updates, RSS feeds or through smartphone apps such as the Ricardo-AEA uBreathe app.

Most of these services are well established but have not been extensively tested with UK-AIR user groups to identify that they best meet their needs.

Analysis of recent use (2012/13) of the UK-AIR website using Google Analytics shows that:

- Most users (217,785) accessed the website by desktop computer, although access by mobile phone (21,168) and by tablet device (10,867) were also popular.
- Users viewed an average of 5 different pages during their visit.
- 36% of the people visiting the site have visited previously, while the remaining 64% were first-time visitors.
- Only 63% accessed the website from the UK, with a significant number of visitors from India and the United States.
- 21% of the visits during the year were 3 minutes or longer in duration. However, the majority of the visits (58%) were less than 10 seconds in duration.

Table 2 indicates the most popular website pages accessed on the UK-AIR database. Number 10 on the list is an example of an innovative automated data scraping process which has been set up by a particular user to re-use the same database query to extract the latest data for all monitoring stations every hour. This is a commendable but inefficient approach, which should be replaced by more open data and web service access routes.

Table 2: Most popular website pages accessed on UK-AIR.

Number	Page	% Pageviews
1	Home Page	8.9%
2	/air-pollution/effects	6.1%
3	/interactive-map	3.6%
4	/data/data_selector	3.5%
5	/data/	2.1%
6	/latest/	2.1%
7	/forecasting/	1.9%
8	/air-pollution/	1.7%
9	/networks/	1.5%
10	/data/data_selector?q=36286	1.4%

The top 1,000 users during the year have been reviewed, but most cannot be assigned to particular sectors or industries. Of those users that can be traced, the largest sector is universities, followed by local authorities, environmental consultants, government agencies, schools, banking and media, industry and charities.

4.1.2 European air quality data – AirBase

AirBase is a European air quality database maintained by the European Environment Agency (EEA) through its European Topic Centre for Air Pollution and Climate Change Mitigation (ETC/ACM). It contains air quality monitoring data and information submitted by participating countries throughout Europe. The air quality database consists of a multi-annual time series of air quality measurement data and statistics for a number of air pollutants. It also contains meta-information on the monitoring networks involved, their stations and their measurements. Geographically the database covers all EU Member States, EEA member countries and some EEA collaborating countries. The EU Member States are bound under Decision 97/101/EC to engage in a reciprocal exchange of information (EoI) on ambient air quality. The EEA engages with its member and collaborating countries to collect the information included in the EoI Decision, including all compliance monitoring data. Users of AirBase are not tracked, however they may form an additional user constituency not fully captured in this report.

4.2 Emerging policy drivers and user needs

It is well recognised that the diverse users of compliance monitoring data do not necessarily all have the same requirements for data access, and some users are now opting to move to a service-based approach with a new demand for automated, web-based information. In addition, Defra has regulatory drivers to meet in the INSPIRE Directive (2007/2/EC) which requires member States to report ambient air quality data to Europe electronically (e-reporting) for both the Ambient Air Quality Directive (AQD) and its Fourth Daughter Directive. In 2010, with these drivers on the horizon, Defra commissioned two complementary studies to evaluate the future of Defra air quality data and information services:

- A scoping study by Monteith et al (2010) investigated the feasibility of a data integration process to optimise access to air quality data and other supporting datasets. The study sought to identify the datasets and tools to support air quality users at all levels and aimed to align these with emergent policy initiatives relating to the EU's Shared Environmental Information System (SEIS)(European Commission, 2014) and INSPIRE, (European Commission, 2015) and to the UK Government's own transparency agenda (Cabinet Office, 2014).

- A review of Defra’s arrangements on the provision of air quality information to the public (Dore et al, 2010) and research communities focused largely on the Air Quality Archive but also extended to a basic assessment of Defra’s approach to air quality communications in general.

The outputs of these studies briefly summarised the key users and their general needs from UK network air quality data as shown in Table 3.

Table 3: Major classes of user of Defra compliance air quality data.

User	Use	Requirements	Metadata	Meteorology	QC level
Defra	Compliance	Real-time and historical data	Yes	Sometimes	High
Defra, Met Office, consultants, others	Forecasting services	Real-time data and historical data	No	Yes	Medium
Public	Information	Real-time data	No	No	Basic
Local authority, planning consultants	Evidence	Historical data	Yes	Sometimes	Medium
Academic users, including health research	Evidence	Historical data	Yes	Yes	High
Schools and higher education	Teaching	Historical data	Yes	Possibly	Medium
Campaigning bodies, e.g. Green Party, Clean Air for London, etc.	Evidence	Historical data	Yes	No	Medium

These studies also led to the following recommendations:

- Catalogue datasets to make them discoverable to external users, for example, so that they are returned when a user searches by network, location, pollutant, time period and so on.
- Improve data presentation, e.g. through GIS tools, interactive maps, metadata and data selector tools.
- Standardise definitions, vocabulary and data formats.
- Aim for service-orientated architecture.
- Review user needs analysis for air quality and related data.
- Restructure UK-AIR into a more complete Air Quality Information Hub.
- Ensure the Air Quality Archive remains an invaluable resource, principally for data access.
- Maintain on-going services to meet Directive requirements whilst more actively considering the requirements of other users.

Since the 2010 studies, the air quality data landscape has continued to evolve. This has largely been driven by the aforementioned regulatory obligations but the Cabinet Office's transparency and open data agenda has become increasingly important.

In response to these drivers and increased demand for machine accessible and readable data formats hosted on the web, Defra commissioned a new study in 2013 to inform on how its future web data services should be implemented in a prioritised way. The objectives of the 2013 study – the "Defra Air Quality: Open Data Roadmap" (Ricardo-AEA, 2015) – were to:

- identify user requirements;
- identify policy framework requirements including European Air Quality e-Reporting (EEA, 2014), INSPIRE (European Commission, 2015) and the Government Digital Service (Government Digital Service, 2015);
- recommend system architecture for Defra's systems; and
- recommend consistent and interoperable approaches for publishing air quality data, for example consistent metadata, file headers, descriptors and so on.

This study has drawn out the changes that need to be implemented to allow Defra's air quality data to be published to meet the requirements of the regulatory drivers as well as the needs of current and future users. As part of this work, core users of existing UK-AIR data services were consulted to identify their current and future requirements. Initial feedback from a questionnaire and workshop, using tools and guidance provided by the Government Digital Service for the development of government information services, formed part of the consultation process and identified core data user stories; these are summarised in Table 4.

Table 4: Core user stories for Defra air quality data.

Actors	Narratives	Goals
Those responsible for implementing INSPIRE for air quality	Require services which respond to legal/policy obligations	Delivery of services that meet the legal/policy obligations and supporting opportunities for businesses/service providers
Those responsible for co-ordinating response to domestic and regional policy	Require services that provide access to central and local data sources	Delivery of high quality and timely information and advice on air quality to the public
Consultants delivering client needs with air quality data	Require services that deliver data in time resolutions appropriate to client needs	Delivery according to the needs of clients
Data providers – network owner (funding authority) – network operator – data publisher/manager	Require services that allow for the checking of consistency of the data provided by UK-AIR systems	To ensure that the air quality information in UK-AIR is accurate and of high quality
Researchers publishing scientific papers	Require services that deliver data in time resolutions that support research needs for modelling and monitoring	Delivery of quality scientific research to advance understanding, policy and improve the environment
Independent developers of apps and websites	Require access to real-time air quality data in simple formats (e.g. JSON)	Easily combine air quality data with other data to create innovative information apps and products

4.3 Improving data access and usability

In response to the above studies, Defra is developing service-orientated architecture to meet user needs and the statutory requirements of the INSPIRE Directive for discovery, view and download of data via services (European Commission, 2015). In addition, the work on e-reporting and INSPIRE has led to significant developments in the availability of metadata and Defra has developed a number of tools and initiatives to improve access to the air quality data.

Defra has developed a searchable catalogue of air quality and emissions datasets on UK-AIR (Defra, n.d.). Information about the datasets (metadata), such as keywords, location covered, website link, responsible organisation and contact details, have been collated and stored in an INSPIRE-compliant form. The metadata conform to the UK GEMINI2 standard (AGI, 2012). In future the UK-AIR catalogue will publish these metadata on data.gov.uk to make the datasets accessible to a wider audience. The UK-AIR catalogue has been developed adhering to the INSPIRE principles that data should be collected only once and kept where it can be maintained most effectively, and that information from different sources should be seamless and made available in a form to share with many users and applications.

UK-AIR and other services are increasingly publishing on-line data analysis tools making use of open data and open-source technology to add value to the underlying data and make the data more accessible. Openair provides free, open-source and innovative tools to analyse, interpret and understand air pollution data using R, a free and open-source programming language designed for the analysis of data. The Openair data analysis tools (Defra, n.d.) on UK-AIR can be used to readily perform complex and innovative analysis of current and archived air pollutant data from the AURN, allowing powerful data visualisation and interrogation of these data. UK-AIR makes it straightforward to download these graphical outputs in document-ready formats.

Some of the Openair data analysis tools currently incorporate hourly modelled temperature, wind speed and wind direction data for AURN stations, although this product isn't assured in the long term. These data have been extracted from the daily WRF modelling used for Defra air quality forecasting between August 2010 and December 2013. The modelled meteorological data are automatically picked up by the Openair data analysis tools and are also available to download directly from the UK-AIR database if required. Example automated visualisations using Openair are shown in Figure 6.

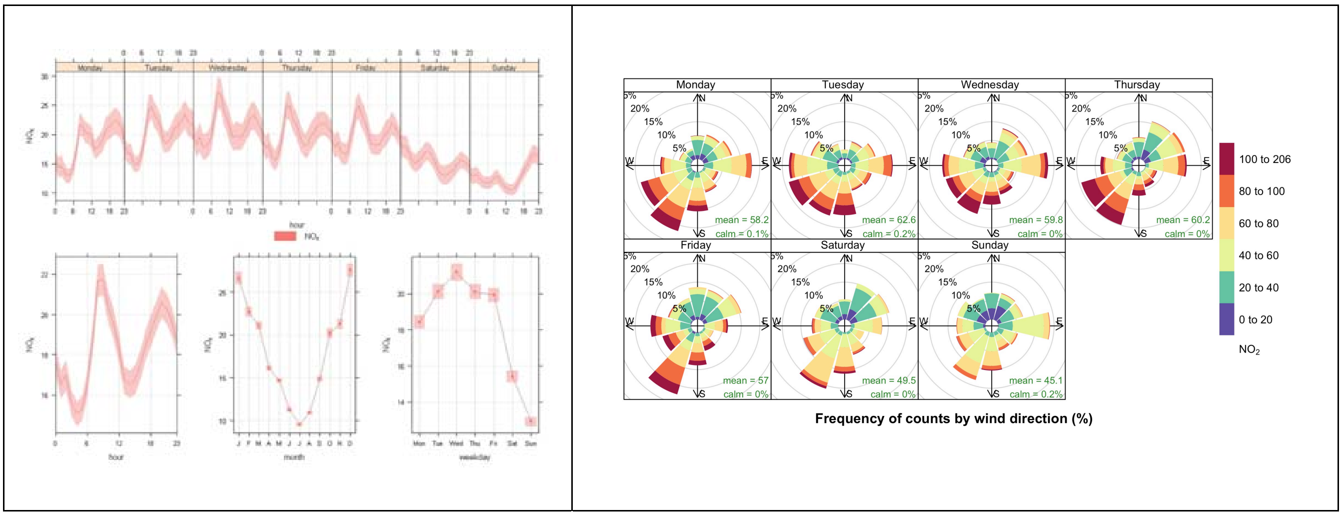

Figure 6: Example visualisation outputs achieved using the Openair data analysis tools with Defra air quality measurement data and model output.

Another recent development is the UK Ambient Air Quality Interactive Map (Defra, n.d); examples of outputs are shown in Figure 7 This interactive tool allows you to explore, interrogate and download ambient air quality concentration data from Defra's national Pollution Climate Mapping (PCM) compliance modelling on-line without the need for desktop GIS software. A sister map also exists for emissions data (NAEI, 2015).

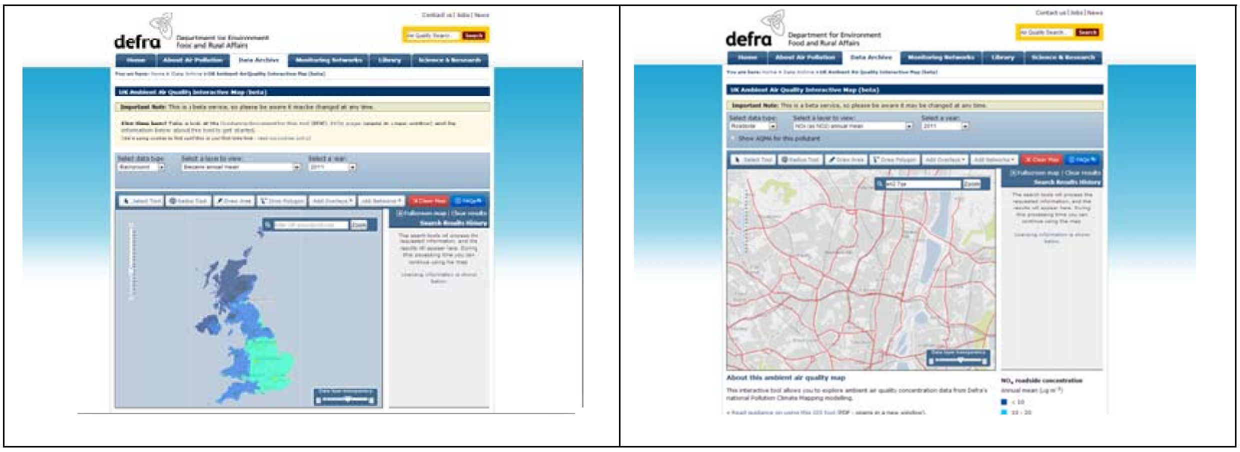

Figure 7: Screen shots from Defra air quality mapping software.

Other notable developments are the use of Twitter (@DefraUKAIR) and RSS to disseminate information and the development of "plug-in" tools for air quality forecast data to allow website providers to embed Defra forecasts in their sites. Data licensing of the compliance monitoring data and other Defra air quality datasets is now clearly stated as being under the Open Government Licence, details of which can be seen on UK-AIR (Defra, 2013b).

The transition to e-reporting of air quality data for the AQD has required the gathering of large amounts of metadata on monitoring stations, instrument configuration, models and model parameterisation. This metadata will add further value to users if handled and published in the most effective way. It will also promote transparency and in the future will be supported by a new standardised and controlled vocabulary for regulatory reporting and sharing of air quality information. The new e-reporting vocabulary has been developed at EU level but will be extensible for a range of UK applications.

Publication of relevant metadata such as location and instrument configuration is being evaluated for inclusion within UK-AIR downloads in order to allow users to make the most of the information available, e.g. to enable tracking of consistent time series for identical instrumentation or of inconsistent time series arising from instrument changes. Viewing and bulk download of metadata for stations will continue to be supported by UK-AIR.

4.4 Recommendations

For air quality monitoring data to be fully exploited they must be freely available and well organised, and include metadata and the information required to assess measurement uncertainties. In large part, Defra compliance monitoring data dissemination meets these requirements. However, accessibility and ease of use requires regular re-assessment to ensure that dissemination routes meet changing Government requirements and keep pace with technological change.

It is recommended that user needs information for data access is integrated with wider national policy initiatives on transparency, open data and the implementation of INSPIRE/SEIS principles, in order to add further value to existing compliance monitoring data. A further recommendation is that academic and policy-making users of compliance monitoring data work more closely together to develop a joint roadmap to improve the accessibility and reusability of air quality data, consistent with the Cabinet Office initiatives for transparency and the open data agenda. There is a further need for publishers of air quality data to work together to ensure consistent approaches to web-serviced information are adopted in line with the INSPIRE principles, to maximise data interoperability, data access and ease of use to support policy, public information and research.

5 Adding value to existing observations

When considering how the evidential and research value of compliance monitoring activities could be enhanced, it is relatively easy to identify opportunities where the addition of new instruments and sites to the network would be scientifically beneficial or add to the evidence base. The costs of new instruments and sites are generally significant however, and adding large swathes of new instrumentation is unrealistic given current pressures on Government resources. This report limits itself therefore to a consideration of how added value can be gained through modest investments in additional observations and changes in data reporting and usage, and whether sites may be further optimised within the existing cost envelop.

A detailed evaluation of meteorological data options is presented in the next section since this is frequently cited as a factor which limits the evidential exploitation of air quality data, particularly by research users, and where provision of additional observations may not add overly to the cost burden of monitoring.

5.1 Meteorological information

5.1.1 Introduction and background information

The analysis of both long-term and short-term air quality trends, and in particular their relationship to estimated trends in emissions, is critically important in assessing how concentrations change in response to different policy measures (Carslaw *et al.*, 2007). Several studies have shown that the influence of meteorology needs to be properly accounted for within this type of analysis (Thompson and Reynolds, 2001; Reiss, 2006).

Meteorology strongly influences local concentrations of airborne pollutants by driving mean and turbulent dispersion processes (Belcher *et al.*, 2013), as well as affecting chemical and physical transformations which may depend on levels of sunlight, cloud cover, mixing height, temperature and humidity. In a study of trends in benzene and 1,3-butadiene concentrations in Houston from 1997-2004, Reiss (2006) found that the mean percentage reductions in concentrations per year were greater for the raw data than for the meteorologically adjusted data. Carslaw *et al.* (2007) analysed oxides of nitrogen (NO_X) concentrations at a central London roadside site and found that unadjusted NO_X trends showed a 28.6% reduction from 1998-2005, whereas meteorologically adjusted trends showed only a 19.3% decline. Differences were not just related to wind speed, but also demonstrated the influence of background wind direction, since there were a higher number of occasions in the early part of the time series that led to strong recirculation of airflows at the in-street site driving exhaust emissions towards the measurement site.

Failing to account for the influence of background meteorological flows on in-street dispersion processes can therefore lead to erroneous interpretation of trends in concentrations and their relationship to emissions trends. Meteorological data were also found to be particularly important in a study of emission and NO_X concentration trends at Heathrow airport from 2002-2006 (Carslaw and Taylor, 2009).

Despite their importance for air quality studies, historically, meteorological data have been collected by the UK Met Office for other purposes such as weather forecasting. The number of urban meteorology measurement sites within the UK is therefore limited. The importance of urban meteorology for air pollution studies has been treated at length within the European Cooperation in Science and Technology (COST) Action Programme 715 (Meteorology applied to urban air pollution problems) which suggests that “meteorological conditions are often applied with little regard to whether urban factors are important”. A detailed account of the sensitivity of air quality predictions to assumptions regarding urban meteorological parameterisations is given in Fisher *et al.* (2005).

Relationships between air pollutant concentrations and meteorological factors can be complex. Thompson and Reynolds (2001) highlighted the non-linear dependence of trends in tropospheric ozone on meteorological factors. Periods of low wind speeds and temperature inversions which inhibit vertical mixing are also associated with elevated concentrations of pollutants derived from ground-level sources (Menut *et al.*, 1999).

At the local scale, e.g. within complex urban areas, street-level mean flow and turbulence govern the dispersion of pollutants away from their sources, and therefore influence roadside concentrations (Dobre *et al.*, 2005; Tomlin *et al.*, 2009; Belcher *et al.*, 2013), with local wind direction proving critical in accurately predicting roadside concentrations of, for example, nitrogen dioxide (NO_2) (Tomlin *et al.*, 2010). Reliable meteorological data are necessary as inputs to the dispersion models used by local authorities (LAs) to assess past trends in air pollution and to predict the impact of future abatement strategies. For this reason many LAs collect their own meteorological reference data as part of their air quality management activities. However, budget pressures on many LAs may impact on future data availability. There is clearly a need for meteorological data suitable for urban air quality investigations to be collected in order to maximise the added value obtained from the air quality compliance network; the report discusses whether existing data meet these needs.

5.1.2 Potential additional observations

Of the meteorological variables that may affect pollutant concentrations (wind speed and direction, solar irradiation, temperature, humidity, opaque cloud cover and mixing height) the first five can be obtained using standard weather stations from which the data can be accessed remotely; possible suitable locations for weather stations are discussed in the next section. The most difficult measurement is probably mixing height, which has an important impact on the vertical dispersion of pollutants, with low mixing heights leading to the trapping of ground-level emissions. The inclusion of mixing height in normalisation procedures could therefore be important if seasonal and diurnal trends are to be assessed.

Chilbolton Observatory in rural Hampshire is equipped with a 905 nm lidar ceilometer for the determination of mixing height (Munkel *et al.*, 2007) which has been in operation since 1996. The British Atmospheric Data Centre provides the measured attenuated backscatter coefficients from the instrument to UK researchers. The determination of mixing height requires the interpretation of these coefficients. Ceilometer measurements are also currently performed at King's College London and at the University of Manchester. For London, data including mixing height estimates are made available on-line, which could be of potential benefit to the analysis of air quality data for London.

The long-term future of these measurements may, however, be dependent on continuing research funding. The Met Office is developing a network under its Future Upper-Air Network Development (FUND) programme in the UK, which will include wind profilers, cloud radars, ceilometers and radiometers and will cover the south east region (Gaffard and Nash, 2008). Its primary purpose is to support weather prediction modelling but the data could potentially also support the interpretation of air quality measurements. Specific urban measurements would however still be useful since the diurnal cycle of wind speeds and mixing height responds to urban heat fluxes, which can exhibit a phase shift with respect to those in rural locations, particularly in low wind conditions (Kastner-Klein and Rotach, 2004; Fisher *et al.*, 2006). The determination of mixing height and cloud cover involves profiling measurements and considerable expertise in data interpretation and is perhaps better performed by specialist meteorological groups. The long-term availability of these data for air pollution research is, however, important and could be further explored via communication with the Met Office and those research groups performing urban measurements.

5.1.3 Locating weather stations to add value

The co-location of a suitable reference meteorological station with air quality measurement sites could be of great value to the interpretation of long-term and diurnal trends in pollutant concentrations. Three possibilities exist for site location:

- direct co-location with air quality instrumentation at street level;
- an above roof site within the urban boundary layer close to the air quality site/s of interest; or
- a 10 m standard reference site representing regional climatology.

The advantages and disadvantages of the different options are discussed below.

Direct co-location with air quality instrumentation at street level: By co-locating instruments at street level the local wind speed and direction can be measured at high time resolution. This is useful in evaluating the influence of local building geometries on local airflow and turbulence patterns which affect near-field dispersion as studied in DAPPLE (Wood *et al.*, 2009) and other urban field campaigns (Longley *et al.*, 2004; Boddy *et al.*, 2005; Tomlin *et al.*, 2009). Significant knowledge about the influence of canyons and junctions on recirculating airflows and local air pollution concentrations has been developed from co-located field campaigns using temporary measurements. However, whilst some general trends can be observed, in-street flows can be complex and very site specific.

The understanding of local wind-driven effects such as particle resuspension could also benefit from in-street wind speed and direction data. In previous studies conducted in London, data were collected at Heathrow airport and an implied relationship between regional background flows and local wind speeds had to be assumed (Thorpe *et al.*, 2007). As exhaust emissions of particulates fall, the estimation of non-exhaust sources of particulate matter, such as resuspension, will become more important. Co-located meteorological measurements may also be of use within dispersion and inverse modelling studies aiming to evaluate temporal profiles of, for example, traffic-related emissions (AQEG, 2014). For these reasons there could be a case for supporting a small number of street-level meteorological stations which could add significant value to existing air quality measurements at low cost. However, it is recommended that they be used in conjunction with an above roof reference measurement, e.g. as in DAPPLE.

An above roof site within the urban boundary layer: The flow within urban streets is extremely complex and in-street wind speed and direction can fluctuate over very short time and spatial scales as has been demonstrated within DAPPLE and other urban field measurement campaigns (Wood *et al.*, 2009; Balogun *et al.*, 2010). For the interpretation of longer-term trends in air quality data, the presence of such fluctuations and the influence of local structures on airflows may overcomplicate normalisation procedures, implying that a reference measurement free from local perturbations may be more appropriate. On the other hand, frictional and surface heat flux effects of the urban surface strongly influence the development of the urban boundary layer above it (Kastner-Klein and Rotach, 2004; Fisher *et al.*, 2006). Flow and dispersion at street level is therefore driven by the flow within an adjusted urban boundary layer which may not be appropriately represented by a ground-level measurement outside of the urban region. A better reference measurement may therefore be directly above the urban area at a height which is relatively undisturbed by the detailed form of the urban surface, but is not separated from street-level flow, i.e. is still within the urban boundary layer.

Relatively homogeneous flow above an urban area is likely to be above heights of 2-5 times the local mean building height (h_m) (Raupach, 1992) where measurements would represent an integrated response at the neighbourhood scale (Grimmond *et al.*, 2002). Locating instruments at such heights could however be difficult within many cities. The World Meteorological Organization (WMO) provided guidance on suitable heights for meteorological instrument siting (WMO, 2008) which was reinterpreted by the COST Action Programme 715 group for urban areas as a height of 10 m above the zero plane displacement height d (Fisher *et al.*, 2005 and 2006). The estimation of d is not easy for cities which contain buildings with very different heights and area density profiles (Millward-Hopkins *et al.*, 2012). However, 10 m above an isolated tall building, i.e. one with a roof top at a significant distance from surrounding obstacles and a height around twice that of the surrounding buildings, may be a realistic suggestion.

The suitability of reference measurements for urban flow and pollution studies in central London was discussed by Barlow *et al.* (2009), who compared the use of near roof-top measurements with those at a height of 190 m ($9h_m$) obtained from the top of the BT Tower. The BT Tower appeared to provide the most suitable reference location since the data were able to explain more of the variability in street-level mean flow than those from the roof-top site. The coupling with the surface however was weaker during rare events (< 1% of data) when the overnight flow was stratified, and therefore turbulence was suppressed at the BT site. The roof-top site was situated well below a height of $2h_m$ and wind speeds and direction were influenced by local building structures in several upwind directions. The work therefore supported the usefulness of a centralised, high reference site in London for applications in emergency response and air quality modelling and data interpretation. The continuation of measurements on the BT Tower may be supported by the National Centre for Atmospheric Science (NCAS) and would be of significant value to the long-term interpretation of air quality data in London.

In other cities there may be similarly useful data sources that are not currently made widely available. For example, for several years Leeds City Council have carried out wind speed/direction and solar radiation measurements at heights of 12 m and 32 m at a relatively undisturbed site within Leeds city centre in order to support dispersion modelling activities. Several university groups also manage roof-top meteorological observatories, including groups at Manchester, Edinburgh, King's College London and Reading (which operates sites in London). At the moment it seems that no integration of data from these sites takes place and not all data are freely available on-line. It would be extremely useful to assess what data sources currently exist and what is the long-term viability of data from available sites, since much of it could be of value for air quality studies.

A 10 m standard reference site representing regional climatology: Historically, UK reference meteorological stations have tended to be placed on the edges of city regions with a measurement height of ~10 m since they are primarily used in weather forecasting[1]. Very few central urban sites remain active, although there may be an emerging need for the Met Office to reconsider the usefulness of urban locations as weather forecasting models are now attempting to provide more detailed representations of urban surfaces.

For London, the most commonly used reference site is Heathrow, which has been used to provide a representation of the airflow that drives dispersion within the city. However, the representativeness of this site is uncertain, so additional such sites would be beneficial. A number of studies have proposed scaling relationships between regional flows and wind speeds within the urban boundary layer based on using on a log profile for the variation of wind with height determined by the incoming regional flow and estimated aerodynamic parameters of the urban surface (Raupach, 1992; MacDonald *et al.*, 1998; Best *et al.*, 2008; Millward-Hopkins *et al.*, 2011 and 2012). Because of the complexity of the flow, the scaling relationships between a specific meteorological reference site and the urban boundary layer flow above different air quality sites will vary for different locations and with wind direction (Millward-Hopkins *et al.*, 2011 and 2012; Weekes and Tomlin, 2013). A more advanced but complex approach is to use a dynamic model of the flow that takes account of a spatially varying surface representation of the buildings (Carruthers *et al*, 1988) to represent the canopy buildings. However, this approach may also need to take account of the zero plane displacement (Barnes *et al.*, 2013).

In the longer term there may be the possibility to use output from the Met Office's Numerical Weather Prediction (NWP) model within pollution studies but at the present time its ability to give accurate predictions over cities is questionable and perhaps needs to be further explored for appropriate case studies (Nelson *et al.*, 2003). The interpretation of data/models can provide insights into the suitability of different reference meteorological measurements. This approach was taken by Barlow *et al.* (2009) with respect to understanding in-street flow patterns. It would be extremely useful to compare meteorological data from Heathrow with measurements above the central London urban surface such as from the BT tower, and with forecasting data for the interpretation of in-street flow and air quality data at various London sites. This could provide insight into whether there is a need for continued urban boundary layer measurements to be used as a reference, rather than the current use of surface level measurements obtained on the outskirts of the city.

5.1.4 Current meteorological site locations

The COST Action Programme 715 group compiled a database of available urban meteorological sites which is available on-line (University of Hamburg, n.d.). The database provides information on the variables measured and the height of the site above sea level. It does not however, provide information on the height of the measurement above ground or above roof if the site presents roof-top measurements.

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[1] Historic weather data available at: http://www.metoffice.gov.uk/climate/uk/stationdata/index.html

The British Atmospheric Data Centre also holds land surface observations data from the Met Office station network and other worldwide stations as stored in the Met Office MIDAS database. A map-based tool (BADC, n.d.) allows the user to search for stations within different regions, although not all stations are currently active and the coverage of different meteorological variables varies markedly between different stations. Many active sites may not be listed, e.g. those run by local authorities. The integration of metadata on available sites, particularly within urban areas, would be useful. The metadata would need to be extended for urban areas to include estimated height above roof or above the local mean building height.

5.1.5 Recommendations

For some scientific and research applications the evidential value of compliance data would be greatly enhanced through the co-measurement and reporting of meteorological parameters. There is a lack of above canopy meteorological measurements in London and other major cities, and an over-reliance on the (often untested) extrapolation of meteorological conditions from a small number of locations where data are easily and freely available. The lack of access to historical Met Office data is considered a constraining factor that limits the extent to which air quality compliance data can be exploited by researchers and business. A case also exists for a limited number of roadside weather stations to be co-located with existing air quality sites for use in particle resuspension and dispersion and inverse modelling studies.

5.2 Enhancing the frequency of observations

Measurements of gaseous pollutant species within the Automatic Urban and Rural Network (AURN) are currently archived as 15-minute means and reported as hourly averages, despite the data from the instruments being logged at frequencies as high as every 20 seconds. For some particulate pollutant species only hourly data are available. The decision to archive in this way was taken many years ago when the first continuously polled telemetry-linked air quality monitoring station was set up in the UK under the Statutory Urban Network (SUN) in 1987. At the time, the costs associated with the provisions of real-time data were large. In the last decade the costs of calls and data storage have decreased making it timely to review whether there is a case for archiving data at a time resolution finer than 15 minutes, although the degree to which this is achievable depends upon the pollutant and instrumentation.

Averaging times of 15 minutes are acceptable for locations beyond the immediate vicinity of sources, where pollutants are relatively well mixed so that any significant variations in concentrations take place over longer timescales. However, near sources, fluctuations in concentration can take place over much shorter timescales (Mylne *et al.*, 1996), such that important information can be lost over long averaging periods. The value of collecting data over short averaging times has been demonstrated at a major airport (Carslaw *et al.*, 2008) where individual aircraft plumes were sampled and analysed. Similarly, data have been logged at a frequency of 1 minute for over a year at Putney, Wandsworth, from 2010 to the present, with a view to linking air quality data with Automatic Number Plate Recognition (ANPR) data to allow estimates to be made of contributions to NO_X and NO_2 concentrations by different vehicle types.

It is therefore worth considering archiving data from short – say 1 minute – averaging times at some kerbside/roadside sites such as London Marylebone Road, or indeed at other sites which are near sources of interest such as steel works or power stations. Near roads such measurements have the potential to show the signatures of individual vehicles, whilst in street canyons they may provide insight about the frequency and length scales of ‘clean’ eddies of air entrained into the canyon from above. At both near road and near industrial sites, insight can be gained into chemical processes from time series of nitric oxide (NO), NO_2 and ozone (O_3) concentrations. At industrial sites there is also the potential to determine contributions from different types of sources (e.g. concentrations of particulate matter (PM) arising from fugitive emissions will show variations in timescale and magnitude different to those arising from a point source). Another application is in the validation of concentration fluctuation models, which have been developed to predict short-term peaks in concentration relevant to odour and acute short-term impacts (Thomson, 1990). The validation of such models has been limited because of the lack of appropriate data.

The feasibility of achieving such changes requires a more in-depth consideration with respect to practicality under the current data collection and reporting procedures via the Central Management and Control Unit and the Data Dissemination Unit. Issues such as existing data tariffs and modifications to communications protocols may incur additional costs; although the benefits of such investment may well outweigh such investments for a small number of sites.

5.2.1 Recommendations

Collection of air pollution data from certain existing AURN instruments at higher temporal resolution is likely to allow new and innovative uses of the measurements to support a range of science and policy needs. High time resolution data are not necessarily required in real time, and can be stored locally and on wider databases at very modest incremental costs. A clear delineation in data products would be required highlighting that higher time resolution data were for research use, rather than compliance monitoring.

5.3 Chemical information

The compliance origins of the Defra networks result in the focused deployment of chemical instrumentation that meets measurement requirements for those regulated species. Section 5.1 earlier described how meteorological data are not currently collected across the Defra compliance networks (since they are not strictly required for reporting purposes) but that great additional evidential value can be derived from their inclusion with air quality data. The same is true of the inclusion of certain other chemical species that are not regulated by European directives. In many cases the compliance network locations are ideal for the co-installation of research grade instrumentation, as shown by the substantial bibliography that has grown around supersites such as Harwell and London Marylebone Road.

A special resource provided by compliance networks is that they give long-term context to additional short-term research observations, and a reference point against which short-term process studies can be compared. They provide air pollution climatology data for a given location that is essential when attempting to extrapolate conclusions, exemplified recently by the additional co-located measurements for the ClearfLo project at sites across London. Co-located measurements are periodically undertaken at other sites, often in association with university research, but exact data on this are not possible to collate. More broadly, compliance networks provide the chemical context for the positioning of research process studies, the comparison of large-scale models and the ground truthing of experiments conducted via Earth observation or from aircraft.

Many additional observations could be proposed that would add evidential value, although in most cases there is also a significant financial cost associated. Of particular merit however is the maintenance of long-lived pollution tracer species such as carbon monoxide (CO) in the compliance network. CO has decreased very significantly as an air pollutant in the UK to the level where, from a compliance perspective, it is possible to justify the continued reduction in monitor numbers. It is however a vital measurement to support wider evidential requirements concerning source apportionment, transport processes, mixing, emissions calculations and, more broadly, model evaluation.

The continued decline in CO in the UK means that existing instrumentation which meets compliance monitoring requirements, for example using infrared adsorption as the measurement technique, is not sufficiently precise to support wider evidential needs, severely limiting the ability of the network to provide useful CO tracer data.

From this perspective it would be a better use of resources to have even fewer CO sites but with more sensitive CO monitors. A similar issue exists for sulphur dioxide (SO_2) monitoring. The SO_2 compliance network has undergone substantial reduction in the number of sites in recent years, but SO_2 is a useful tracer for particular industrial sources and shipping. The present SO_2 monitors are operating at close to their limit of detection and consideration should be given to focusing resources on more sensitive instrumentation at fewer sites.

Although not widely deployed in the compliance networks a similar argument can be made for the inclusion of carbon dioxide (CO_2) measurements. Whilst not a classical regulated air pollutant itself, its co-measurement with classical air pollutants may provide considerable insight into the sources and emissions of regulated species. At present greenhouse gas emissions measurements and air pollution measurements fall under the remit of different Government departments, the Department of Energy and Climate Change (DECC) and Defra, but many anthropogenic sources (e.g. transport, energy, industry, etc.) emit both types of pollution. Some potential exists for integrated measurements using the comprehensive Defra network infrastructure, which may help validate the emissions of both long-lived and short-lived pollutants.

In addition, it is important to consider that many air pollutants also play important roles in climate regulation, for example black carbon and aerosols both contribute some of the largest climate forcing uncertainty in the Fifth Intergovernmental Panel on Climate Change report, and tropospheric ozone remains a major and increasing greenhouse gas.

The value of well-instrumented supersites with detailed chemical information is reflected in the bibliography, however there are perhaps fewer such locations than might be desired. An aspiration would be to develop one or more urban background supersites (sites measuring a large suite of gas and PM components), analogous to the European Monitoring and Evaluation Programme (EMEP) rural supersites at Harwell and Auchencorth Moss. To some extent this is already happening at London North Kensington, but a designated urban background supersite in one or more major population centres, such as London, Birmingham, Glasgow or Manchester, should be considered. An expansion in supersite activity might be financially balanced by a reduction in single pollutant monitoring activities at other locations.

The continued growth in measurement capability for aerosols has resulted in an improved ability to quantify the contributions from individual sources to overall PM loading. The focus of additional chemical characterisation should be on the development of comprehensive source apportionment of PM in different urban locations. The chemical speciation measurements that inform PM source apportionment include:

- Major chemical components of PM (urban and rural), i.e. the major ions ammonium (NH_4^+), sulphate (SO_4^{2-}), nitrate (NO_3^-) and chloride (Cl^-), and organic carbon (OC) and elemental carbon (EC). The Black Carbon Network provides information for EC.
- Estimates for the abundance of different categories of PM organic matter (OM) as derived from analyses of continuous aerosol mass spectrometer (AMS) data. It is possible currently to estimate components of OM including primary OM associated with transport emissions, biomass burning OM, cooking OM, nitrogen-containing OM and various categories of oxygenated OM distinguished according to volatility.
- Other molecular tracers (by gas chromatography analysis of PM filters) for sources of OM, e.g. levoglucosan for wood burning, cellulose for primary plant material and mannitol for primary fungal material.
- Elemental tracers, e.g. zinc (for tyre wear), copper and barium (for brake wear), titanium and silicon (for crustal material), etc.

Measurements of transient gas phase species, such as hydroxyl, hydroperoxyl and nitrate radicals, oxidation intermediates of volatile organic compounds (VOCs) such as oxygenated organics and acids, or VOC precursors such as higher hydrocarbons, can only be made using sophisticated research grade instrumentation. It is unlikely that any of these species can be easily added to the compliance network as routine year-round measurements, although they do provide exceptional insight into the basic chemical mechanisms at play in any given location. There is precedent for the co-measurement of such species at Defra compliance sites over short time periods as part of research campaigns, and the value of this could be further enhanced by the provision of enhanced supporting infrastructure and a greater variety of supersite locations. Once again improved co-ordination of policy requirements, science needs and national capabilities between Defra, research organisations and the UK research councils could enhance the evidential value of current investments.

5.3.1 Recommendations

As ambient concentrations have fallen, the networks for measurement of CO and SO_2 have reduced in scope, and levels are often close to instrumental detection limits. Data on these species are however widely exploited in other applications and have great evidential value. A recommendation is made for Defra to consider the introduction of a smaller number of higher precision CO and SO_2 monitors in locations that meet appropriate Defra needs for compliance whilst also supporting the exacting measurement requirements for wider evidential needs. Further instrument-related recommendations are: (i) to consider how co-location of air quality and climate monitoring may help Defra and DECC generate evidential data on the relative emissions of climate and air pollution emissions from source; and (ii) to examine the current measurement technology for particulate composition and consider whether the additional investigation of molecular speciation at a limited number of locations may aid in PM source apportionment.

5.4 Site locations

Insights into the nature and sources of emissions and the processes contributing to pollutant concentrations within an urban area can be gained by analysis of the urban and roadside increments in concentrations. These can be derived from data from nearby roadside and urban background sites that are in turn further matched to a rural background site for that geographical region. In particular, the chemical comparison of PM components collected at such sites can usefully separate the contributions of regional background, local urban and traffic sources (Yin *et al.*, 2010; Harrison *et al.*, 2012).

Whilst development of triplicate rural, urban background and roadside sites has not generally been a consideration in the AURN, the deliberate reorganisation of the Black Carbon Network into triplicates of sites provides a good example of adding value through careful experimental design. Not all sites in a triplicate need to be formally part of the AURN. When considering locations of future AURN monitoring sites, consideration could also be given to formation of triplicates with well-established local authority monitoring sites or research activities.

The location of monitoring sites in a rough transect across major centres of population provides a similar opportunity for distinguishing between regional, suburban and urban sources. The use of the term transect is not meant to imply that there is a consistent direction of travel of air masses, although approximate alignment of a transect in a direction that matches the dominant upwind–downwind direction would be helpful. Increasingly sophisticated models of air mass flow now exist that are able to indicate when two or more sites are coupled by the same air mass, or to apportion the fraction of a given time for which a monitor site has experienced air masses that have passed over particular source areas (Fleming *et al.*, 2012). This allows not only insight into source origins but also into chemical processing within air masses. The approach is being applied in the ClearfLo project in London using monitoring sites at Harwell, North Kensington, Marylebone Road, the BT Tower and Detling in Kent.

In general, and within the constraints imposed by reporting requirements and cost, etc., one guiding principle for optimising networks should be to maximise the number of components measured at a given site. The benefits of this are multiple and include:

- more comprehensive data would lead to the potential for greater understanding of the sources and processes (chemical and meteorological) that determine concentrations at a receptor site;
- greater coherence in datasets used to challenge and validate atmospheric models; and
- conformity in the data used to estimate simultaneous exposure to multiple pollutants for health epidemiology analyses and for health impact assessment.

6 Evidential applications using compliance data

6.1 Discovery science

Air pollution monitoring data serve multiple important purposes. For compliance assessment the focus is on comparing the concentrations of different species with national or international limits or guidelines. Generally these types of comparisons are relatively straightforward and involve comparing simple statistics such as annual means to determine the number of sites that do or do not comply with various limits. However, while the main purpose of these sites is compliance assessment, they also serve a key role in providing numerous, important insights into the fundamental nature of air pollution – what might be termed 'discovery science'.

Data from the UK compliance networks have long been used either directly or in support of more in-depth analysis to better understand some of the underlying factors controlling air pollutant concentrations in the UK. While particular sites (or networks) were not necessarily located to answer wider questions concerning the nature of air pollution, it is certainly the case that UK compliance data have been used very effectively to provide new and important insights into air pollution in terms of dispersion, atmospheric chemistry and source characteristics. This is an important aspect of the compliance networks: while they may not have been designed to answer wider questions concerning air pollution, they have nevertheless proved to be extremely valuable in providing unexpected new insights.

Many instances of the use of compliance monitoring to gain new understanding have been documented. For example, the discovery that emissions of primary nitrogen dioxide (NO_2) from road vehicles were increasing was based entirely on the analysis of Automatic Urban and Rural Network (AURN) and London Air Quality Network (LAQN) data (Carslaw, 2005). The analysis of oxidant levels in the UK (Clapp and Jenkin, 2001; Jenkin 2004), which was based on data from the AURN, developed a framework for understanding how oxidant levels are partitioned and also a method by which atmospheric models could predict concentrations of NO_2 (Grice *et al.*, 2010a). Researchers have shown over a series of papers (for example in Derwent *et al.* (2013)) how hourly Defra-supported ozone concentrations at Mace Head on the west coast of Ireland (not part of the compliance network) can be analysed to provide valuable information on the 'baseline' ozone conditions that affect western Europe. Importantly, UK compliance data can also help build a more comprehensive picture of air pollution trends at a European scale. For example, Wilson *et al.* (2012) used rural background ozone (O_3) monitoring data to show how trends vary across Europe and found that anthropogenic oxides of nitrogen (NO_X) and volatile organic compound (VOC) reductions have not had a substantial effect on observed annual mean O_3 trends in most of Europe. This is far from an exhaustive list, and many more examples could be given.

6.2 Informing emissions estimates

Compliance measurements have an important role in providing information on emission sources. The linkage between ambient measurements and emissions inventories is covered in detail in AQEG (2015). Of particular importance is the fact that trends in ambient measurements can be compared with trends in emissions. There are many ways in which the comparison between ambient concentration data and emission estimates can be carried out, however, a commonly used approach is to filter ambient measurements in various ways to emphasise particular sources. For example, focusing on roadside increments in concentration above urban background concentrations or considering specific wind sectors where particular sources are most important can help isolate a source of interest and enable a comparison with trends in emissions. Compliance measurements can also be analysed to directly provide estimates of the NO_2/NO_X ratio of vehicle emissions, which again can be used for comparison with emission inventories.

As shown in AQEG (2015), compliance data can be statistically analysed to remove the effects of meteorology, leaving meteorologically ‘normalised’ trends (i.e. trends in ambient concentrations that would be expected from invariant meteorology), which can be compared on a more like-for-like basis with trends in total emissions. These techniques are potentially very useful but are not commonly used. Moreover, such techniques can also be used to reveal diurnal, day of the week and seasonal variations in the data that can in many circumstances be compared with similar temporal variations in emission source strength.

6.3 Importance of the monitoring networks to models

Measurements from the compliance and other monitoring networks are essential for a broad range of model-related activities including the evaluation of model performance, their use as input into models as boundary conditions or for constraining models, for example through data assimilation, and for model development. Numerous examples of the use of monitoring data in model evaluation and as boundary conditions were incorporated into the 2013 Defra air quality Model Intercomparison Exercise[2]. This project brought together most of the wide range of modelling approaches currently used in the UK and comprised the evaluation of urban models in Greater London for NO_X, NO_2, O_3, PM_{10} and $PM_{2.5}$, the evaluation of regional models for the prediction of O_3 concentrations across the UK and, in a separate study, dry/wet deposition budgets and critical load exceedences.

The intercomparison exercise and many earlier studies (e.g. Jenkin *et al.*, 2002; Derwent *et al.*, 2009) demonstrate the importance of measurements of the common target pollutants – the components of particulate matter (sulphate, nitrate and ammonium ions), along with the closely chemically-related species sulphur dioxide (SO_2), NO_X, ammonia (NH_3) and nitric acid (HNO_3) – and the importance of a network covering the full range of monitoring location types. For instance, roadside sites are important for urban model validation, background sites are important both for regional model evaluation and to provide boundary conditions for urban models, and remote sites are important to provide boundary conditions for regional models. The studies noted have also shown the added value of co-located observational data for related groups of species; this is particularly well documented for O_3, NO_2 and NO_X (and recommended in AQEG, 2004).

Other examples of the use of monitoring network data (specifically AURN data) include modelling assessment studies, for example those undertaken as part of LAQM, for permitting of industrial sources or for environmental impact assessments. Data have also been used in a diverse range of scientific studies. For example, monitoring data have been used to define observational constraints on box modelling studies of the chemistry of reactive free radicals (e.g. hydroxyl and hydroperoxyl radicals), in which the concentrations of longer-lived species (e.g. ozone, NO_2, VOCs) are constrained to observations (e.g. Emmerson *et al.*, 2005). Murrells *et al.* (2012) used O_3 and NO_X data to initialise simulations of oxidant formation over the London

[2] For more information see http://uk-air.defra.gov.uk/research/air-quality-modelling?view=intercomparison

conurbation under photochemical episode conditions using a multi-layer column model, with hydrocarbon levels constrained by Automatic Hydrocarbon Network data in some calculations.

The use of monitoring data as observational constraints is an important component of empirical modelling studies, such as those used routinely in UK air quality compliance modelling activities (e.g. Grice *et al.*, 2010b; Brookes *et al.*, 2011). Beevers *et al.* (2012) constrained model output to observed NO_X levels at roadside locations in London to improve predicted levels of O_3 and NO_2. Hayman *et al.* (2010) implemented a surface correction algorithm for simulated levels of NO_X, NO_2 and O_3 derived from measured concentrations at urban locations. More generally, assimilation of monitoring data is likely to become increasingly important as techniques develop further. Where data are used to constrain models, alternative datasets may be required to undertake model evaluation. Compliance data have also been used in modelling conducted in the development of methods to calculate uncertainty for compliance modelling for the EU under the Fairmode initiative (Thunis *et al.*, 2012).

6.4 Long-term trends

An important use of data from the AURN and other networks is to help understand long-term trends in the concentrations of key pollutants. The most important use of long-term trend data is to reveal the extent to which concentrations are changing as expected due to the adoption of different emissions control measures. Most emission controls do not result in substantial changes in emissions over short periods of time or over wide areas. Most changes in emissions are relatively gradual and hence several years of monitoring data are needed to observe the effect on atmospheric concentrations. However, there are exceptions such as changes to fuel quality and interventions such as the London Congestion Charge Scheme. Plotting annually averaged data has the advantage of removing the sometimes strong seasonal and diurnal variation present in time series. Over long time periods (greater than about 5 years) it becomes possible to discern statistically significant changes in concentration.

In relation to the compliance networks, long-term trends are generally considered in annual reports for the specific networks and in *Air Pollution in the UK*, the annual report for all UK monitoring networks. These trends are generally displayed as annual time series plots that can help give a general idea of how different sites or species compare over time. There are a few examples of more detailed analysis where, for example, trends are quantified in some way. One recent example is the *2011 Annual Report for the UK Black Carbon Network* (Butterfield *et al.*, 2012) that quantified recent trend estimates of black carbon and showed, for example, that black carbon levels increased at roadside sites over 2009-2011, but that uncertainties in the slope indicated the trends were not statistically significant. Such information is useful because it helps to put trend information on a more robust footing, such that a simple interpretation of ‘concentrations are increasing’ can be properly interpreted as ‘no evidence of a change in concentration’.

One of the difficulties in presenting more comprehensive trend information is that it can require statistical techniques that are not commonly or routinely available in software packages typically used for trend analysis (e.g. Microsoft Excel). Another difficulty is the specialist knowledge required to ensure that trend estimates are robust and that certain statistical violations are avoided or correctly handled, such as auto-correlated data. To some extent the effort that goes into carrying out careful trend estimates reflects the problem at hand. In many cases it is acceptable to have only a graphical plot of annual values to gain an overall impression of trends. In the climate change arena, however, enormous care is exercised to ensure that trend estimates are rigorously carried out. As discussed in Section 5.2, the opportunities to carry out more comprehensive trend analyses have increased through the use of readily accessible tools.

A key issue for all air quality networks in providing data for use in long-term trend estimation is consistency. Established long-term sites are extremely valuable in providing annual and decadal scale trend information. Clearly sites sometimes need to be relocated for practical reasons, or closed, and this can break valuable long-term records. Also important is the consistency of the monitoring equipment used; this is of particular concern for particulate concentrations when moving from TEOM (tapered element oscillating microbalance) to FDMS (filter dynamics measurements system) techniques.

Long-term trend analysis can be refined through the use of statistical techniques that aim to remove or account for meteorological variation (AQEG, 2015). These analyses yield concentration trends that can be more easily reconciled with trends in emissions because much of the variation due to meteorology is removed. However, such analyses require that appropriate and representative meteorological data are available, which might not always be the case.

6.5 Health effects

The evidence linking air pollution to adverse effects on health has been comprehensively reviewed by authoritative bodies such as the World Health Organization (e.g. WHO, 2006 and 2013) and the United States Environmental Protection Agency (e.g. USEPA, 2009, 2013a and 2013b).

Much of the detailed mechanistic knowledge of the effects of air pollutants on human health is derived from human challenge studies in a clinical setting. These allow controlled exposure of human subjects and associated monitoring of physiological and biochemical responses. Disadvantages of this approach include the inability to study the more susceptible members of the population for ethical reasons and the impracticality of studying complex air pollutant mixtures such as occur in the atmosphere.

Consequently, much current knowledge derives from very different studies of individuals or populations exposed during their everyday life. This can take the form of panel studies involving relatively small groups of people, in which case it may be possible to collect individual personal exposure data using lightweight personal samplers.

However, much greater progress has been made through larger studies involving whole urban populations or large numbers of city dwellers. These fall into two main categories. In *time series studies*, day-to-day changes in morbidity and mortality are related to daily variations in outdoor air pollutant concentrations, often measured at a single outdoor monitoring site within a city. *Cohort studies*, which follow people’s survival over a number of years, have shown an increased mortality risk to be related to long-term exposure to air pollution after allowing for other risk factors. In both study types, long-term high quality monitoring datasets are an essential input to generating exposure–response functions which link outdoor concentrations to effects upon public health.

The results of both time series and cohort studies have been used in estimating the public health burden of air pollution exposure and the benefits which would accrue from emissions reductions (e.g. COMEAP, 1998 and 2010; Defra, 2007). The latter estimates depend upon detailed knowledge of pollutant concentrations derived from interpolated monitoring data. There are also cross-sectional studies that compare health outcomes between cities or in different areas within a city (e.g. Elliott *et al.*, 2007). These, and increasingly also the time series and cohort studies, require spatially-resolved concentration data derived from interpolation of monitoring data, air quality models or land use regression models, all of which depend ultimately upon monitoring data.

The following paragraphs describe the use of compliance monitoring data in various methodologies for the study of air pollution health effects.

Epidemiological studies and estimates of health effects using UK air pollution monitoring data: Routine UK air pollutant monitoring data have been used in a number of different types of health study. As well as allowing individual epidemiological studies to be undertaken in the UK, the availability of such data has enabled the UK to be included in international studies. Studies undertaken in the UK have also been included in reviews of the evidence linking air pollution with adverse health effects, thus contributing to the shared understanding of the scientific community. Exposure assessments based on both monitored and modelled data have been used in UK studies; where modelling data are used, the monitoring data are an essential component in either calibrating or validating the relevant model. Modelled and monitored data have also been used to estimate the health burdens of air pollution and predict the benefits of improving air quality.

Time series studies of effects of short-term exposures: Time series epidemiological studies investigate associations of health effects with short-term (often daily) variations in pollutant concentrations. Health effects typically studied are those for which data are routinely collected and readily available, such as mortality, hospital admissions or visits to accident and emergency departments for respiratory or cardiovascular conditions (e.g. Anderson *et al.*, 2001; Atkinson *et al.,* 2010), although other effects, such as firing of implantable cardiac defibrillators (Anderson *et al.*, 2010), have also been investigated.

A search of the St George's, University of London, systematic Air Pollution Epidemiology Database (APED) indicates that UK studies, or multi-city studies with a UK component, have investigated associations of such health effects with variations in concentrations of particulate matter (i.e. total suspended particulate (TSP), black smoke, PM_{10}, $PM_{2.5}$, coarse PM, sulphate, particle number concentration (PNC)), O_3, NO_2, SO_2 and carbon monoxide (CO) (Anderson *et al*, 2007). Some of these studies are within individual cities, others cover several cities within the UK and one is in a rural area (Norfolk). In addition, UK data have been included in a number of international collaborations, such as the APHEA I & II (Air Pollution and Health, a European Approach; e.g. Samoli *et al.,* 2003) and APHENA (Air Pollution and Health, a European and North American Approach; e.g. Katsouyanni *et al.*, 2009) projects. Monitoring data have also been used to investigate the effects of specific air pollution episodes (e.g. Anderson *et al.*, 1995).

Ongoing time series studies in the UK include the use of monitoring data in the TRAFFIC project (KCL, 2015), and the use of daily modelled time series data (validated using monitoring data) in the NERC-funded AWESOME project (LSHTM, 2012).

Cross-sectional and longitudinal studies of long-term exposure: Studies investigating the health effects of long-term exposure to air pollutants have shown stronger associations with effects on health, particularly mortality, than those identified in time series studies. These studies have been important in identifying the public health importance of air pollution and in providing a basis for the quantification of effects, particularly of particulate air pollution. Although studies conducted in the US have been particularly influential, studies undertaken in the UK have been important in confirming effects in UK populations, e.g. Elliott *et al.*, 2007; Beverland *et al.*, 2012; Yap *et al.*, 2012; Carey *et al.*, 2013. Studies investigating associations of other health end-points with chronic exposures have also been undertaken (e.g. Forbes *et al.*, 2009).

The ongoing TRAFFIC study includes the use of modelled data, validated using monitoring data, in analyses of associations of exposure to traffic-related air pollutants with adverse health effects (KCL, 2015).

Studies of interventions: Monitoring data have been used in studies aimed at assessing the impacts of interventions affecting air pollutants, for example of London's congestion charge and low emission zone (LEZ) (Kelly *et al.*, 2011a and 2011b). Another example is an evaluation of EC legislation to reduce sulphur content in fuel undertaken as part of the APHEKOM project (Le Tertre *et al.*, 2014).

Monitoring data are being used in the ongoing AsPIRe (Air Pollution Intervention Research) study aimed at evaluating the cost effectiveness of an existing alerting system which provides information on air quality to individuals with medical conditions that might make them particularly sensitive to elevated levels of air pollutants.

Adjusting for air pollution as a possible confounder in studies of other risk factors: Some other environmental factors that increase mortality risk and/or contribute to the same health effects as air pollution can be correlated with pollutant concentrations. In studies of the health effects of such risk factors, it is important to adjust for air pollutants as potential confounders. Examples include studies of the effects of temperature and noise on health.

Reviews and health burden/impact assessments using UK data: COMEAP (2010) used modelled $PM_{2.5}$ concentrations calibrated against background AURN sites to estimate the mortality effect of particulate air pollution on the UK population and to predict the benefits of specified reductions. UK monitoring data have also been used in European projects with similar aims, e.g. APHEIS (APHEIS, n.d) and APHEKOM (APHEKOM Project, n.d.).

Epidemiological studies undertaken in the UK have been included in recent important reviews, such as the WHO's 'Review of evidence on health aspects of air pollution' (REVIHAAP) project (WHO, 2013) undertaken to inform the European Commission's review of air quality legislation. Similarly, the results of studies in the UK are being used, along with other European evidence, in the complementary ongoing 'Health risks of air pollution in Europe' project (HRAPIE, 2013) to recommend concentration–response functions for use by the European Commission in policy evaluation and formulation.

A discussion of the evidential value of monitoring network data by COMEAP[3] highlighted a number of issues. First, the need for complete datasets, especially for time series studies. Missing data for a single pollutant can require that all data are deleted for that measurement

[3] COMEAP-AQEG Joint Meeting, March 2013. Meeting report available at https://www.gov.uk/government/groups/committee-on-the-medical-effects-of-air-pollutants-comeap#minutes

period, considerably reducing the data available for model input and reducing the statistical power to detect effects.

Having a number of monitors for the same pollutant in close proximity to allow imputation of missing measurements was considered potentially beneficial, but the ratification of data in near real time to allow air quality data issues to be identified and rectified immediately was thought to be possibly a more resource efficient way of achieving data completeness. It was noted that modelling of air pollutant concentrations is being used increasingly in health effects studies and this emphasised the need for high quality monitoring data, including rural data, for the full evaluation and validation of models. In order to provide evidence on possible differential toxicity of particle components, a considerable expansion of the measurement of specific components such as elemental carbon, trace metals and tracers of specific sources (e.g. levoglucosan for wood smoke, barium for brake dust, etc.) would be highly beneficial. Also, the co-location of PM_{10} and $PM_{2.5}$ monitors would facilitate the study of the effect of coarse particles.

6.6 Planning and permitting applications

Many applications for the development of infrastructure under current planning law and Integrated Pollution Control (IPC) regulations require the submission of an environmental statement. This includes major projects such as new incinerators and road schemes, but also lesser developments such as housing estates and new supermarkets. The environmental statement that accompanies the planning application (and/or permit application in the case of processes subject to IPC) includes an examination of the existing air quality in the locality as well as a prediction of the incremental pollution due to the new development. Rather than go through the process of making air quality measurements to support the environmental statement – which can be both expensive and long in duration – developers and their consultants typically use data from the closest air quality monitoring site.

For pollutants where annual mean data are relevant, frequent use is additionally made of background maps derived from the PCM model for national assessment, which are underpinned by monitoring data. Many thousands of such environmental statements are produced annually within the UK, hence representing a major use of air quality monitoring data either directly, or indirectly through the pollution maps. This provides for considerable added value from the use of compliance data acquired by Defra-funded networks.

7 Dual uses of the compliance network infrastructure

The air quality compliance network represents a very substantial investment of public money in atmospheric monitoring instrumentation and the associated support infrastructure. The networks have built up over many years and present a unique resource for measurement. The sites within the various Defra networks have overcome basic issues of power provision, communications, planning permission and so on; issues that even at one location can take years to resolve.

It is reasonable therefore to look at other national evidential requirements that may potentially draw on the resources and capabilities of the air quality compliance monitoring networks for parallel or complementary activities. These can be thought of as 'dual use' activities, where the compliance network can support, for example, evidential needs related to emerging pollutants or emissions, or other needs associated with civil contingency or national security. A number of potential dual use activities are considered here and summarised in Table 5 below, along with a brief commentary on the current capabilities of the compliance network to provide evidential support. Later sections expand on the measurement or data requirements of particular dual uses and how the networks may require adaptation to meet their needs.

Table 5: Potential dual use applications of the UK air quality infrastructure.

Future/dual use activity	**Broad data/infrastructure requirement**	**Ability of existing compliance network to support dual use**
Assessment of fracking gas releases to the atmosphere, including fugitive emissions flaring and processing	Measurements of methane (CH_4) or specific tracers of natural gas condensate, e.g. C3/C4 non-methane hydrocarbons (NMHCs) and benzene, toluene and xylenes (BTX) emissions from flaring	Very limited; no CH_4 data in network; few C3/C4 data as part of automatic NMHC network; infrastructure may support new instruments in the future
Assessment of emissions from retrofit carbon capture and storage (CCS)	Gas and particulate impacts from nitrogen-containing compounds released by CCS	Existing filter networks may provide some insight into chemical composition
Impact and distribution of new materials to the atmosphere	Physical sample collection on appropriate media for laboratory analysis	Potential of metals/persistent organic pollutants (POPs) networks is good; historical archives also exist from past particulate matter (PM) sampling
Assessment of airborne biomaterials in the atmosphere	Physical sample collection on appropriate media for laboratory analysis	Metals/POPs networks may be suitable, dependent however on sampling media
Impact of biomass combustion on air quality	Gaseous and particulate impacts from point source and distributed domestic emissions; sample collection and analysis of marker compounds, e.g. levoglucosan	Existing particulate filter networks may provide some insight into chemical composition; networks may not necessarily be well located for assessment of domestic emissions
Support for security/defence monitoring	Physical sample collection on appropriate media for laboratory analysis	Good, wide network for PM materials, including urban locations; suitable for collection of PM materials, e.g. from explosive releases; no gaseous collection

Volcanic ash detection	On-line detection of PM materials; physical sample collection on appropriate media for laboratory analysis	Likely to assist in validation of model performance and in surface hazard prediction in extreme events
Industrial accidents, e.g. Buncefield, 1997 English Channel petrol spill	On-line detection of NMHCs; physical samples for laboratory analysis taken during incident	Networks may not necessarily be well located for accidents; limited volatile organic carbon (VOC) network; PM samplers likely to be most useful asset
Airborne disease, e.g. foot and mouth	Bioaerosol and genetic analysis of airborne material	No on-line instrumentation within existing networks; filter samplers may provide a resource; infrastructure can be used during prolonged events
National events, e.g. Olympics	Real-time information on key air pollutants to support short-term interventions during major events in support of public health	Networks generally good; information on many species available in real time; information on others inferred from long-term known relationships

Case study 1: Tracking industrial pollution incidents – Tanker spill in the English Channel

Industrial accidents often release chemicals to the atmosphere that are detected as part of on-going compliance monitoring activity. In 1997 a tanker collision in the English Channel resulted in around 7,000 tonnes of unleaded gasoline being discharged to the sea. The ensuing evaporation of volatile organic compounds (VOCs) to the atmosphere and transport on an easterly wind over the UK could be tracked using the Automatic Hydrocarbon Network. At the time of the emission the automatic monitoring network was more comprehensive than in 2013, and data were available on the spread of species such as benzene and toluene across most large UK cities.

The data collected by the compliance network provided for close to real time public health surveillance and could be compared with plume transport data predicted by the Met Office NAME model. The measurements and model agreed at many measurement locations, providing confidence in the predictive capability of the model for this particular event (see Welch *et al.* (1999) for further details).

Case study 2: Air quality advice and support for major events – London 2012 Olympics and Paralympics

During major events additional value may be drawn from compliance monitoring for a little additional investment in specific areas. In the case of the London 2012 Olympics and Paralympics this was to support policy makers in understanding any air quality issues in the run-up to and during the Games, and to provide additional public health alerts for both visitors to the Games and the athletes themselves.

Aspects of Defra's compliance monitoring and advice programmes enhanced during London 2012 and the Paralympics were as follows:

- Defra and its contractors worked closely with the Health Protection Agency (HPA) and the London Organising Committee of the Olympic and Paralympic Games (LOCOG) over the 12 months or more preceding the Games in order to develop the protocol and format for providing air quality bulletins.
- Polling frequency at monitoring stations is normally reduced overnight when pollutant concentrations generally decrease and telemetry costs can therefore be minimised. However, polling frequency was increased to every hour during the evenings for the duration of the Games so that up-to-date information was available during all events.
- Air quality forecasts were tailored for the Games, including developing higher spatial resolution daily CMAQ model runs for London and south east England. The Olympic torch route and major venues were overlaid on forecast model maps so that any potential problem hot spots could easily be identified and reported. "Normal" emissions inventories were however used for the modelling, i.e. they were not adjusted for the exceptional transport situation or any expected changes to London working hours.

7.1 Emerging pollution issues

7.1.1 Unconventional gas extraction

The natural gas released by hydrological fracturing of geological features (commonly referred to as fracking) has emerged as a major natural resource of fossil fuels. The activity is very widespread in the USA, however only a very small number of pilot-scale experiments has so far been carried out in the UK to date. Substantial financial imperatives exist for fracking gas exploitation in addition to benefits associated with national security of energy supplies.

The major direct environmental impacts of fracking are the release of hydrocarbons and drilling chemicals into underground water supplies and the uncontrolled leakage of methane and other non-methane hydrocarbons (NMHCs) to the atmosphere. Indirect environmental impacts include, of course, the generation of carbon dioxide (CO_2) gas on combustion.

Studies in the US have shown that significant releases of gases to the atmosphere in fracking regions can impact on ozone formation, and that very high ambient mixing ratios of various NMHCs can occur. Many fracking emissions in the US are in relatively remote regions away from large population centres, although there is also some activity close to populations. Should fracking become more widespread in the UK, the higher population density may by default lead to the co-location of fugitive emissions with significant populations.

The most significant impact of enhanced fracking emissions is likely to be the release of directly regulated VOCs such as benzene, and the generation of ground-level ozone, induced through additional releases of methane (CH_4) and NMHCs (from both released gas and from gas processing activities). Detection of enhanced emissions and tracing of these emissions to an actual fracking source is likely to be complex since all of these species have numerous sources. Perimeter fence monitoring of CH_4 is likely to form part of future permitting of the activity and emissions from gas capture facilities will be regulated.

More widespread detection of fugitive and processing emissions is likely to be challenging from an observation perspective. The UK has a tall-tower CH_4 monitoring programme supported by the Department of Energy and Climate Change (DECC) that makes seasonal and annual large area estimates of emissions using model inversion techniques. The high spatial and temporal variability of CH_4 in the atmosphere may make the detection of diffuse leakage rather complex. Detection of natural gas leakage from the Total Elgin gas platform demonstrated that near a point source the scale of emissions could be estimated using high time resolution CH_4 measurements, but that detecting the leak far downwind was possible only by the examination of the behaviour of other NMHC tracers.

Evaluation of the widespread influence of fracking emissions, should the sector develop in the UK, may potentially utilise measurements of various NMHCs currently made within the Automatic Hydrocarbon Network; although that network is rather sparse and monitoring stations are some distance from likely extraction zones. Natural gas condensate for example has a distribution of propane (C3) and n-butane (C4) that differs markedly from that seen in ambient air. Deviations from expected C3/C4 NMHC slopes in ambient data can potentially be used as indicators of natural gas emissions, but very few practical fracking data are available at present. Figure 8 shows a comparison of ambient air *vs.* air impacted by North Sea natural gas leakage demonstrating the differences in NMHC distributions that can be detected in samples impacted by this source.

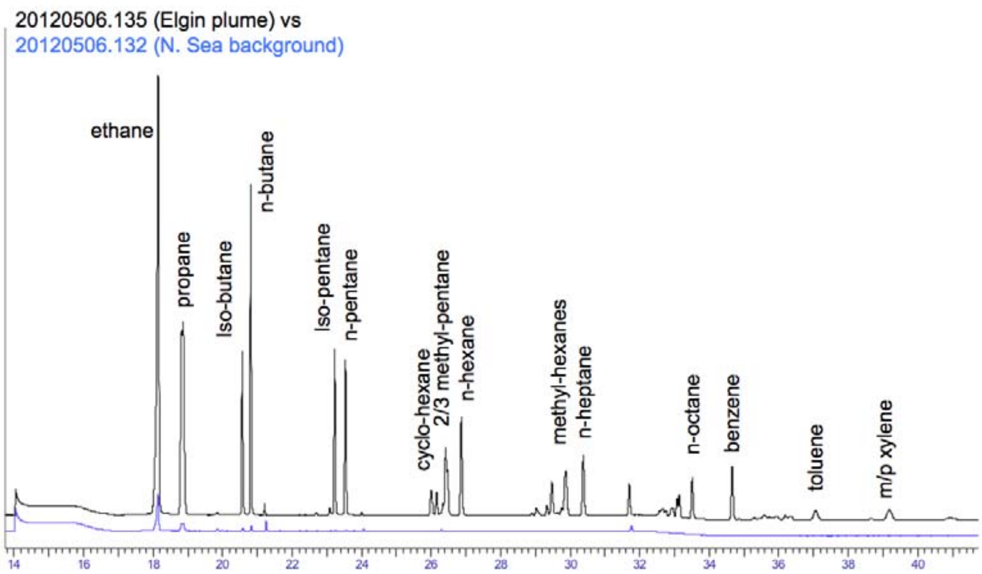

Figure 8: A comparison of light hydrocarbon content in ambient air and from natural gas leakage, as shown in gas chromatograms from the North Sea boundary layer.

Any expansion of the NMHC monitoring networks could operate with a dual purpose. The Non-Automatic Hydrocarbon Network (using adsorption tubes) is unlikely to have sufficient trapping efficiency to measure light hydrocarbons, however, any additional release of, for example, benzene from waste processing would be detected by this network.

7.1.2 Retrofit carbon capture and storage

The UK Government has highlighted retrofitted carbon capture and storage (CCS) technology as a potential tool to enable the UK to achieve its climate change obligations. The most developed technology in this field uses regenerative amine chemical scrubbers to remove carbon dioxide (CO_2) from coal and gas combustion flue gas. The reaction between CO_2 and the amine is reversible on heating and a pure stream of CO_2 is then released for storage. The amine is regenerated and returned to the flue gas scrubber. Atmospheric emissions of amine-related materials from the flue gas are expected from this process, along with oxidation products formed in the oxidative environment (6-12% oxygen) of the scrubber.

Very little is known about the potential scale of atmospheric emission of amine-related materials from this possibly large future source. During the capture process there is potential for some of the feedstock amine and related solvents to escape from the recycling step and be emitted into the atmosphere. In addition, oxidative and thermal degradation products created during the capture process may also result in the emission of nitrosamines, nitramines, amides, aldehydes, imidazoles, oxazolidones and ammonia.

Recent studies suggest that commonly used materials in post-combustion CCS, such as ethylamine, dimethylamine and monoethanolamine, are primarily removed from the atmosphere via reaction with hydroxyl (OH) radicals and by aerosol uptake (in roughly equal proportions) (Onel *et al.*, 2012 and 2013). Of significance to air quality are the potential contributions of this source to particulate matter levels and the direct toxicology of the oxidation products. Nitrosamines and nitramines have known carcinogenic properties, and both classes of compound contribute significant toxicity to cigarette smoke. Whilst not regulated in current air quality directives, guideline values of 0.3 ng m^{-3} for the total concentration of nitrosamines and nitramines in ambient air have been proposed by the Norwegian Institute of Public Health.

Once emitted, these compounds can undergo further oxidation processes in the atmosphere by photolysis or reaction with OH and nitrate (NO_3) radicals, thus contributing a source of organic nitrogen to the atmosphere. Furthermore, gas to particle partitioning or uptake in cloud droplets may lead to further chemical reactions and constitute a potential route of deposition to surface ecosystems and thus impact human health.

Existing Defra compliance networks may provide some opportunity for monitoring new emissions of this type, either via filter collection of particulate matter, e.g. through the heavy metals or PAH networks, or possibly measurement of gas phase organic nitrogen via the Non-Automatic Hydrocarbon Network of diffusion tubes. In both cases future analytical research would be required for method validation.

7.1.3 Novel materials including nanomaterials

There is currently a huge expansion in the use of novel materials, particularly of nanomaterials, in commercial products. Some such uses may lead to releases to the atmosphere, during either manufacture or use of the product. Whilst current examples are scarce, monitoring data for particulate matter, and especially data for particle number or size distribution, have the capacity to recognise the introduction of particulate matter with a novel size distribution to the atmosphere and might be valuable in the protection of public health. The only important recent example of this type of application of monitoring data has been concerned with a decline rather than an increase in airborne nanoparticles which occurred when a reduction in the sulphur content of motor fuels led to a change in both the number and size distribution of nanoparticles arising from road vehicle emissions (Jones *et al.*, 2012).

7.1.4 Biomass combustion

A number of policies and initiatives originating from both the EU and the UK Government may influence the use of biomass as an energy source within the UK in the near future. The UK is legally committed to meeting 15% of its energy demand from renewable sources by 2020 and this is incentivised through the Renewables Obligation (RO) (European Commission, n.d.). At the domestic scale the Renewable Heat Incentive (RHI) and the Renewable Heat Premium Payment (RHPP) are designed to encourage the uptake of renewable heat installations including biomass boilers. In addition, fears over future gas prices may encourage householders to use biomass combustion as a source of domestic heat through for example multi-fuel stoves. Emissions from large-scale power generation sources and biomass boilers covered under the RHPP are controlled through emissions limits. However, estimating emissions from domestic sources could be far more challenging since they depend on a large number of factors such as stove type, fuel type and quality, dilution conditions, operator know-how, ambient weather conditions, etc. Such sources may have an impact on future air quality in heavily populated areas, with particulates being of particular concern. Data and samples from the compliance network could potentially be used to evaluate proposed emissions factors for domestic biomass burning, although there may be some concerns as to whether the location of current monitors (often close to traffic sources) are suitable to assess trends in emissions from domestic sources. Molecular tracers such as levoglucosan have been identified for wood burning and trends in their concentrations could be assessed by gas chromatography analysis of PM filters from the compliance network. Reporting on trends in air quality that may result from policies designed to tackle climate change could also be of importance to DECC.

7.2 Other civil contingency

7.2.1 Security and defence applications

A range of potential chemical, biological, radiological and nuclear (CBRN) threats exist in the UK. The Defra compliance monitoring network in itself offers no capability to provide first response detection or warnings of emissions that may be immediately harmful to health. There are however a number of potential scenarios where widespread windborne dispersion of damaging materials through the atmosphere could be evaluated using compliance monitoring infrastructure.

Airborne particulate matter generated from explosive releases – whether deliberate or accidental – may be sampled automatically by the various PM monitoring instruments in Defra and local authority networks. Timely access to filter samples is potentially an important resource to establish the spread of CBRN-type materials. The visibility and capability of the Defra networks to respond is potentially not as high as it might be, but is likely to be the single most significant national asset available for monitoring the regional spread of airborne particulate pollution from an explosive event.

7.2.2 Volcanic ash

Whilst rare, it is possible for overseas volcanic eruptions to cause significant impact on the UK public. The 2010 Icelandic eruption of the Eyjafjallajökull volcano caused very widespread disruption to international air travel, with large economic losses to business and airlines in particular. This event placed a number of demands on atmospheric measurements to determine: whether dispersion models were providing a reasonable simulation of spread of material; whether the event was having an impact on the UK population at the surface; whether particulate matter and sulphur dioxide (SO_2) at the surface were likely to damage aircraft engines on take-off; and whether there were any wider ecosystem impacts of the volcanic event.

The compliance networks offer some notable capability in this regard. Measurements of SO_2 and PM_{10} are widespread through the UK compliance network and both species give some information on the potential grounding of volcanic plumes at the surface. The elemental analysis of PM material in the Defra networks also now includes fluorine, the determination of which is essential if entry of this chemical to the food chain, via surface deposition and then uptake by grazing cattle, is to be evaluated.

Experiences in 2010 suggest that the monitoring network is generally well configured to respond to a similar event, and that this dual use provides an additional motivation for the maintenance of a countrywide SO_2 monitoring capability within the compliance network.

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